Generative Adversarial Networks

A gentle introduction and application for domain adaptation

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Outline

- Generative Adversarial Networks (GANs)
  - What are GANs?
  - How GANs work?
  - Types of GANs and applications
- Domain adaptation

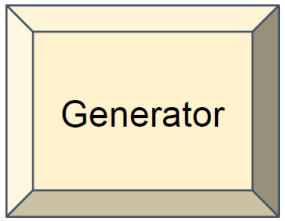
What are GANs?

- GANs are unsupervised deep learning methods
- GANs are considered one of the greatest deep learning breakthroughs in recent years
- They all operate under the same principle of having modules with adversarial (*i.e.*, competing objectives)

What are GANs?

- Two separate networks compete against each other: **generator** and **discriminator**

- This can be thought of as a game between a **counterfeiter** and an **art curator**

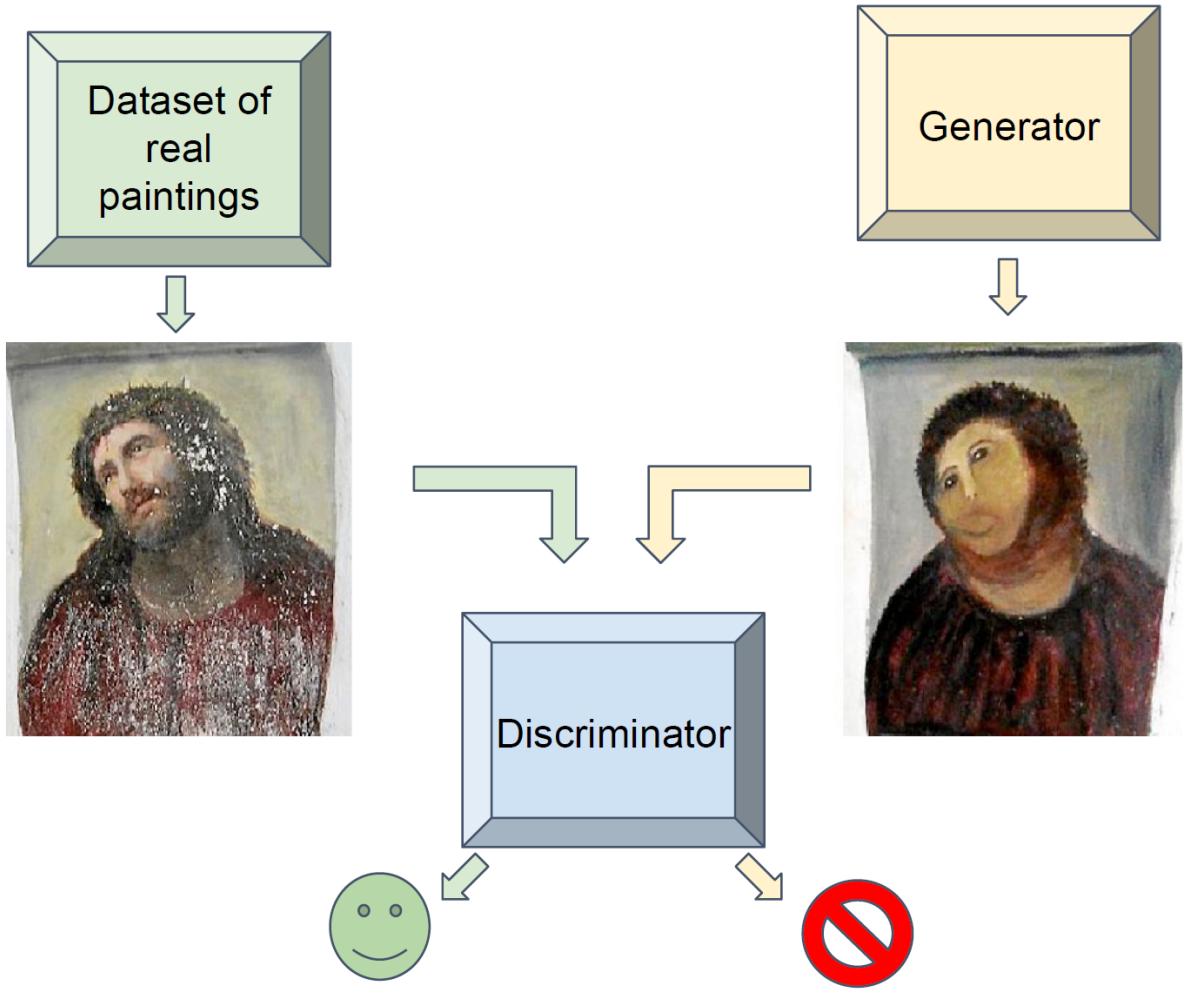


Generates samples that look convincingly real

Determines whether a sample is real or generated

What are GANs?

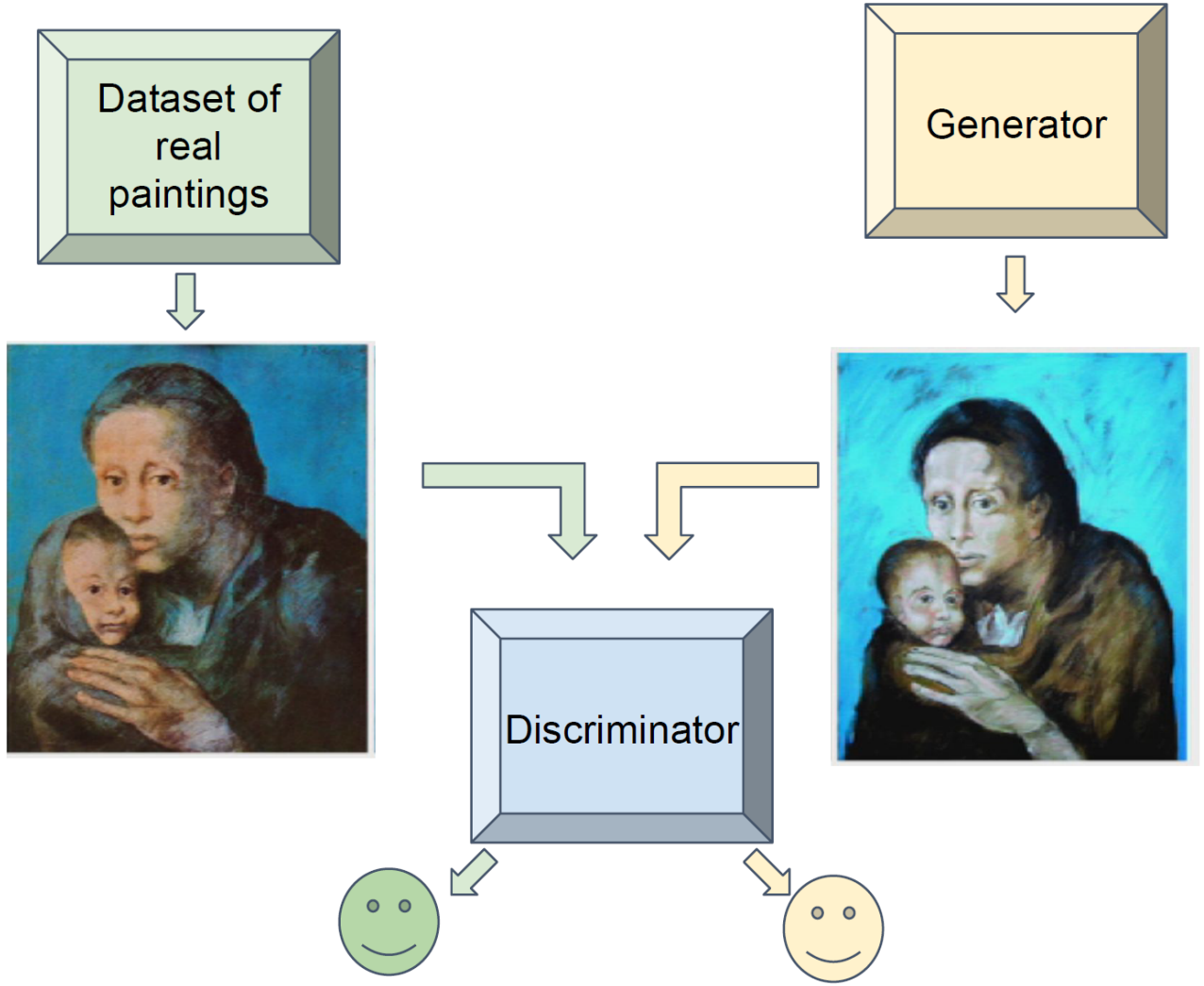
- The counterfeiter (generator) attempts to generate real looking images
  - At first the generator is pretty bad



https://www.pri.org/stories/2012-08-25/amateur-restoration-botches-jesus-painting-spain

What are GANs?

- Eventually, the generator learns to fool the discriminator and can generate convincing images

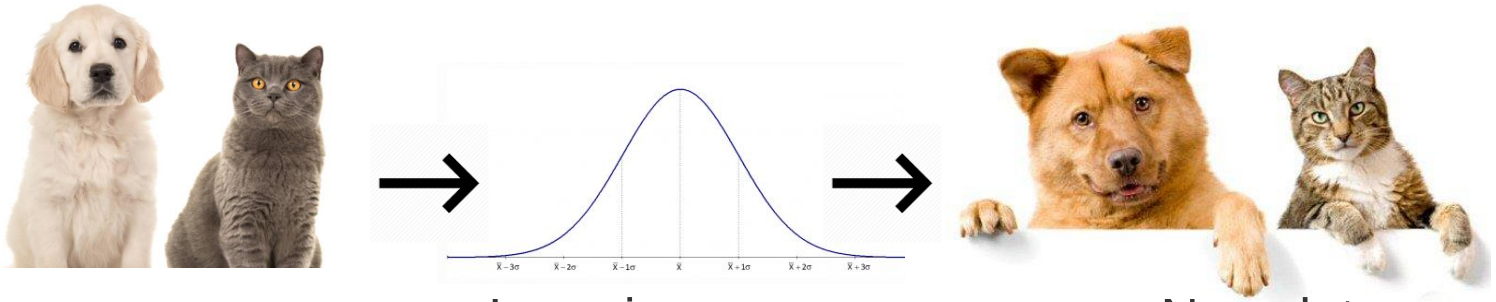


https://www.channel4.com/news/art-forgery-beltracchi-wolfgang-ernst-picasso-paraic-obrien

Generative vs Discriminate Models

1) Discriminative models

2) Generative models



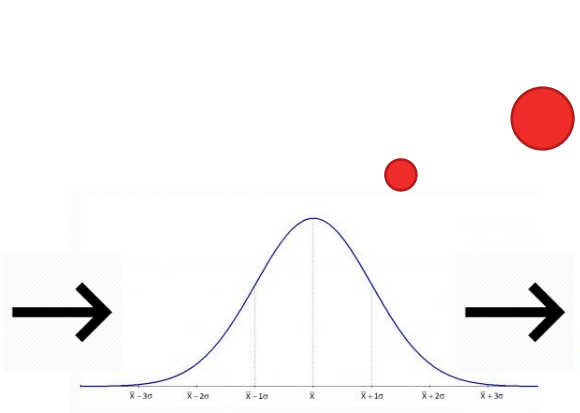
- Dataset
- Learning distribution
- New data

Generative vs Discriminate Models

1) Discriminative models

GANs are generative models where the data distribution is learned implicitly

2) Generative models

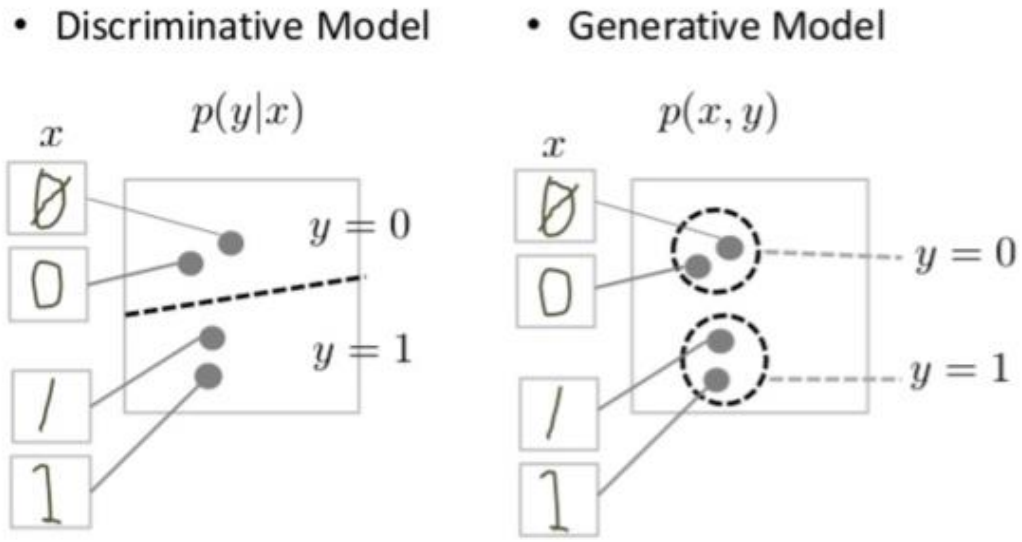


- Dataset
- Learning distribution
- New data

Generative vs Discriminate Models

- The discriminative model tries to tell the difference between handwritten 0's and 1's by drawing a line in the data space

- The generative model tries to produce 1's and 0's that fall close to their real counterparts in the data space
  - Model the distribution throughout the data space



Question #1

- You have IQ scores for 1000 people. You model the distribution of IQ scores with the following procedure:
  - Roll three six-sided dice
  - Multiply the roll by a constant w
  - Repeat 100 times and take the average of all the results
  - You try different values for w until the result of your procedure equals the average of the real IQ scores. Is your model a generative model or a discriminative model?

- (a) Generative model
- (b) Discriminative model
- (c) Not enough information to tell

Question #1

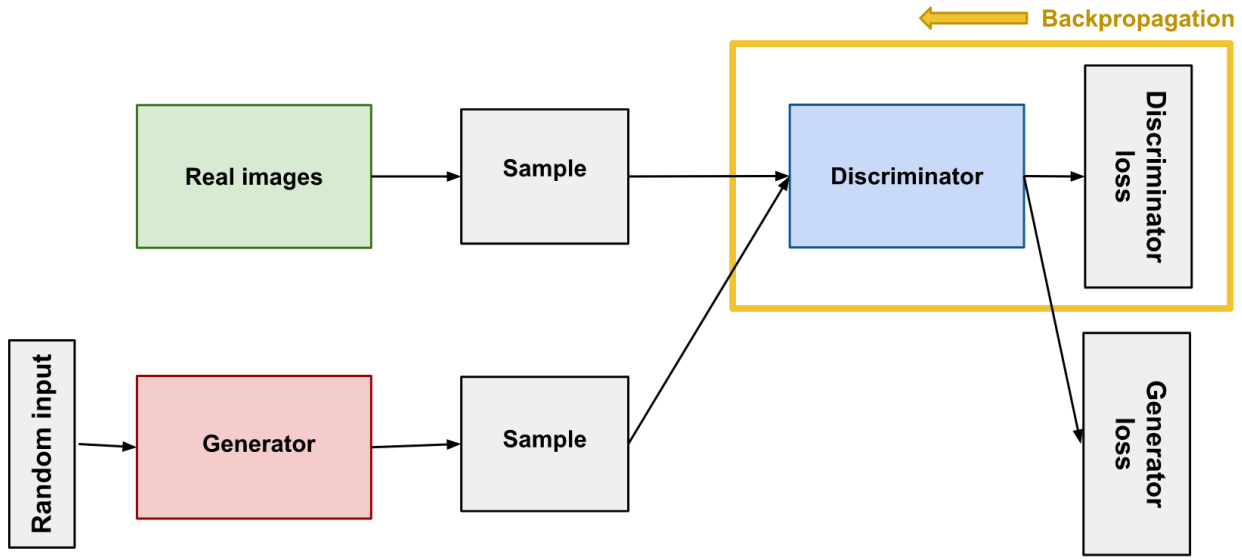
- You have IQ scores for 1000 people. You model the distribution of IQ scores with the following procedure

- **(a) Generative model**: with every roll you are effectively generating the IQ of an imaginary person. Furthermore, your generative model captures the fact that IQ scores are distributed normally (that is, on a bell curve)

- (b) Discriminative model: might try to classify an IQ as fake or real

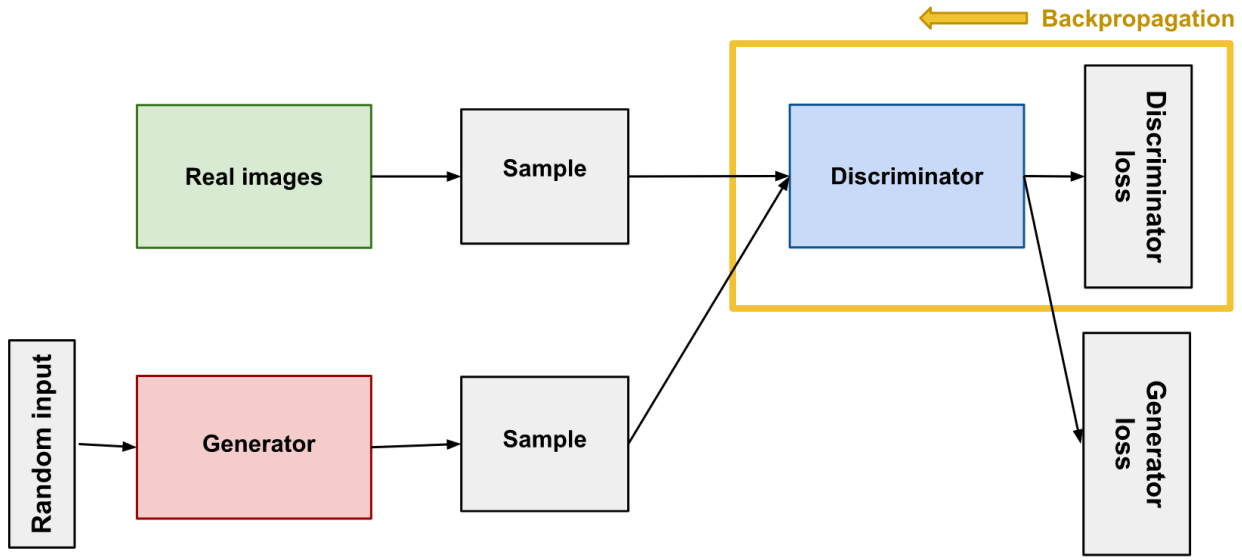
Discriminative Models

- The discriminator in a GAN is simply a classifier
- During discriminator training:
  - Classifies real data and fake data from the generator
  - The discriminator loss penalizes it for misclassification
  - Updates its weights through backpropagation



Discriminative Models

- The discriminator connects to two loss functions:
  - During discriminator training, the discriminator ignores the generator loss and just uses the discriminator loss
  - The generator loss is used during generator training



Generative Models

- Learns to create fake data by incorporating feedback from the discriminator
  - Learns to make the discriminator classify its output as real

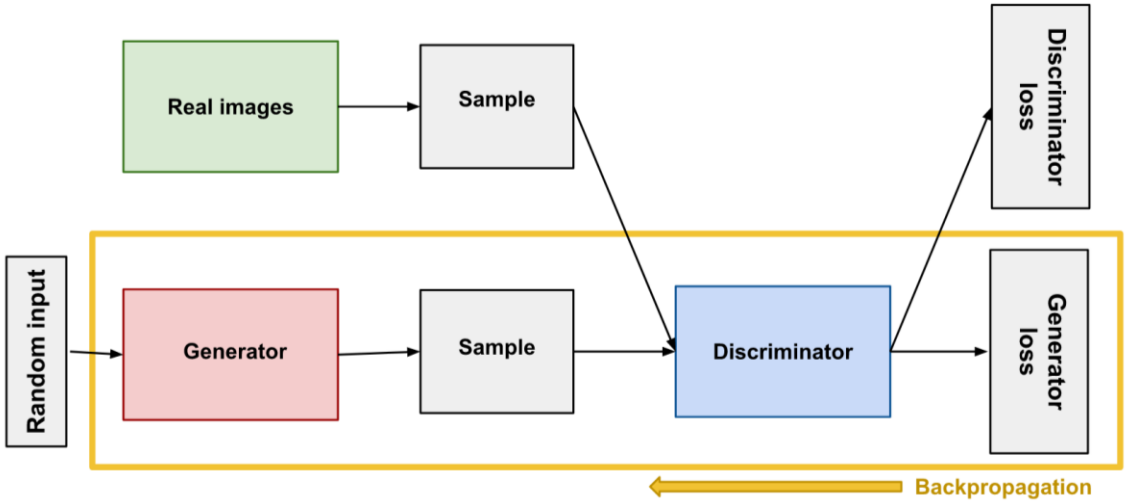
- Generator training:
  - random input
  - generator network, which transforms the random input into a data instance
  - discriminator network, which classifies the generated data
  - discriminator output
  - generator loss, which penalizes the generator for failing to fool the discriminator

Generative Models – Random Input

- GAN takes random noise as its input
- The generator transforms this noise into a meaningful output
- By introducing noise, the GANs can produce a wide variety of data, sampling from different places in the target distribution
- Experiments suggest that the distribution of the noise doesn't matter much, so we can choose something that's easy to sample from, like a uniform distribution

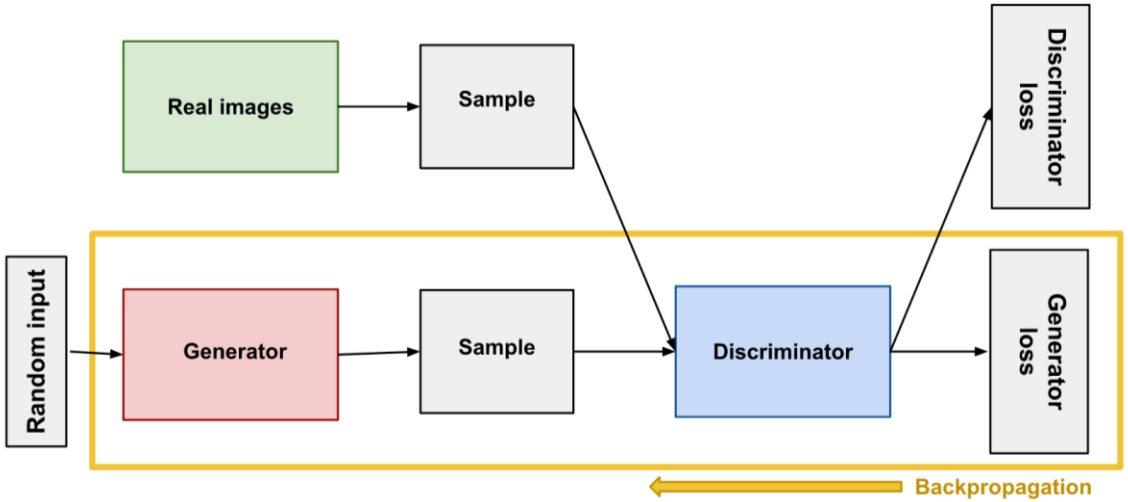
Generative Models – Discriminator to train the generator

- The generator feeds into the discriminator
- D*iscriminator* produces the output
- The generator loss penalizes the generator for producing a sample that the discriminator network classifies as fake
- **The discriminator do not change during generator training**
  - Trying to hit a moving target would be a harder problem for the generator



Generative Models – Training

- Sample random noise
- Produce output from sampled random noise
- Get discriminator "Real" or "Fake" classification for generator output
- Calculate loss from discriminator classification
- Backpropagate through discriminator and generator to obtain gradients
  - Change only the generator weights



Question #2

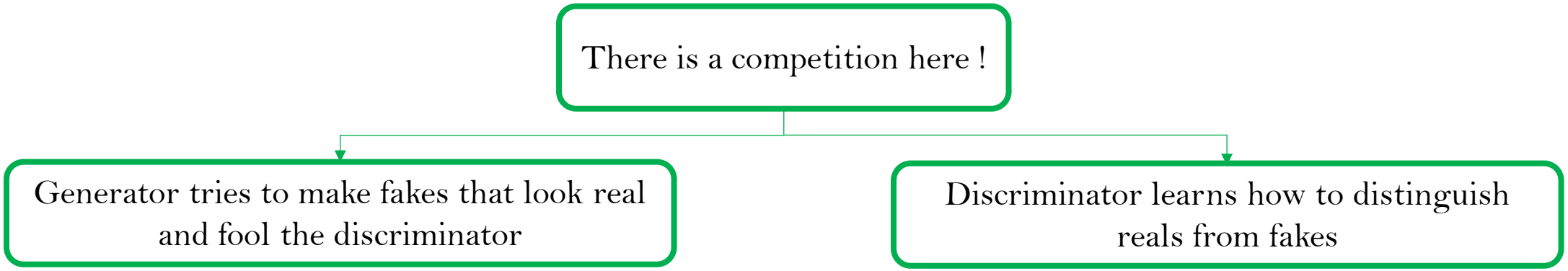
- GANs are trained by having a _____ and a _____, two separate networks that _____ each other:

- (a) discriminator, generator, compete
- (b) discriminator, generator, collaborate
- (c) discriminator in the source data, discriminator in the target data, compete

Question #2

- GANs are trained by having a _____ and a _____, two separate networks that _____ each other:

- **(a) discriminator, generator, compete**



How do GANs Work?

- Mathematically, this can be expressed as a **MinMax** game, where the generator tries to **minimize** the objective function *V* while the discriminator tries to **maximize** it. Both networks are trained successively

$$\min_G \max_D V(D,G) = \mathbb{E}_{\boldsymbol{x}\sim p_{\text{data}}(\boldsymbol{x})}[\log D(\boldsymbol{x})] + \mathbb{E}_{\boldsymbol{z}\sim p_{\boldsymbol{z}}(\boldsymbol{z})}[\log(1 - D(G(\boldsymbol{z})))].$$

$D(x)$ is a neural network that predicts how confident it is that the input image ***x*** is real. "The **probability** that the sample is real"

$G(z)$ is a neural network that generates an image given a noise signal *z*

How do GANs Work?

- When training the **generator**, we want to **minimize** the term in blue, i.e. we want to maximize the error that *D* will make on a generated image *G(z)*

$$\min_G \max_D V(D,G) = \mathbb{E}_{\boldsymbol{x}\sim p_{\text{data}}(\boldsymbol{x})}[\log D(\boldsymbol{x})] + \mathbb{E}_{\boldsymbol{z}\sim p_{\boldsymbol{z}}(\boldsymbol{z})}[\log(1 - D(G(\boldsymbol{z})))].$$

- When training the **discriminator**, we want to **maximize** the terms in red, i.e. we want to minimize the error that *D* will make on a generated image *G(z).*

$$\min_G \max_D V(D,G) = \mathbb{E}_{\boldsymbol{x}\sim p_{\text{data}}(\boldsymbol{x})}[\log D(\boldsymbol{x})] + \mathbb{E}_{\boldsymbol{z}\sim p_{\boldsymbol{z}}(\boldsymbol{z})}[\log(1 - D(G(\boldsymbol{z})))].$$

Question #3

- Select the true statement about GANs

  - (a) When training the generator, we want to minimize the error that the discriminator will make on a generated image
  - (b) When training the discriminator, we want to maximize the error that the discriminator will make on a generated image
  - (c) When training the discriminator, we want to minimize the error that the discriminator will make on a generated example

Question #3

- Select the true statement about GANs

  - (a) When training the generator, we want to minimize the error that the discriminator will make on a generated image
  - (b) When training the discriminator, we want to maximize the error that the discriminator will make on a generated image
  - **(c) When training the discriminator, we want to minimize the error that the discriminator will make on a generated example**

Question #4

- A typical GAN trains the generator and the discriminator simultaneously
  - True or False

Question #4

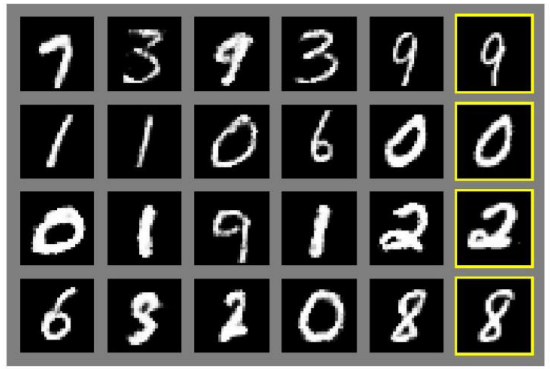
- A typical GAN trains the generator and the discriminator simultaneously

- True or **False:** A typical GAN alternates between training the discriminator and training the generator

- **The discriminator do not change during generator training**
  - Trying to hit a moving target would be a harder problem for the generator

Types of GANs and applications

- In the original paper, both digits and faces were generated by the network and look convincingly real. The yellow boxes show the closest match to its generated neighbors in the training dataset

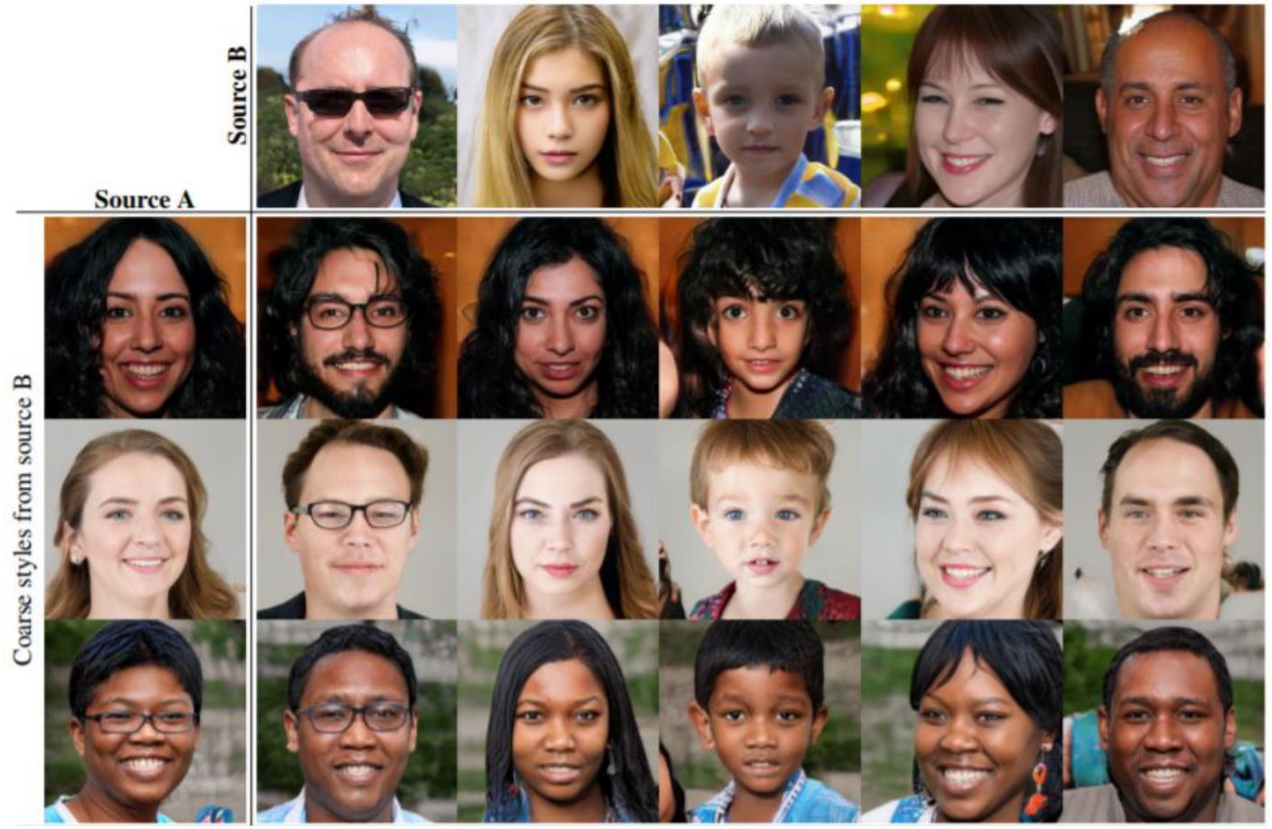


https://arxiv.org/pdf/1406.2661.pdf

Image Synthesis

- We can teach networks to generate realistic images that have never been seen before by the network. Which face is fake?

Style Transfer



https://arxiv.org/pdf/1812.04948.pdf

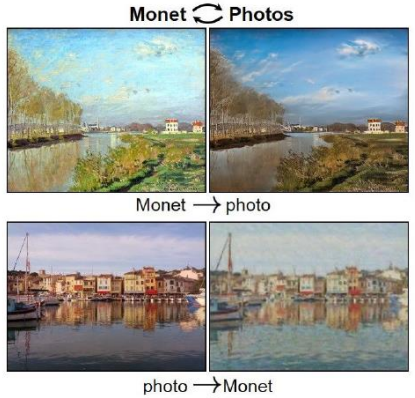
Face Inpainting

- Chunks of an image are blacked out, and the system tries to fill in the missing chunks
- GAN outperformed other techniques for inpainting images of faces

CycleGAN

- CycleGan introduced the concept of **cycle-consistency** loss to their GANs. This allowed training generators that would translate from domain X to domain Y
- This allows map between arbitrary domains with realistic results

$horse \rightarrow zebra$

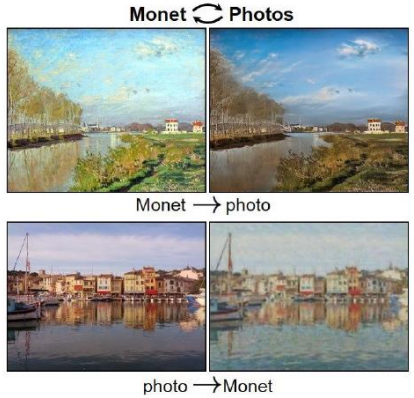


https://junyanz.github.io/CycleGAN/
https://github.com/junyanz/pytorch-CycleGAN-and-pix2pix

CycleGAN

- The training data for the CycleGAN is simply two sets of images (a set of horse images and a set of zebra images). The system requires no labels or pairwise correspondences between images

$horse \rightarrow zebra$



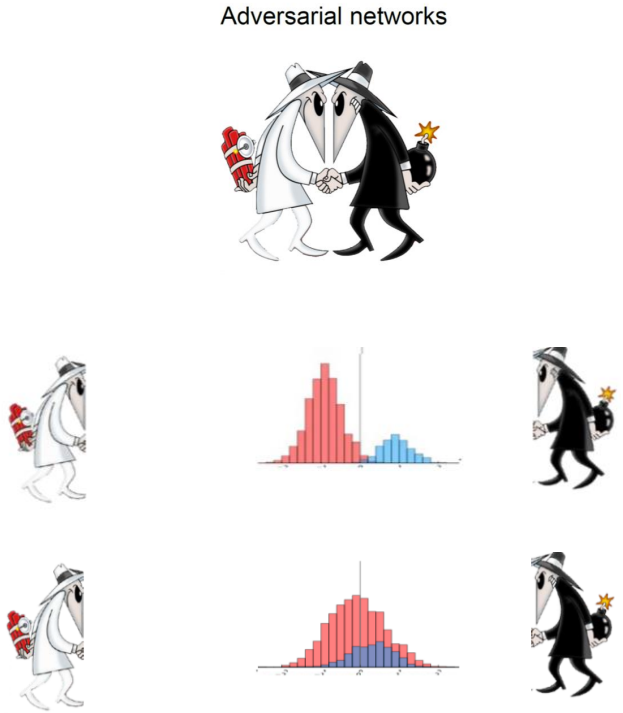
https://junyanz.github.io/CycleGAN/
https://github.com/junyanz/pytorch-CycleGAN-and-pix2pix

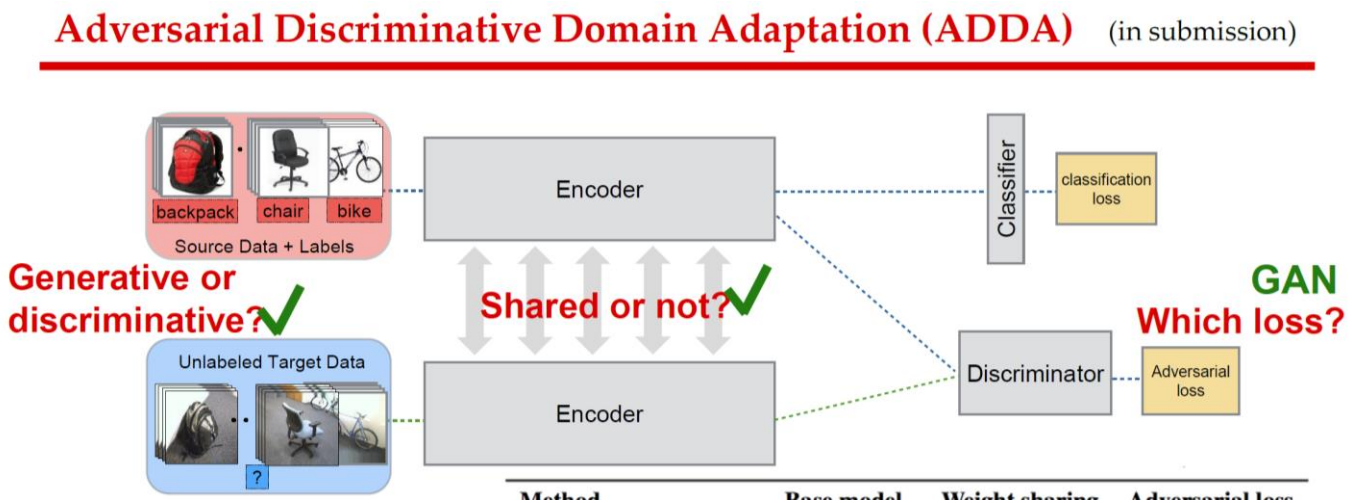
GANs Limitations

- **Non-convergence**: the model parameters oscillate, and the model does not converge
- **Mode collapse**: the generator collapses and produces a limited number of different samples
- **Diminished gradient**: the discriminator is too good that the generator gradient vanishes and learns nothing
- **Highly sensitive** to the hyperparameter selections

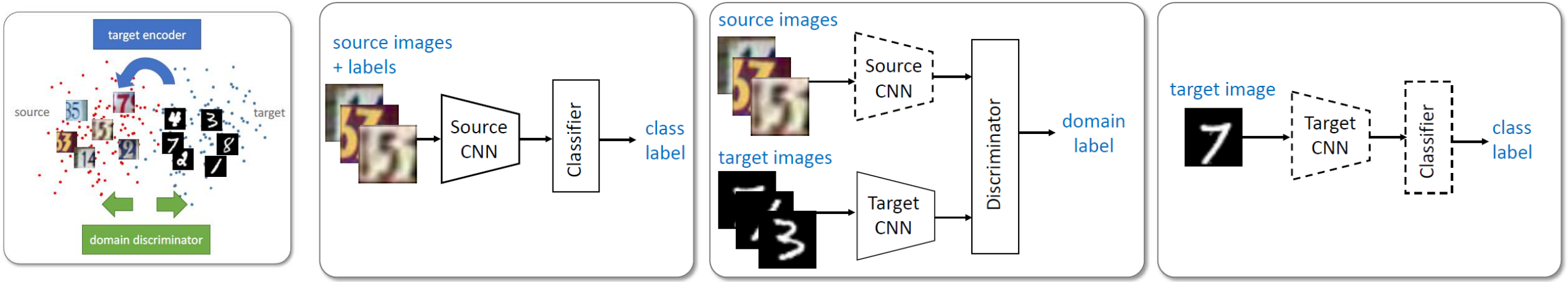
Domain Adaptation - Feature Space

- Train a network to minimize classification loss AND confuse two domains



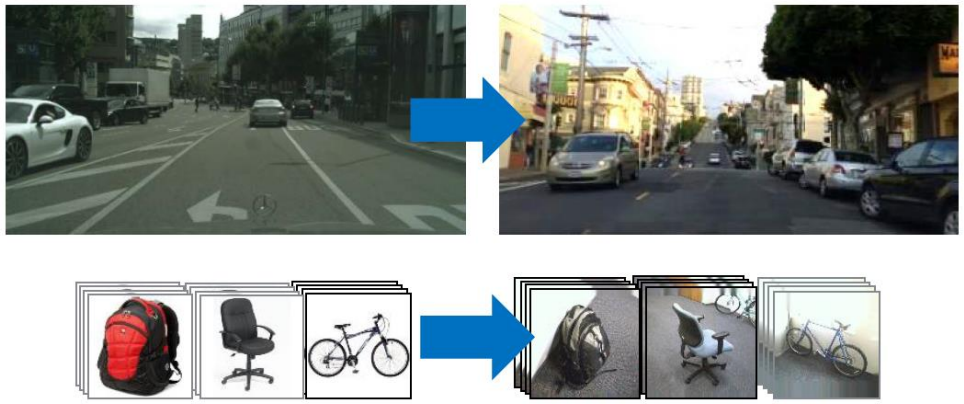


Domain Adaptation using Adversarial Networks

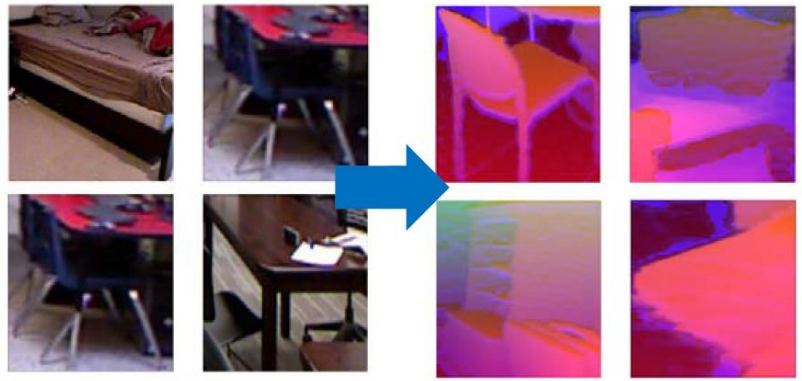


Domain Adaptation using Adversarial Networks

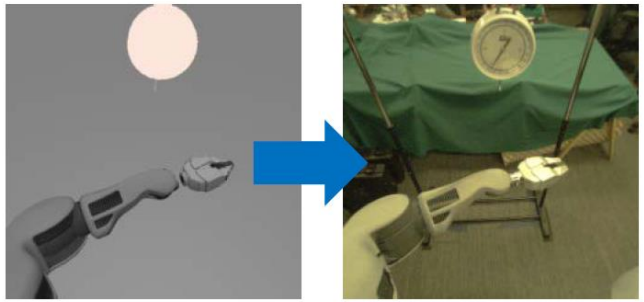
From dataset to dataset



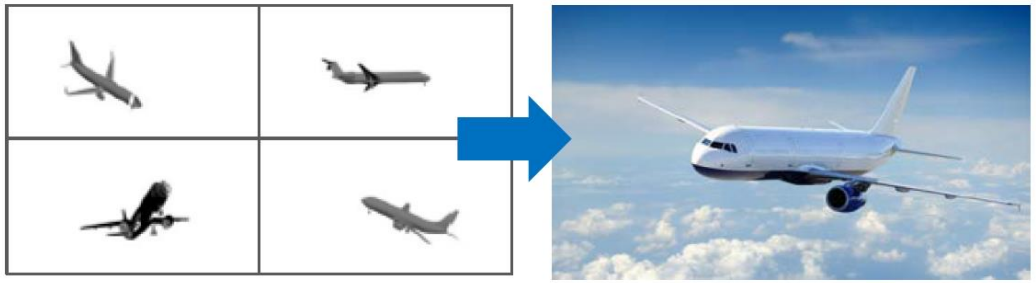
From RGB to depth



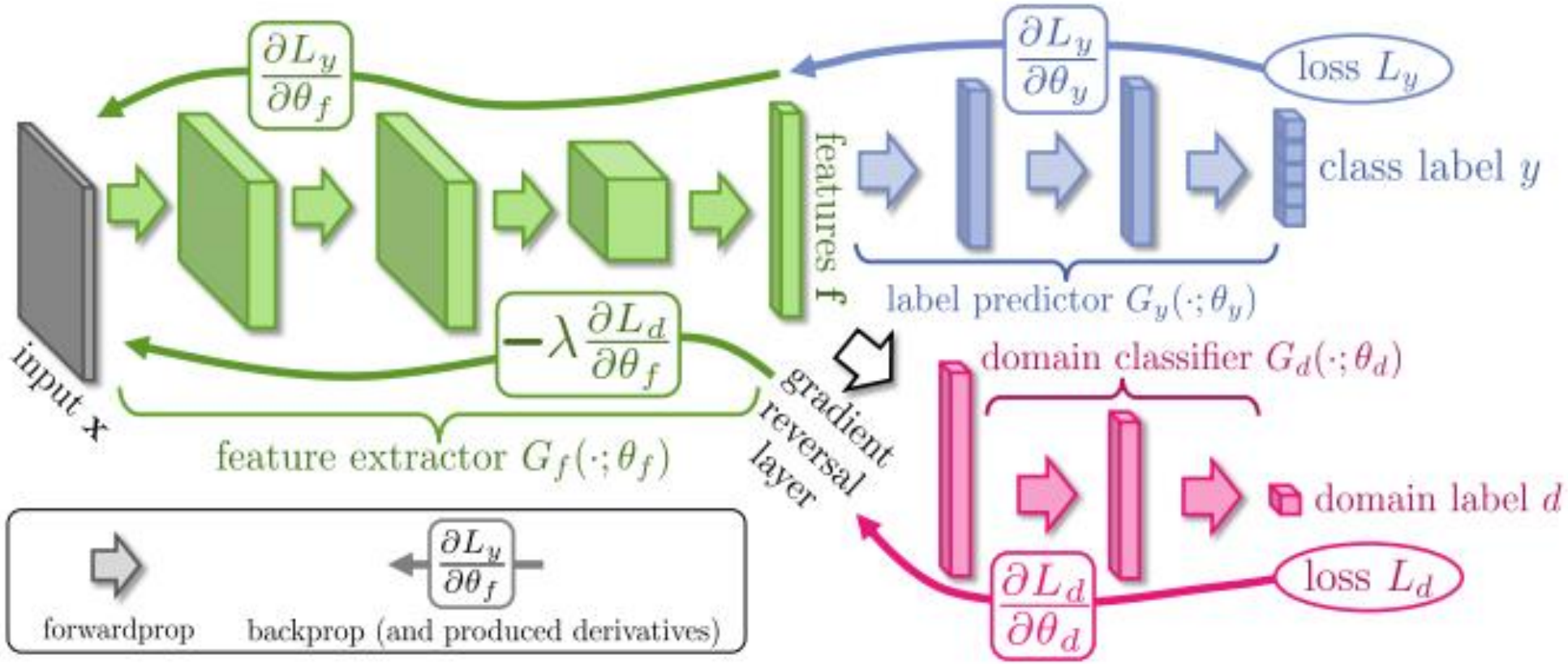
From simulated to real control



From CAD models to real images

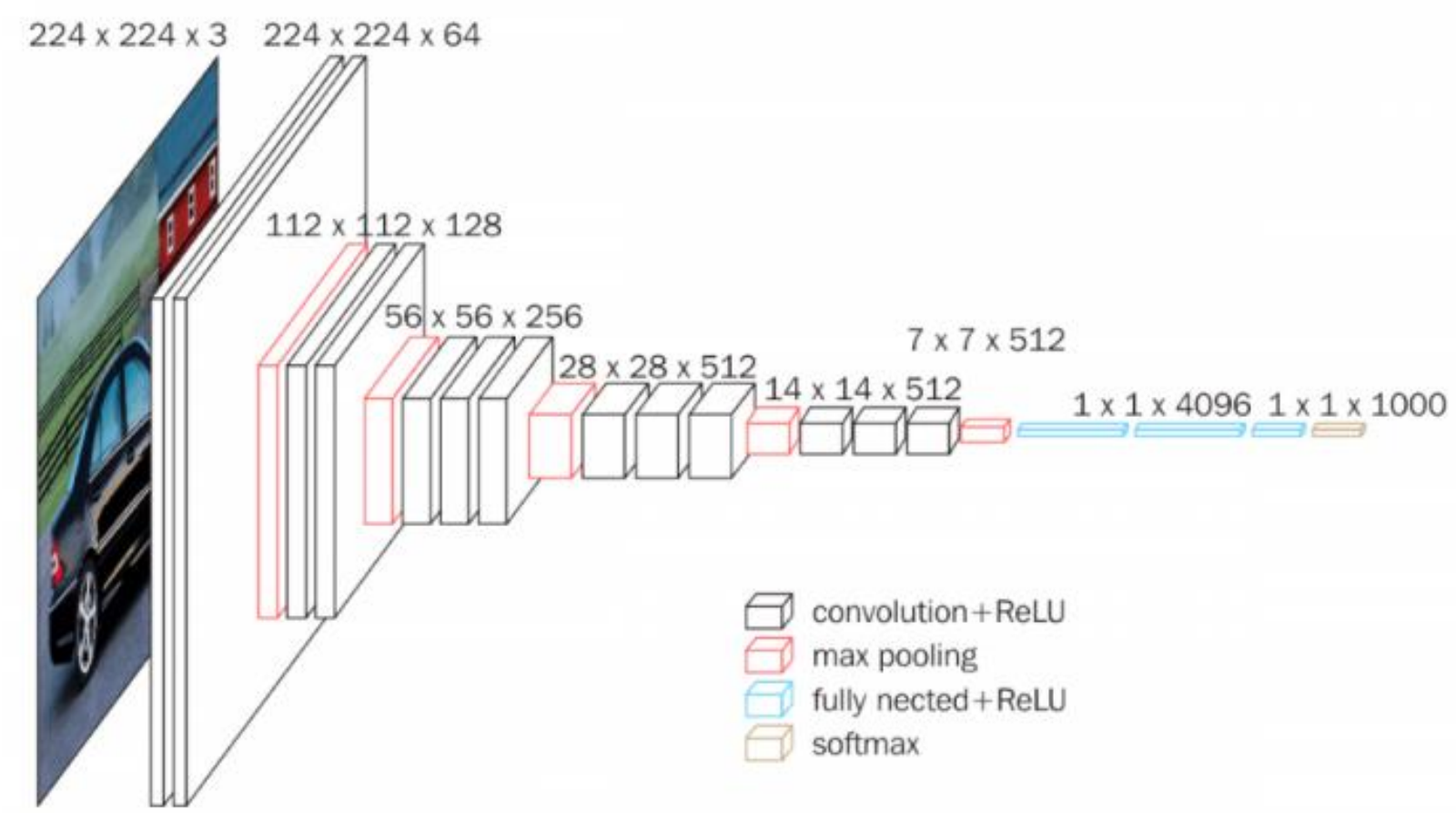


Domain Adaptation – Gradient Reversal



Domain Adaptation – Gradient Reversal

- VGG16 as a feature extraction

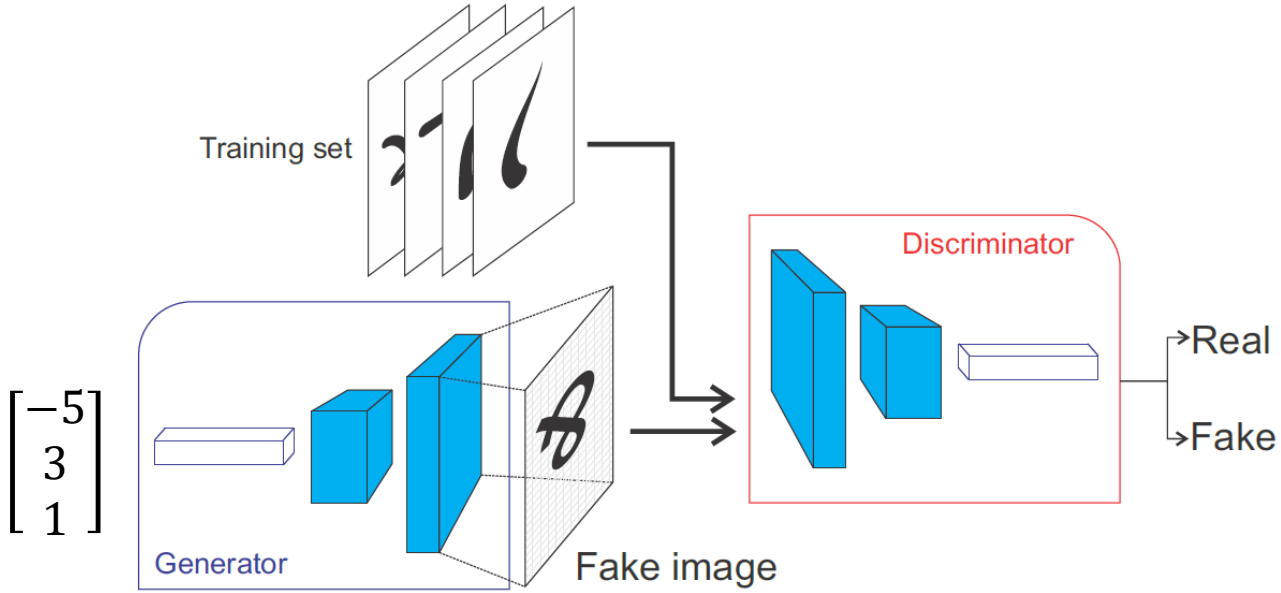


GAN

To produce Realistic Presentation of different classes

To distinguish real images from fake ones (produced by generator)

$\begin{bmatrix} -5 \\ 3 \\ 1 \end{bmatrix}$ Noise → Generative Model →  → Discriminative Model → x

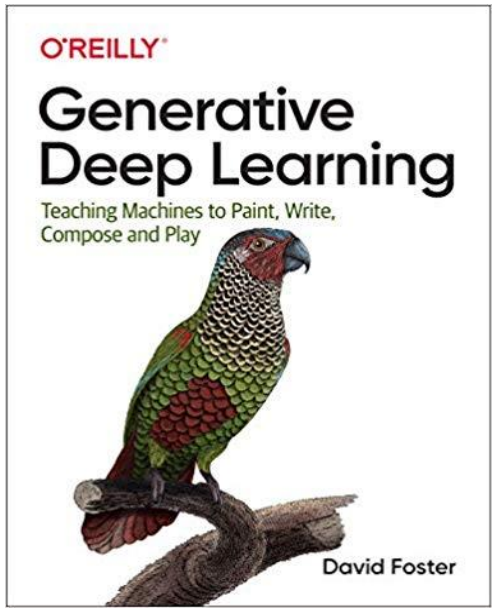


$\begin{bmatrix} -5 \\ 3 \\ 1 \end{bmatrix}$

Summary

- GANs are unsupervised techniques
- They can be used to generate synthetic data that can potentially be used to train other deep learning models
- There are different GAN types, but they are all based on the principle of having two competing objectives
- GANs often face instabilities during training

References



Adversarial Discriminative Domain Adaptation

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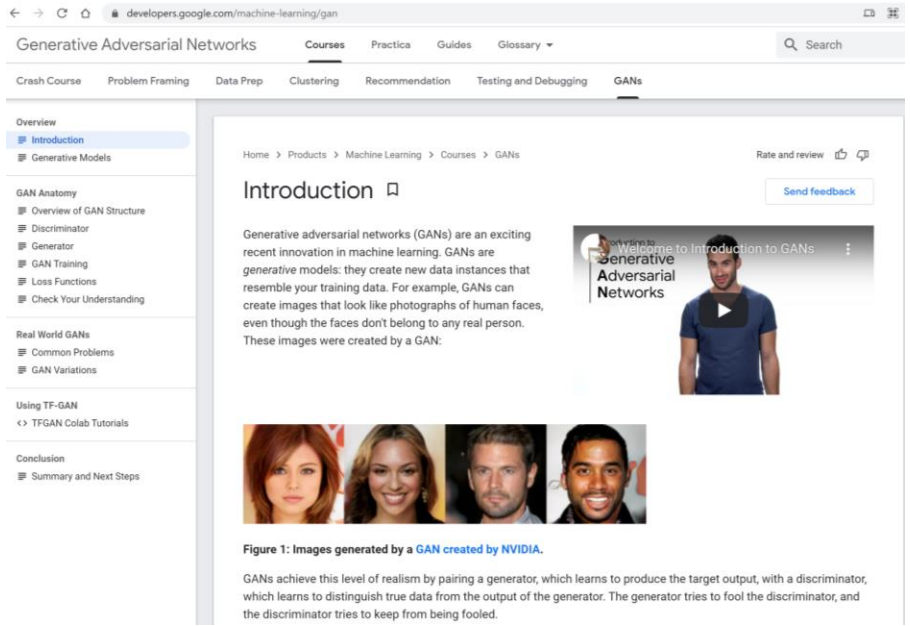

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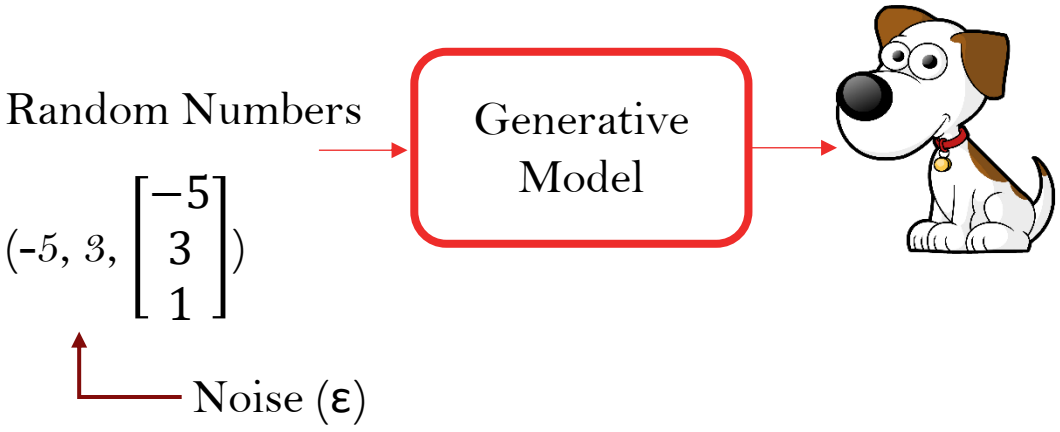
Thank you!

Generative vs Discriminate models

- Generative Models
  - Generate realistic representation for each class.



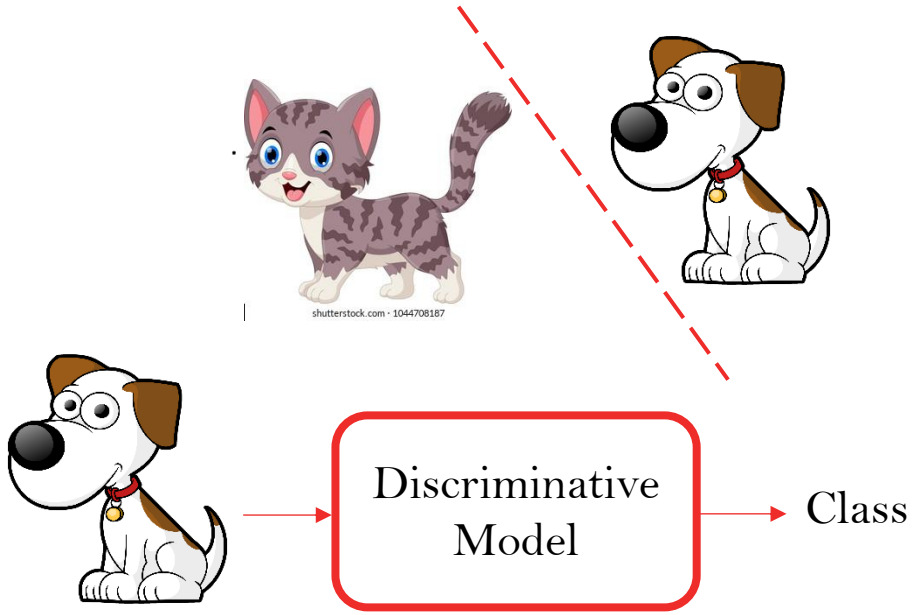
Y, ε → X (features)

$$P(X|Y)$$

or

$$P(X)$$

- Discriminative Models
  - Used for classification problem

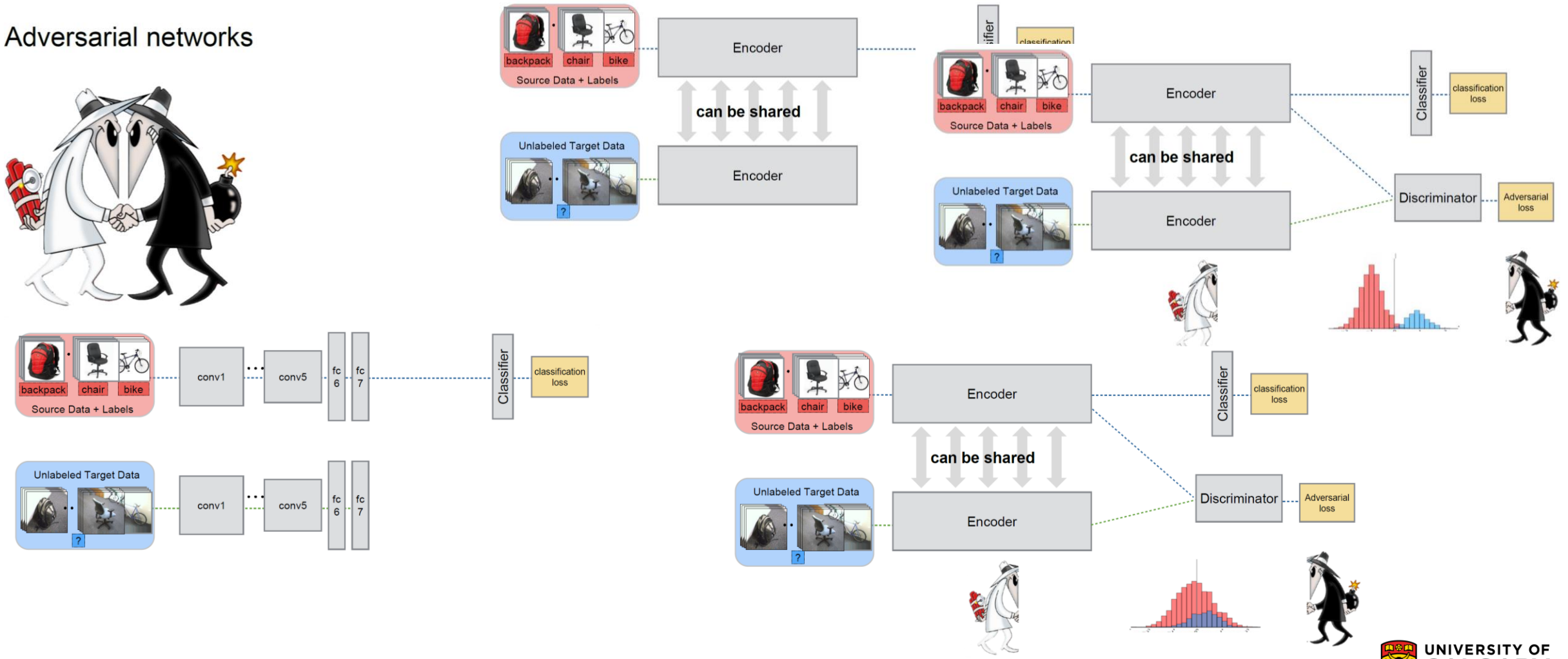


X (features) → Y

$$P(Y|X)$$

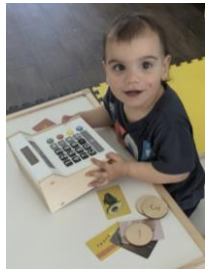
42

Domain adaptation using adversarial networks



How do GANs work?

- Notice that the discriminator and generator are trained **iteratively**.



ıed

Maximize

Minimize

Algorithm 1 Minibatch stochastic gradient descent training of generative adversarial nets. The number of steps to apply to the discriminator, k, is a hyperparameter. We used $k = 1$, the least expensive option, in our experiments.

for number of training iterations **do**

  for k steps **do**

  - Sample minibatch of m noise samples $\{\boldsymbol{z}^{(1)}, \ldots, \boldsymbol{z}^{(m)}\}$ from noise prior $p_g(\boldsymbol{z})$.
  - Sample minibatch of m examples $\{\boldsymbol{x}^{(1)}, \ldots, \boldsymbol{x}^{(m)}\}$ from data generating distribution $p_{\text{data}}(\boldsymbol{x})$.
  - Update the discriminator by ascending its stochastic gradient:

$$\nabla_{\theta_d} \frac{1}{m} \sum_{i=1}^{m} \left[\log D\left(\boldsymbol{x}^{(i)}\right) + \log\left(1 - D\left(G\left(\boldsymbol{z}^{(i)}\right)\right)\right) \right].$$

  end for

  - Sample minibatch of m noise samples $\{\boldsymbol{z}^{(1)}, \ldots, \boldsymbol{z}^{(m)}\}$ from noise prior $p_g(\boldsymbol{z})$.
  - Update the generator by descending its stochastic gradient:

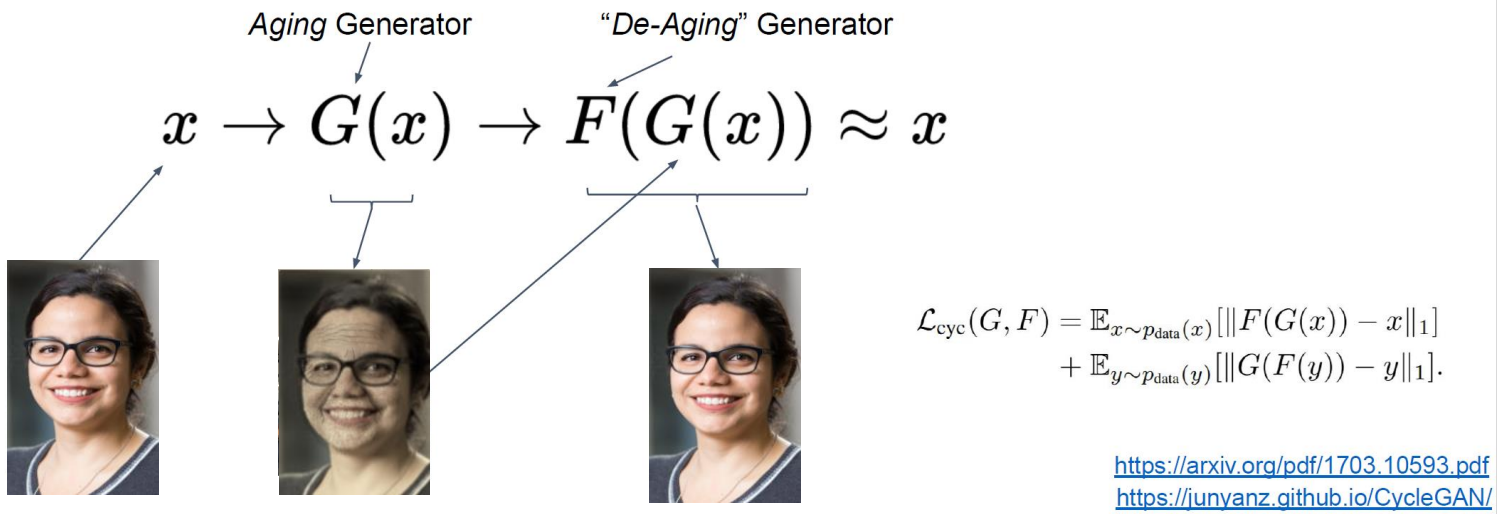
$$\nabla_{\theta_g} \frac{1}{m} \sum_{i=1}^{m} \log\left(1 - D\left(G\left(\boldsymbol{z}^{(i)}\right)\right)\right).$$

end for

The gradient-based updates can use any standard gradient-based learning rule. We used momentum in our experiments.

CycleGAN

- CycleGan introduced the concept of **cycle-consistency** loss to their GANs. This allowed training generators that would unpaired images from domain X to domain Y



https://arxiv.org/pdf/1703.10593.pdf

https://junyanz.github.io/CycleGAN/