

Final Project Report

pix2pix

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Abstract—Colorizing black and white images has been one of the most exciting applications of deep learning. The goal of this project was to build a model able to perform colorization of colorless images. To do so, we used one of the baseline model in the image-to-image translation problem: pix2pix [1]. The first step was to replicate the initial results in pix2pix original paper to understand its Conditional GAN architecture. The main dataset used was Paris facade images and the goal was to rebuild the picture from a colored architectural sketch. One major problem of image-to-image translation is that it's very difficult to quantify the model efficiency. In order to find an alternative, we compared and mixed the use of different losses ($L1$, $L2$ and the Binary Cross Entropy loss) in order to obtain the most visually realistic images.

To perform colorization, we used the *Country211* dataset, created black and white images and then applied the pix2pix model. We succeed to achieve visually interesting results. The model retrieves the colors of main object or places such the sun yellow or the blue of the sea.

Index Terms—conditional GAN, Image colorization and reconstruction, U-Net architecture, PatchGAN discriminator.

I. INTRODUCTION

Generative Adversarial Network (GAN) has turned out to be extremely efficient in performing image-to-image translation tasks. The main idea of GANs is to simultaneously train two models; a generator G that captures a certain data distribution, and a discriminator that determines whether a sample came from the original distribution or from a generated image. Conditional GAN is a type of GAN that involves the conditional generation and discrimination of images. In cGAN, the generator and the discriminator also take as input a prior knowledge about the desired output. For example, in the particular case of colorization, this information corresponds to the black and white image.

pix2pix proposes a general solution to many image-to-image tasks based on the cGAN. It's a model who has turned out to be extremely efficient and general. It succeeds to perform well on a lot of different tasks such as image colorization, sketches to images, architecture labels to photo, semantic segmentation... The architecture of this generator is

based on the *U-Net* encoder-decoder network to keep track of high frequency information and its discriminator uses an architecture called *PatchGAN* which divided the images in patches and classifies each patch as real image or fake one. In this context, we focused our work in two steps. The first one was to implement the pix2pix architecture, understand the influence of the different kind of losses present in the model and try to replicate a part of the initial results [1]. Then, we used this model to perform black and white picture colorization.

II. DATA

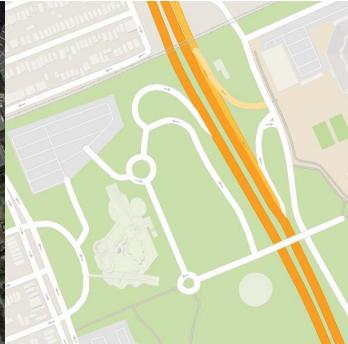
With our pix2pix implementation, we aimed to resolve the three following tasks: creating realistic facade images from semantic segmentation images, creating realistic sky-view Maps from Maps, and coloring black and white images. Thus, we needed to collect all the relevant datasets for these tasks.

This process was not a challenge for Facades and Maps since pix2pix authors shared their datasets [2]. There is 400 training, 100 validation and 110 testing images in Facades, and 1096 training, 1098 validation images for Maps. Each image is 256×512 and their structure is always the same: in the left-hand part of the image we have the ground-truth 256×256 picture and in the right-hand part we have the label Maps. Obviously, pix2pix's GAN has only access to the label map during inference time.

Nonetheless, the dataset for the black and white task – which is our main focus task for this project – was not provided; we thus had to build it ourselves. To do so, we looked for an already existing dataset that would provide a good variety of colorful images (i.e. not just cat and dogs); the authors from pix2pix used ImageNet dataset, but its size (150GB) might be overbearing given our limited computing resources. Hence, the dataset we looked for also had to have a reasonable size. For all of these reasons, we chose the *Country211* [3] dataset from OpenAI. It is a



(a) Facades



(b) Maps

Fig. 1: Examples from Facades and Maps datasets; ground-truth is to the left and label map to the right

subset from the *YFCC100m* (Yahoo Flickr Creative Commons 100 Million) dataset, keeping only images that have GPS coordinate corresponding to a ISO-3166 country code. It matches all of our requirements and weighs 11GB, which is a reasonable size given our computing resources. It consists of 31,650 training, 10,550 validation and 21,100 testing images of various sizes.

We then converted all of these images to the pix2pix format as described for Facades and Maps datasets. To do so, we resized each image to a 256×256 , then created their label Maps for our particular coloring task, which is here is just a black and white version of the image; we used Python library `PIL` which is adapted for this kind of task. We then horizontally concatenated each image to its corresponding black & white label map, which finally gives us our adapted images for pix2pix.

We did not always use all of the images for training and parameterizing our models, only a portion of it; we then gradually increased the number of images used as we found best parameters until we included all of training/validation images from Country211 for our final training run.

This closes the Data part, and we will now describe the pix2pix model as well as our implementation of it.



(a) Before transformation



(b) After transformation

Fig. 2: Examples of an image from *Country211* dataset before and after our black & white transformation in pix2pix format

III. MODEL

In order to complete the image-to-image translation task, we use the same approach as pix2pix [1], exploiting an adversarial paradigm and training both a generator and a discriminator.

A. Generator

The generator component is an encoder-decoder with skip connections between mirrored layers in the encoder and decoder stacks. The type of architecture is referred as "U-Net" in the original paper [1].

The input image is first downsampled through a sequence of convolution blocks and then upsampled through a sequence of deconvolution blocks. Each blocks, contains, in addition to its main layer, a module processing the filter maps with one or several of the following : batch normalization, dropout and ReLU/LeakyReLU activation. The skip connections involve the concatenation of the output channels from layer i in the downsampling block with those of layer $n - i$ in the upsampling block. The idea behind this operation is to allow to some "early" features to flow easily through the complex architecture and not to suffer from too heavy compression. More details can be found on the architecture diagram 3.

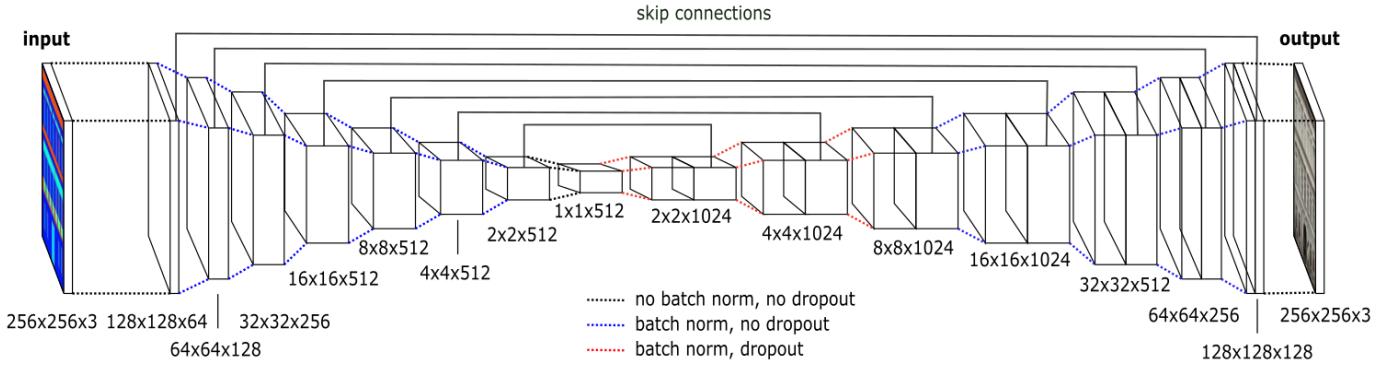


Fig. 3: pix2pix generator architecture

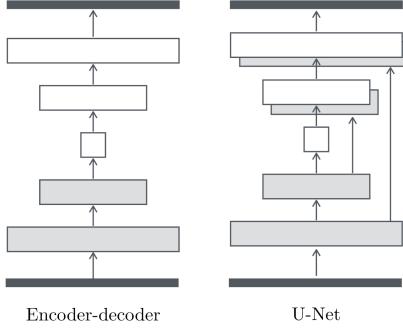


Fig. 4: Encoder-decoder vs U-Net architecture

B. Discriminator

The discriminator takes both the condition image (e.g. architecture label in the case of Facades dataset) as well as an other candidate image, either the one created by the generator or the real corresponding image. Its architecture first concatenate the channels of both inputs and then operates a succession of convolution and batch normalization operations. The output is a one-channel feature map of size 30x30. The values obtained might be interpreted as the pre-sigmoid probabilities of each cell being a real image. A binary cross entropy loss with logits is used to process to improve the discriminator behavior against the one of the generator.

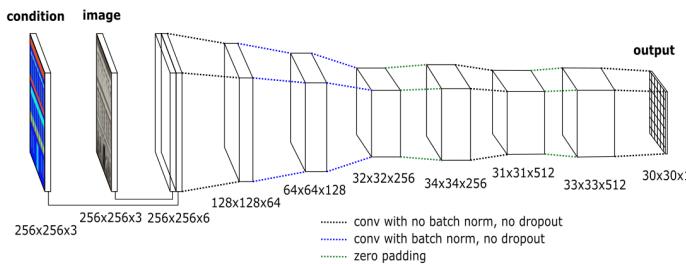


Fig. 5: pix2pix discriminator architecture

C. Implementation

We implemented pix2pix from scratch on PyTorch.

IV. TRAINING

A. Objective function

The objective function of a conditional GAN (cGAN loss) can be written as:

$$\mathcal{L}_{cGAN}(G, D) = \mathbb{E}_{x,y}[\log(D(x, y))] + \mathbb{E}_{x,z}[1 - \log(D(x, G(x, z)))]$$

where G and D are respectively generator and the discriminator, z the random noise, x is the prior information and y the ground truth. It should be noted that there is no random noise fed to the pix2pix model, but it is replaced by adding random dropout in the generator architecture to the first three decoder layers. The way of training the model of cGAN is equivalent of how to train a classic GAN: the generator tries to minimize this function again a discriminator which tries to maximize it.

In the image-to-image translation task, the generated image must be close to the ground truth image. Thus to the cGAN loss is added an $L1$ loss in pix2pix:

$$\mathcal{L}_{L1}(G) = \mathbb{E}_{x,y,z}[\|y - G(x, z)\|_1]$$

The $L1$ norm is preferred to the $L2$ norm because it generates less blurred images. $L1$ norm succeeds to extract high frequencies in the image which corresponds to the little details whereas the $L2$ norm tends to extract mainly low frequencies (i.e. the general pattern of the image such as the light or building colors).

The overall pix2pix optimization problem can be written as:

$$\min_G \max_D \lambda \mathcal{L}_{cGAN}(G, D) + \lambda \mathcal{L}_{L1}(G, D)$$

where λ is an hyper-parameter of the model which controls how close we want the generated image to the ground truth. The higher λ is, the closer the two images are. In the original paper [1], this parameter is to 100, but in our study, we found that the model was more efficient with a parameter of 200.

B. Data Augmentation

As for data augmentation, authors from the paper applied a random jitter to their Maps and Facades dataset: they resize each image to 286×286 and then randomly crop them back to 256×256 size. They also use mirroring on all of their datasets. We found that using these data augmentation routines slightly worsened our results – and in fact some images from pix2pix datasets were already jittered –, so we decided not to use them in our final implementation.

C. Model Weights

The following table (IV-C) contains the number of parameters and the memory needed to save the generator, the discriminator and the overall pix2pix model:

	Generator	Discriminator	pix2pix
Parameters	54,413,952	2,768,641	57,182,593
Memory (in Mo)	217.7	11.1	228.8

V. RESULTS

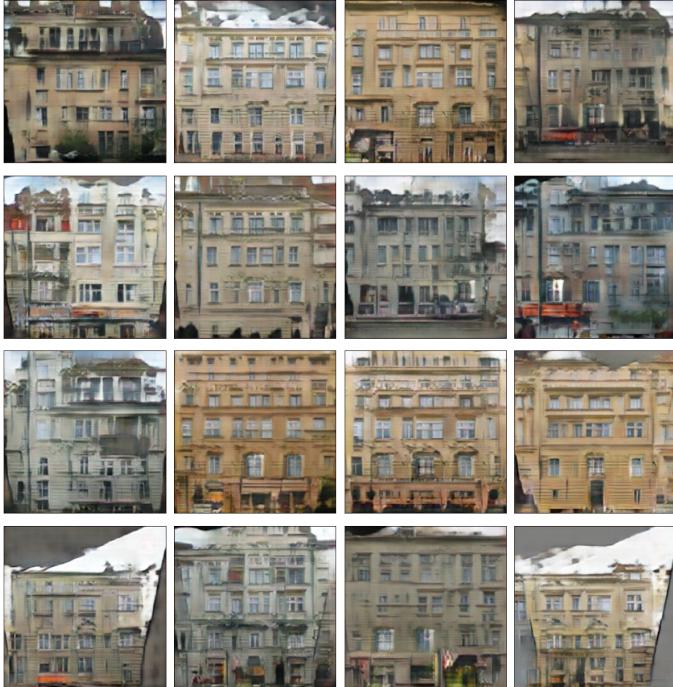


Fig. 6: Generated images after training of 200 epochs with data augmentation

VI. ABLATION EXPERIMENTS

A. Generator Losses

We first took a look at the impact of the generator loss on the training and outputs. We used different possibilities for the generator loss. We took into account the two initial losses present in pix2pix model: the $L1$ norm and the cGAN loss. In addition, we incorporated also the $L2$ norm loss in order to

understand its effect on the outputs. We run the model over 50 epochs with the facade dataset and used the seven following combinations for the generator loss and keeping the cGAN loss for the discriminator. The combination are:

- $L1$ loss
- $L2$ loss
- $L1$ loss + $L2$ loss
- cGAN loss
- $L1$ loss and cGAN loss
- $L2$ loss and cGAN loss
- $L1$ loss + $L2$ loss and cGAN loss

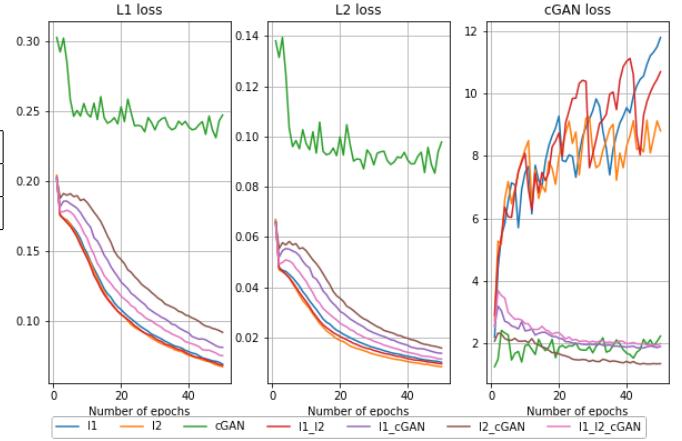


Fig. 7: Evolutions of the three main metrics for the generator while training it with different losses over 50 epochs.

We noticed on Figure 7 that if we train the model using only the $L2$ norm for the generator, it produces a model with a low $L1$ metric, even lower than if we train the model with $L1$ norm as generator loss. It means that in the particular case of image reconstruction from architectural label, $L2$ norm seems to not produce blurred images for the training set. Looking at different outputs as 8, the model using $L2$ norm loss tends to be a little more blurred than a $L1$ model. Nevertheless, it always tries to capture the color of the ground truth image for the training set. It captures low frequency patterns. It generates over-fitting when we use the validation set. Because what is relevant here is to define a model able to rebuild an image from a sketch in a general case and not just outputting the correct color only for the training set. The model loses its generality.

Figure 8 was built only with a low number of epochs (50) over the training set in order to avoid over-fitting and being able to identify the true influence of each training method.

As we could expected, training the model only using the cGAN loss doesn't produce satisfying results(8). In order to achieve visually satisfying results, the cGAN loss must be mixed with other losses. Still after 50 epochs, we can distinguish in the output the influence of the generator convolution kernels.

Lastly, the most realistic models are mixing the cGAN loss

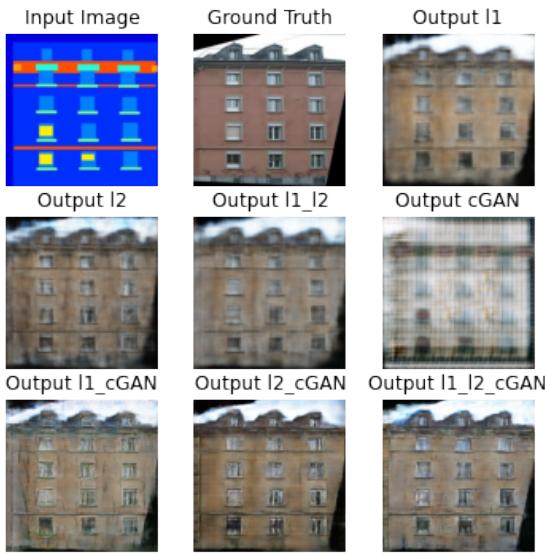


Fig. 8: Output of the model trained for 50 epochs using different losses. Training set.

with $L1$ and/or $L2$ norms over the training set. Looking at the outputs for the validation set(9), we can clearly see the difference of which frequencies the two different norm are extracting: the image details produced by the $L1$ norm model are realistic but it keeps track of the input color, whereas the $L2$ norm model gives realistic colors with a blurred output image.

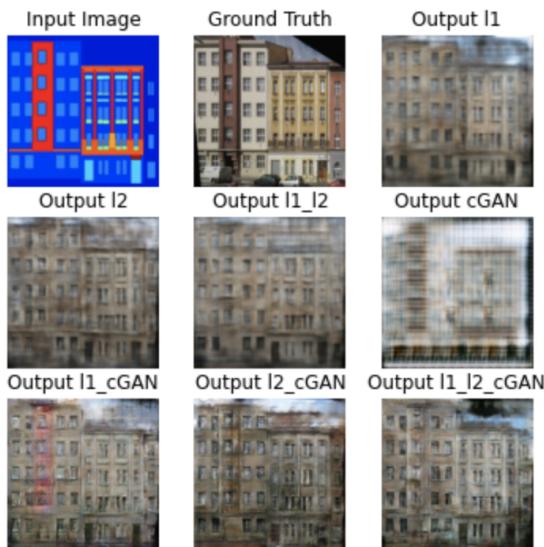


Fig. 9: Output of the model trained for 50 epochs using different losses. Validation set.

B. Impact of data augmentation

As we were in possession of relatively small datasets (e.g. 400 training images for Facades), our complex model was naturally prone to overfitting. In order to assess the significance of data augmentation, we trained pix2pix on Facades for 200 epochs with and without data augmentation using $L1$ + cGAN loss. In this part, data augmentation refers to random mirroring and cropping. Namely, we first toss a coin and mirror both the condition image and the real image accordingly, and then we rescale our image to 286x286 and random crop it to 256x256. This strategy is used to enrich our dataset so as to prevent overfitting.

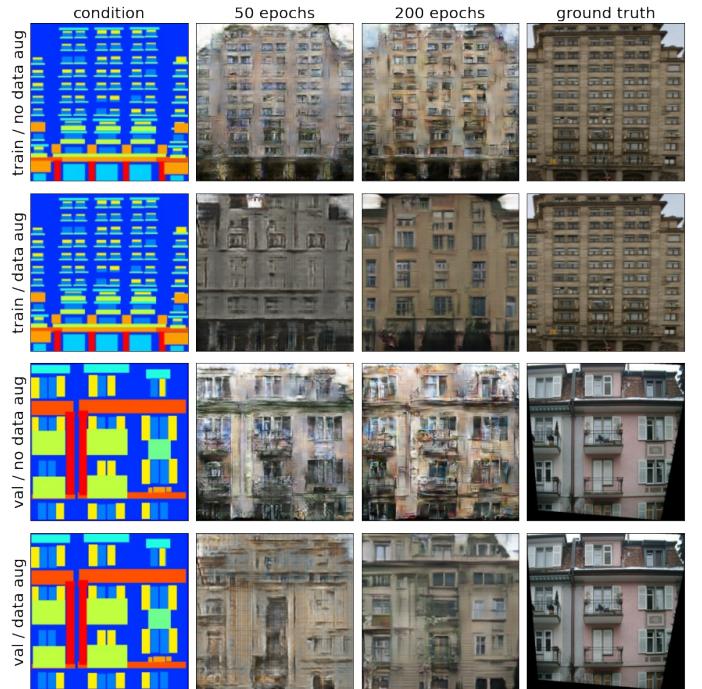


Fig. 10: Outputs of the generator with input with training or validation set with or without data augmentation (random mirroring and cropping)

On figure 10, we observe the results of our training experiment. The first two rows show the output of the generator on conditions encountered during training. We observe that without data augmentation, the network is trying to replicate the ground truth as much as possible, whereas with data augmentation the output image is more credible as a real image while being more structurally different from the ground truth. This is an indicator of overfitting. Indeed, the lack of data augmentation makes our generator able to perfectly replicate the ground truth given the input condition after a sufficient number of epochs. This is due to the overcomplexity of our model with respect to our dataset diversity. When encountering a new input condition, our model will behave poorly and produce an image likely to be unrealistic. Indeed, this is what we observe on the third vs fourth row of figure 10, exhibiting outputs on the validation set. Model trained with

data augmentation produces a credible facade while the other model’s output is easy to distinguish from a real facade.

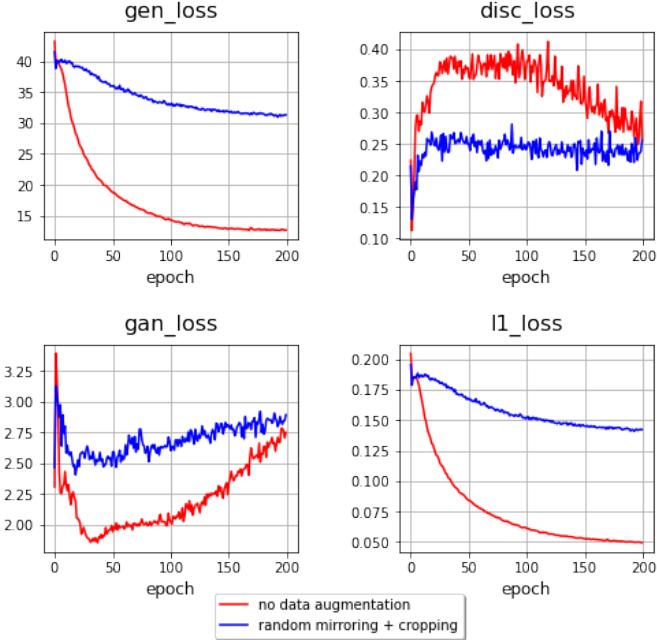


Fig. 11: Evolution of losses throughout training on Facades with or without data augmentation (random mirroring and cropping)

It is also interesting to track the different losses with and without data augmentation. As we can see on figure 11, the generator loss decreases extremely rapidly without augmentation. This is due to our model believing that it fully understands the dataset underlying distribution and producing output very close to ground truth but with poor generalization capability. Indeed, we observe that the training $L1$ loss depletes a lot faster without augmentation than with augmentation.

C. Image colorization

For image colorization, only a portion of the generated images seem to indeed have realistic coloring, even when taking the same hyperparameters as in the pix2pix paper. This might be explained by the lack of data (30,000 for our implementation vs 1.2 Millions for pix2pix), but also by the lack of power of the model itself. Indeed, the color outputs from the model presented in the original paper are not all impressive (cf Fig. 12), and on the Internet many other users came up with the same conclusion. This is why we decided to enhance our colorization model, inspired by [4] (itself inspired by *Super Resolution* literature <https://arxiv.org/abs/1609.04802>); the idea is to pre-train the Generator on a supervised task at the beginning of the training.

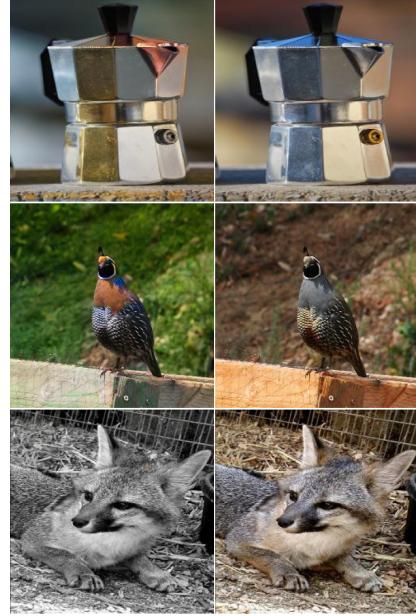


Fig. 12: Original pix2pix results on colorization task; left: generated images, right: ground-truth

Firstly, we pre-train the down sampling path of the Generator for classification (in fact, we use a ResNet-18 pre-trained on ImageNet). Then, we then pre-train the whole generator on the task of colorization with $L1$ loss using our training dataset. After these two stages, we will train our Generator and Discriminator as before with the cGAN and $L1$ loss.

VII. CONCLUSION

REFERENCES

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- [4] Colorizing black white images with U-Net and conditional GAN <https://towardsdatascience.com/colorizing-black-white-images-with-u-net-and-conditional-gan-a-tutorial-81b2df111cd8>
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