

# Neural Network Tools and Principles, part 2

Generative models

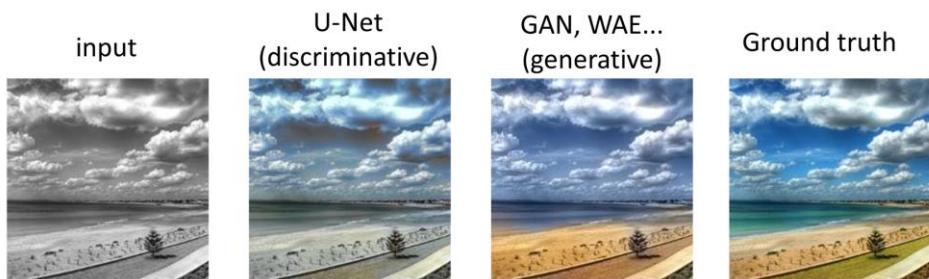
Computational Intelligence in Games, Spring 2018

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## Generative models

- Learn a probability distribution  $p(\mathbf{x})$  – e.g., facial images – and a way to draw samples from it
- More common in practice: learn a conditional distribution  $p(\mathbf{y} \mid \mathbf{x})$
- Same as approximating some function  $\mathbf{y} = f(\mathbf{x})$ , but with multiple possible  $\mathbf{y}$  for each  $\mathbf{x}$
- Example: image colorization. Many possible interpretations.



Simply training a convolutional neural network with input and output pairs makes the system output the average color, which is often unrealistic. Generative model needed to sample valid possible colors.

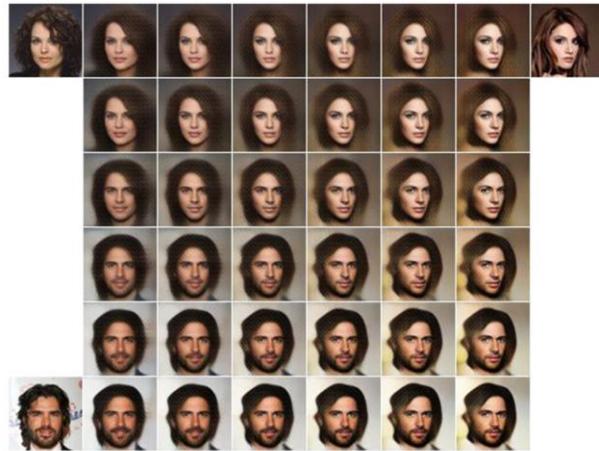
## Basic principle

- Sample some random numbers and feed them through a network that converts them into images, sound, text...
- Three main types of models: Autoencoders (VAE, WAE), Generative Adversarial Networks (GAN), Flow-based models

## Latent space, representation learning

- If one samples image pixels or audio values, one gets noise.
- The models try to learn an  $N$ -dimensional "latent space" where all positions (vectors of  $N$  numbers) in some region map to some meaningful image or sound, when passed through a generator or decoder network.
- If  $N$  is small, this enforces the networks to learn about relations. E.g., similar images should have similar latent encodings
- Directions often have semantic meaning: Along some axis, male faces might be to the left, and female to the right
- This allows interesting manipulations...

## A 2D latent space of an autoencoder trained with faces



<https://medium.com/@juliendespois/latent-space-visualization-deep-learning-bits-2-bd09a46920df>

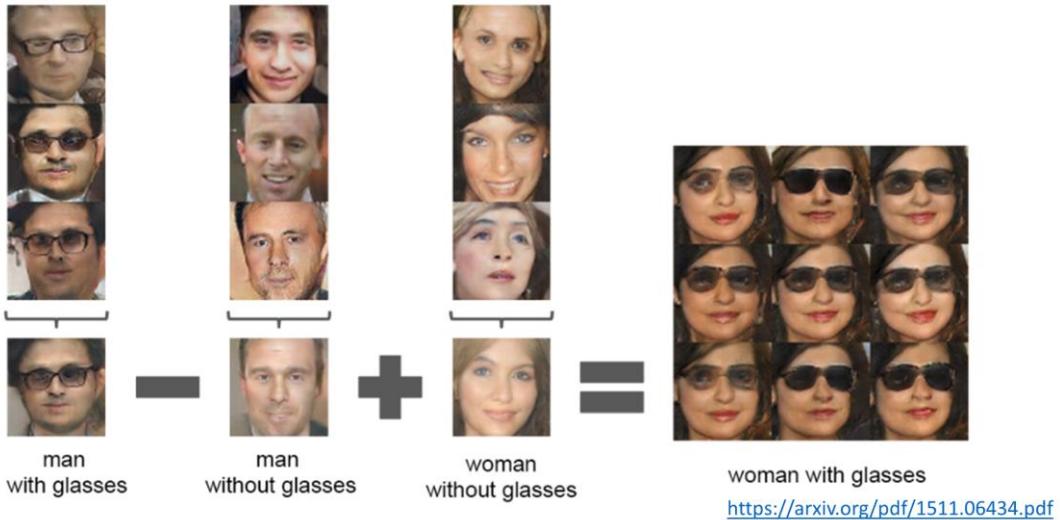
An autoencoder is an encoder-decoder network trained with the same signals as the inputs and target outputs.

Here, a convolutional autoencoder has learned a 2D encoding where the horizontal axis denotes face rotation and vertical denotes personality.

The interpolations are produced simply by linearly interpolating the 2D encodings (position vectors) of the corner images.

If one simply interpolates in the image pixel space, one gets a crossfade effect instead.

## Latent space math



Strikingly, one can often perform "semantic math" with latent space vectors.

Here's another example. In this case one just adds and subtracts the latent space (encoded) vectors corresponding to images, and gets interesting semantically meaningful results. This seems to emerge as a side result of the networks being forced to represent complex data with just a few numbers.

<https://arxiv.org/pdf/1511.06434.pdf>

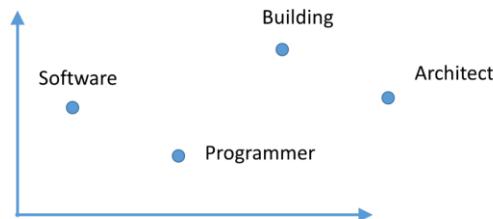
## Pixel-space math



Again, if one simply adds and subtracts pixels, the results are less interesting.

## Same with words

- King - Man + Woman = Queen
- Note that this is equivalent to King - Man = Queen - Woman
- Software - Building + Architect = Programmer
- Precomputed dictionaries of such encodings are available, e.g., Fasttext (<https://fasttext.cc/>)

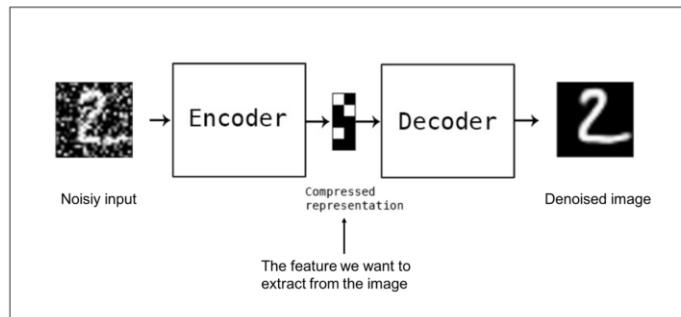


See also:

<http://mccormickml.com/2016/04/12/googles-pretrained-word2vec-model-in-python/>

## Variational autoencoder (VAE, 2014)

- Random samples in the latent space (the encoder outputs) of an autoencoder sometimes generate valid decoded output, sometimes not
- A basic autoencoder does not guarantee what happens when the encoding lies between training examples.
- VAE is an autoencoder where the compressed representation is forced to be normally distributed => easy to sample



Generating new images from this kind of model is simply done by ignoring the encoder, sampling a compressed representation, and passing it through the decoder.

## Wasserstein Autoencoder (WAE, ICLR 2018)

- VAE is old and usually doesn't give great results (details beyond the scope of this lecture)
- WAE is the modern version, but a bit more costly to train

### Wasserstein Auto-Encoders

Ilya Tolstikhin<sup>1</sup>, Olivier Bousquet<sup>2</sup>, Sylvain Gelly<sup>2</sup>, and Bernhard Schölkopf<sup>1</sup>

<sup>1</sup>Max Planck Institute for Intelligent Systems

<sup>2</sup>Google Brain

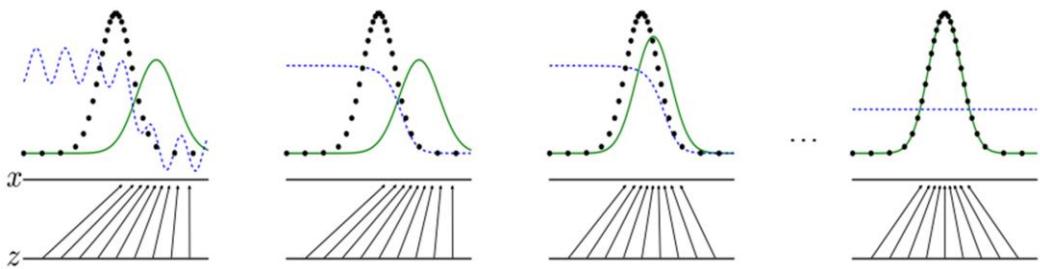
#### Abstract

We propose the Wasserstein Auto-Encoder (WAE)—a new algorithm for building a generative model of the data distribution. WAE minimizes a penalized form of the Wasserstein distance between the model distribution and the target distribution, which leads to a different regularizer than the one used by the Variational Auto-Encoder (VAE) [4]. This regularizer encourages the encoded training distribution to match the prior. We compare our algorithm with several other techniques and show that it is a generalization of adversarial auto-encoders (AAE) [2]. Our experiments show that WAE shares many of the properties of VAEs (stable training, encoder-decoder architecture, nice latent manifold structure) while generating samples of better quality, as measured by the FID score.

<https://arxiv.org/abs/1711.01558>

## Generative Adversarial Networks (GANs)

- Produces highest-quality image and sound samples (so far)
- A *generator* network maps random vectors  $\mathbf{z}$  to data vector  $\mathbf{x}$
- A *discriminator* network: 2-class classifier, trained to distinguish actual data from  $\mathbf{x}$



Original paper by Goodfellow et al.: <https://arxiv.org/abs/1406.2661>

In the figure, green is the distribution resulting from randomizing  $\mathbf{z}$  uniformly and passing the values through the generator to generate corresponding  $\mathbf{x}$ . The black dots represent the real data distribution. Blue denotes the so-called discriminative distribution, i.e., whether the probability of some  $\mathbf{x}$  should be increased or decreased.

## GAN: two networks in a single compute graph

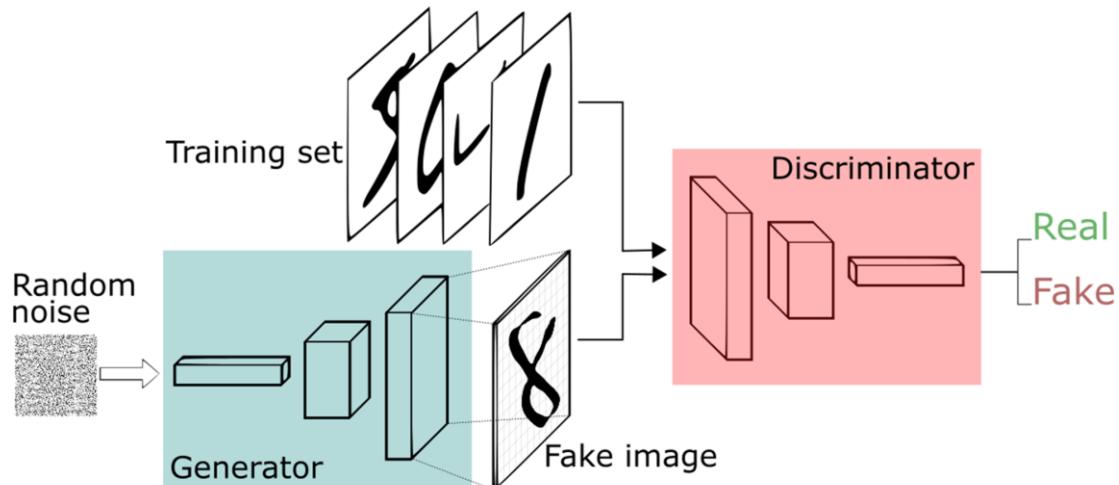


Image source: <https://deeplearning4j.org/generative-adversarial-network>

Generator is similar to the decoder part in encoder-decoder networks, and the discriminator is similar to an encoder.

## GANs are trained in interleaved manner

1. Keep generator fixed, optimize discriminator to maximize discriminator performance with both generated and real data
2. Keep discriminator fixed, optimize generator to minimize discriminator performance with generated data

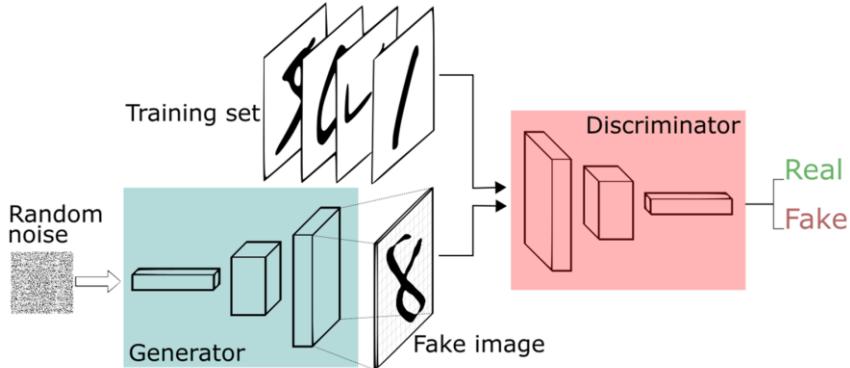
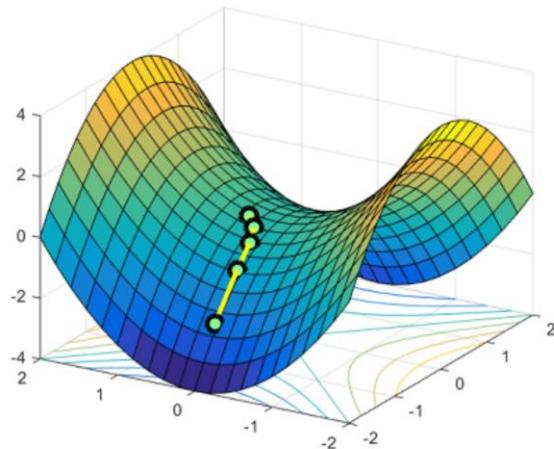


Image source: <https://deeplearning4j.org/generative-adversarial-network>

Full details in the Goodfellow et al. paper <https://arxiv.org/abs/1406.2661>

Problem: saddle-point optimization is unstable



In effect, GANs try to find a saddle point, as pointed out by Tom Goldstein:  
<https://www.youtube.com/watch?v=78vq6kgsTa8> ("What do neural loss surfaces look like?")

However, the optimization may easily fall off the saddle, i.e., the discriminator or generator may "win" the competition

## Improving GAN training stability

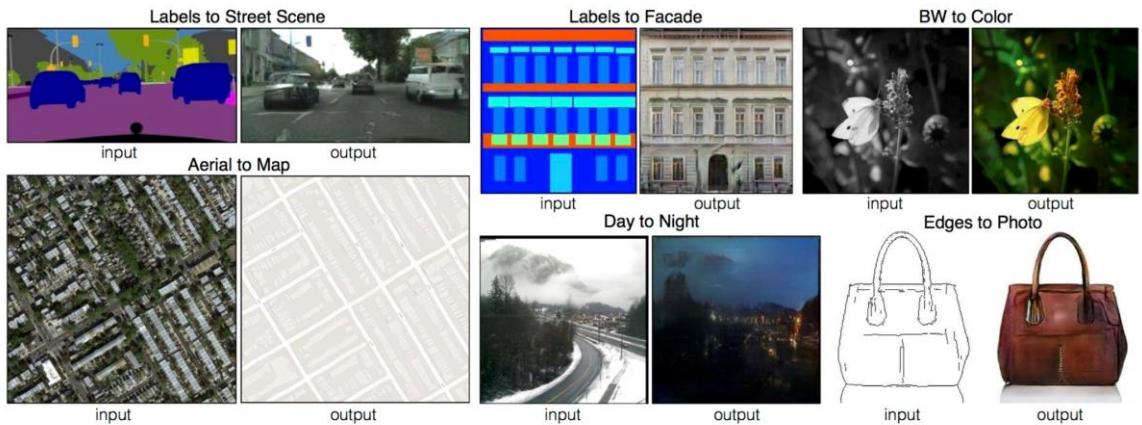
Yadav, A., Shah, S., Xu, Z., Jacobs, D., & Goldstein, T. (2017). Stabilizing Adversarial Nets With Prediction Methods. *arXiv preprint arXiv:1705.07364*. (Using saddle-point optimization theory)

Gulrajani, I., Ahmed, F., Arjovsky, M., Dumoulin, V., & Courville, A. C. (2017). Improved training of Wasserstein gans. In *Advances in Neural Information Processing Systems* (pp. 5769-5779).

## Demos and source code

- Browser-based interactive visualization:  
<https://cs.stanford.edu/people/karpathy/gan/>
- Browser-based image-to-image (pix2pix) translation:  
<https://affinelayer.com/pixsrv/>
- An accessible tutorial: <https://deeplearning4j.org/generative-adversarial-network>
- BigGAN art creation tool: <https://www.artbreeder.com/>
- State of the art code from NVIDIA:
  - <https://github.com/NVlabs/stylegan2>
  - <https://github.com/NVIDIA/pix2pixHD>

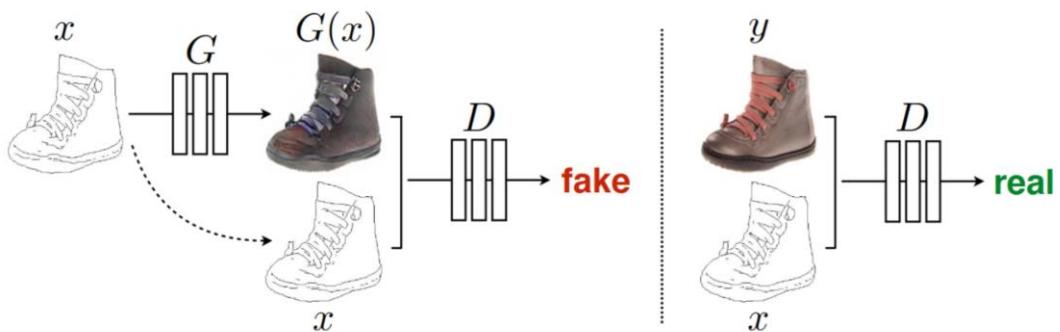
## pix2pix (Isola et al. 2017)



<https://arxiv.org/pdf/1611.07004.pdf>

## pix2pix (Isola et al. 2017)

- pix2pix is an example of conditional GAN
- Generator input: edge map, noise
- Discriminator input: edge map, real or generated images



<https://arxiv.org/pdf/1611.07004.pdf>

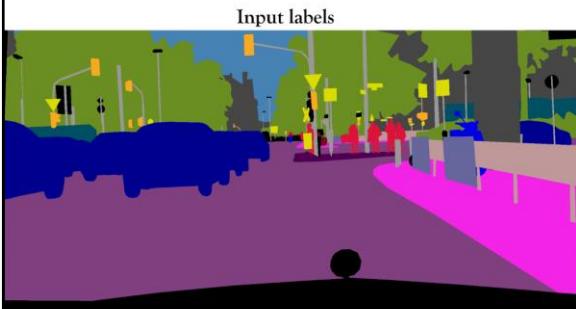
Conditional generative model: Generation is not completely random but conditioned on some extra variables such as the edge maps.

The noise is interpreted as the latent random variables that encode the variation possible without changing the conditioning variable values.

Other example: A game playing agent might sample an action conditioned by the current observation or game state.

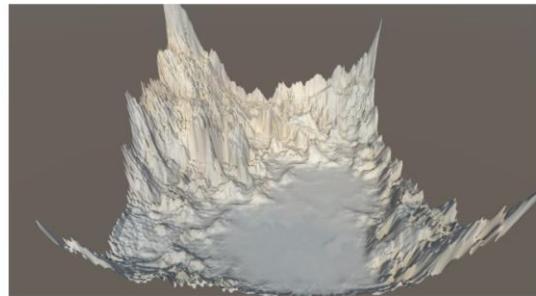
**pix2pixHD**

<https://github.com/NVIDIA/pix2pixHD>



## Generating terrain (Beckham 2017)

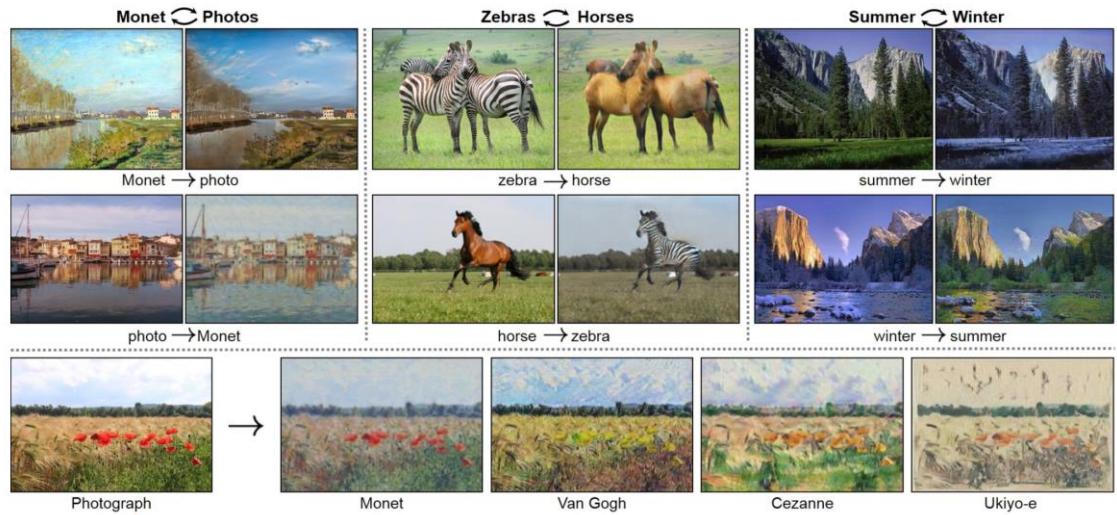
- Generate heightmaps with GAN
- Use pix2pix to generate textures from heightmaps
- Not yet super good results (dataset problem?)



<https://arxiv.org/pdf/1707.03383.pdf>

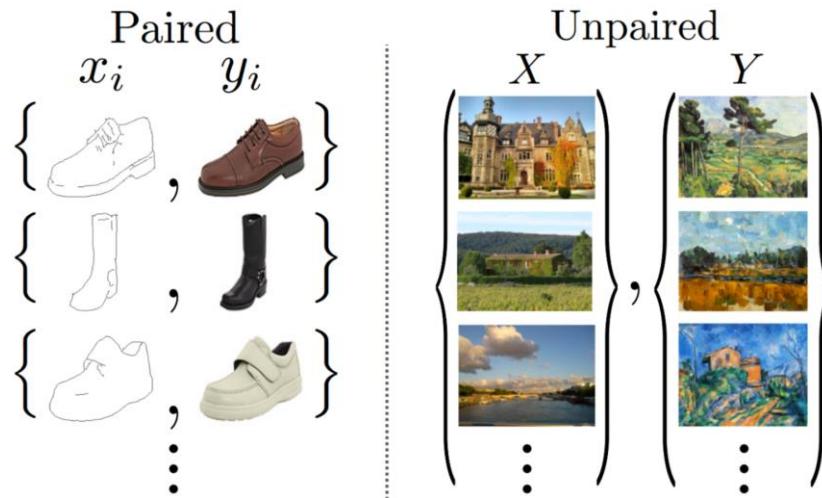
<https://github.com/christopher-beckham/gan-heightmaps>

# CycleGAN (Jun-Yan Zhu et al. 2017)



<https://github.com/junyanz/CycleGAN>

## CycleGAN: no training pairs needed!



$x$  and  $y$  can be arbitrary samples from different but related image classes.

## CycleGAN: no training pairs needed!

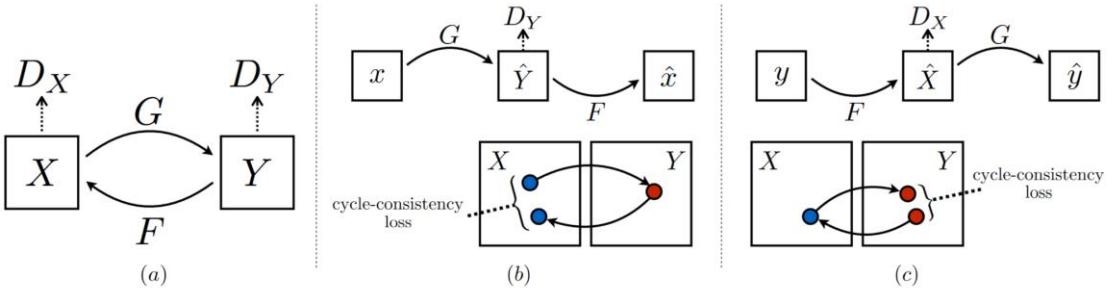


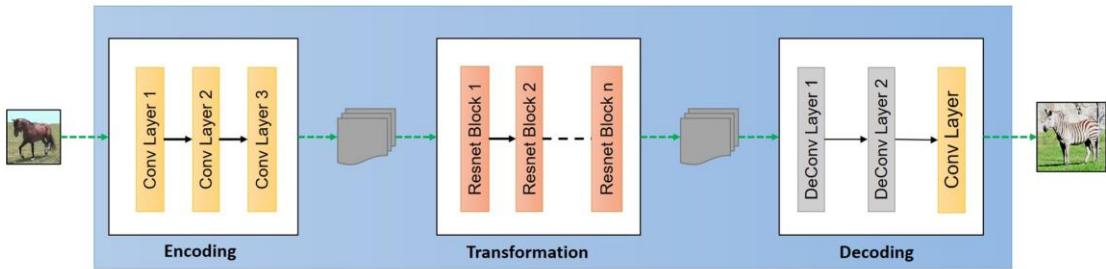
Figure 3: (a) Our model contains two mapping functions  $G : X \rightarrow Y$  and  $F : Y \rightarrow X$ , and associated adversarial discriminators  $D_Y$  and  $D_X$ .  $D_Y$  encourages  $G$  to translate  $X$  into outputs indistinguishable from domain  $Y$ , and vice versa for  $D_X$  and  $F$ . To further regularize the mappings, we introduce two *cycle consistency losses* that capture the intuition that if we translate from one domain to the other and back again we should arrive at where we started: (b) forward cycle-consistency loss:  $x \rightarrow G(x) \rightarrow F(G(x)) \approx x$ , and (c) backward cycle-consistency loss:  $y \rightarrow F(y) \rightarrow G(F(y)) \approx y$

How this works is there's two generator networks  $G$  and  $F$  that take the training samples as inputs instead of noise, and try to fool two discriminator networks  $D_X$  and  $D_Y$

Basically, one tries to minimize the error in translating from one domain to another and back. This error is measured by the discriminator.

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

# CycleGAN: no training pairs needed!



Both G and F have this structure.

<https://hardikbansal.github.io/CycleGANBlog/>

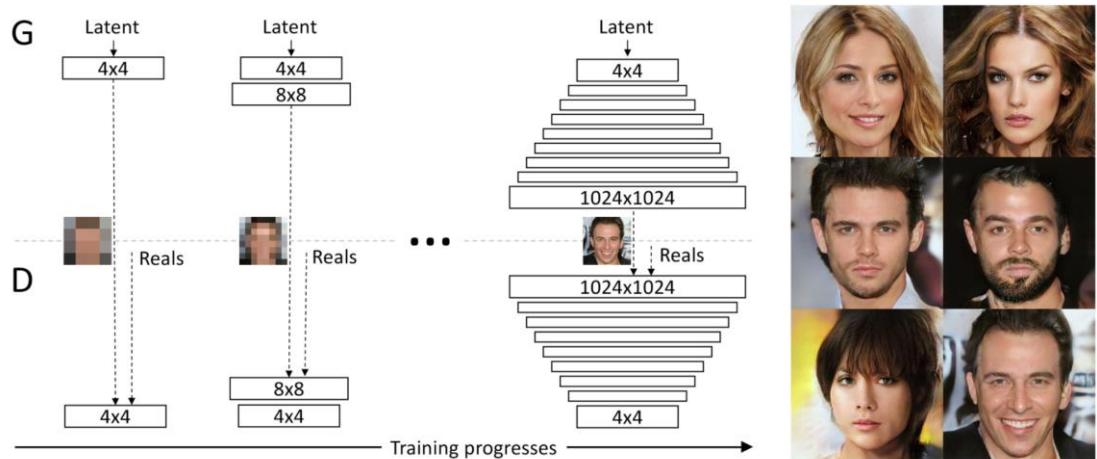
## Progressive GANs (Karras et al. 2017)



The first GAN that scaled up to megapixel images

<https://arxiv.org/pdf/1710.10196.pdf>

## Progressive GANs (Karras et al. 2017)



<https://arxiv.org/pdf/1710.10196.pdf>

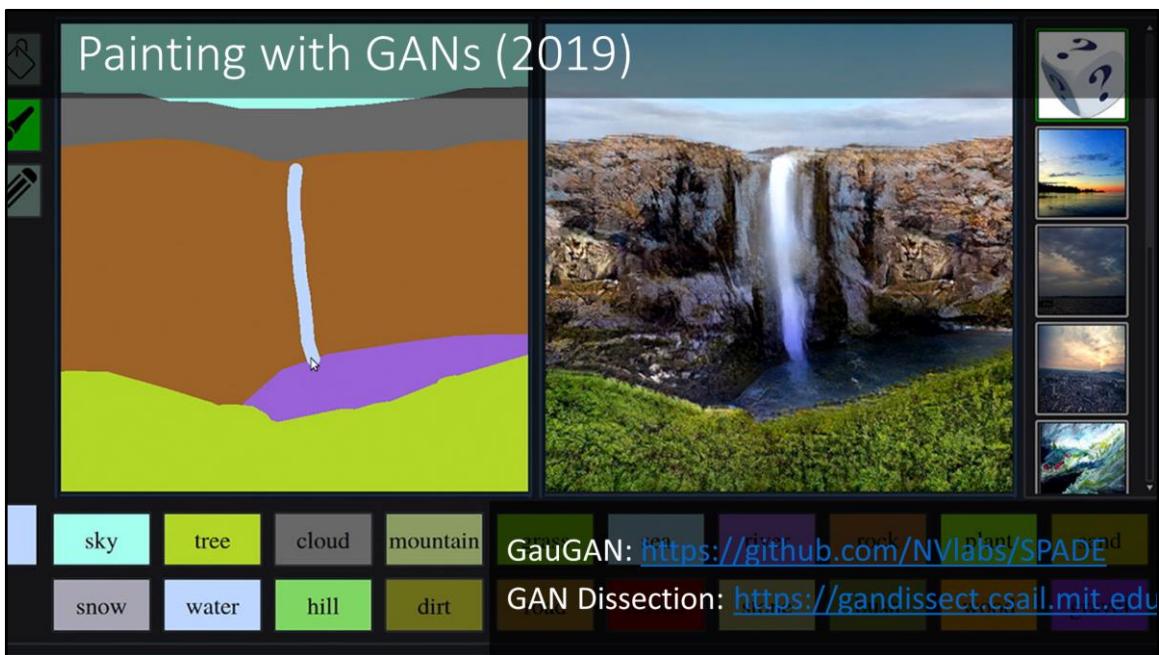


## StyleGAN 2 (2020)



StyleGAN can provide similar results if one is lucky, but StyleGAN 2 produces high quality much more consistently and predictably

<https://github.com/NVlabs/stylegan2>



## StyleGAN 2 "circuit bending"

Finetuning a pretrained Nvidia StyleGAN 2 network with only 250 images (google image search with "dragons")

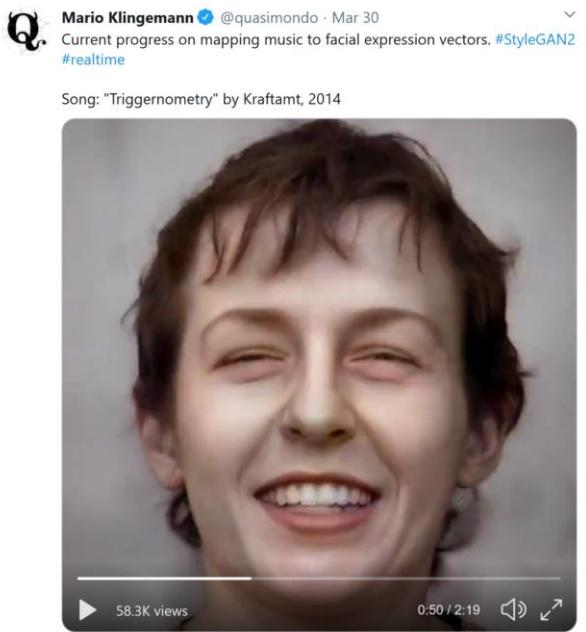
<https://twitter.com/Norod78/status/1218282356391530496?s=20>



Training a GAN with so few images doesn't usually produce meaningful results. However, here we see that first training "properly" and then continuing the training with a small dataset breaks the network in interesting ways.

# Music visualization using StyleGAN 2

<https://twitter.com/quasimondo/status/1244562140217905153?s=20>



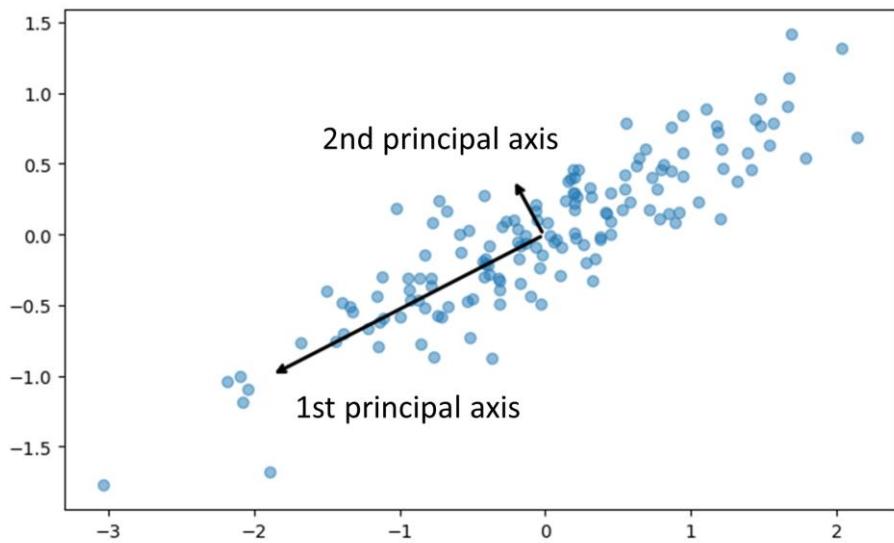
## PCA-based GAN control (Härkönen et al. 2020)



<https://arxiv.org/abs/2004.02546>

[https://youtu.be/jdTICDa\\_eAI](https://youtu.be/jdTICDa_eAI)

## Principal Component Analysis (PCA)



Classic data science technique, finds principal axes of variance in a dataset.

Härkönen et al. applied this in StyleGAN latent space. Remember, StyleGAN maps N-dimensional latent space noise to images. Each training image can also be encoded as an N-dimensional latent space vector. PCA can be computed on this N-dimensional set of data points, just like the 2D data points in the image.

Surprisingly often, moving along the axes seems to have a clear visual meaning.

# BigGAN: Generating all 1000 ImageNet image classes

[Submitted on 28 Sep 2018 ([v1](#)), last revised 25 Feb 2019 (this version, v2)]

## Large Scale GAN Training for High Fidelity Natural Image Synthesis

Andrew Brock, Jeff Donahue, Karen Simonyan

Despite recent progress in generative image modeling, successfully generating high-resolution, diverse samples from complex datasets such as ImageNet remains an elusive goal. To this end, we train Generative Adversarial Networks at the largest scale yet attempted, and study the instabilities specific to such scale. We find that applying orthogonal regularization to the generator renders it amenable to a simple "truncation trick," allowing fine control over the trade-off between sample fidelity and variety by reducing the variance of the Generator's input. Our modifications lead to models which set the new state of the art in class-conditional image synthesis. When trained on ImageNet at 128x128 resolution, our models (BigGANs) achieve an Inception Score (IS) of 166.5 and Frechet Inception Distance (FID) of 7.4, improving over the previous best IS of 52.52 and FID of 18.6.

# ARTBREEDER

Extend your imagination



Thousands of users have collectively made 59946402 images

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Formerly known as Ganbreeder: A tool for exploring the latent space of BigGAN by "breeding" together images.

<https://ganbreeder.com/> is a service for producing high-quality art prints out of one's Ganbreeder creations.

**Bay Raitt**  
@bayraitt

Artbreeder is a nuclear powered pencil.

have a spin remixing some of mine here:[artbreeder.com/bayraitt/starr...](http://artbreeder.com/bayraitt/starr...) #artbreeder #ai #ganbreeder #conceptart #comics

8,991 2:29 AM - Sep 18, 2019

2,942 people are talking about this

**Henry Lynch**  
@HenryLynch\_Art

'New World Officer'

Character created with AI image breeding and paint-over. Fast and interesting. It is the future. @Artbreeder 🎉 #ConceptArt #CharacterDesign #SciFi #AI #ConceptArtist

58 5:18 AM - Oct 9, 2019

See Henry Lynch's other Tweets >

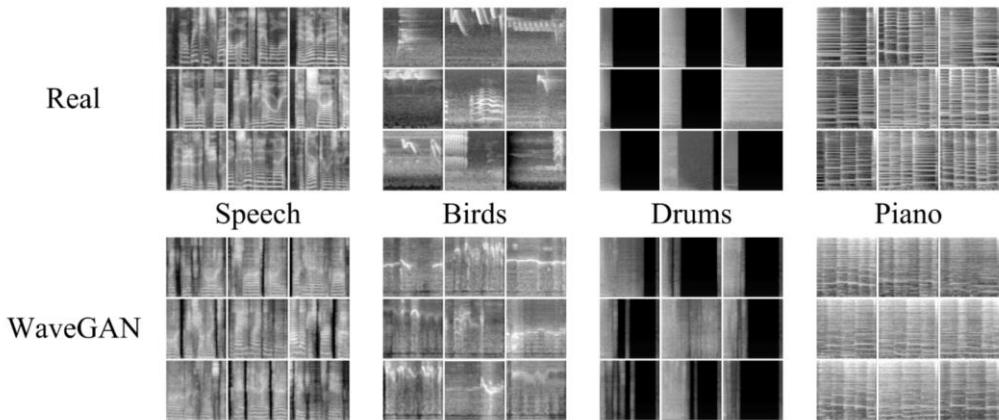
**TELTHONA**  
@telthona

I generated bunch of concepts with new AI powered website - it's the best AI app that i tried so far! It's amazing for creature exploration, mood thumbnailing and more ❤️ finally AI that i can truly use in the creative process! [ganbreeder.app](https://ganbreeder.app) #Aimakesart #ganbreeder

69 8:41 PM - Jun 29, 2019

See TELTHONA's other Tweets >

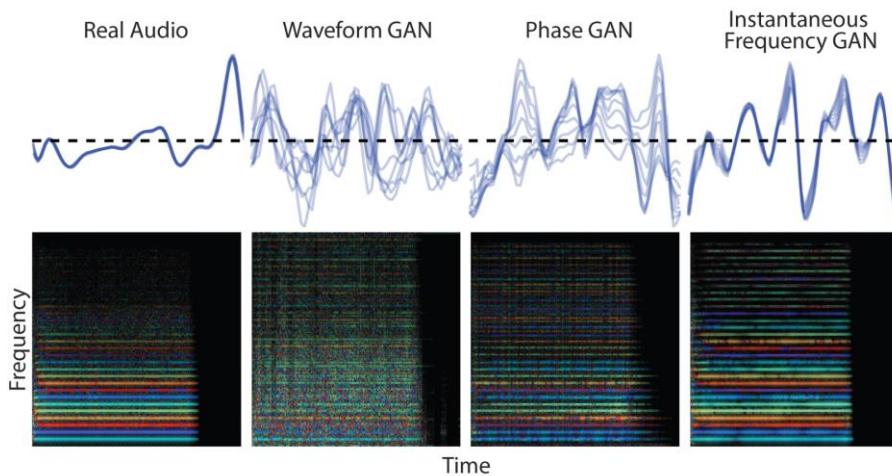
## Audio and GANs: WaveGAN



<https://github.com/chrisdonahue/wavegan>

<https://github.com/chrisdonahue/wavegan>

## GANSynth (2019)



<https://magenta.tensorflow.org/gansynth>

Like discussed in this paper, audio synthesis using GANs is still difficult, as the human ear is very sensitive to both large scale global structure, and local microstructure, perhaps more than vision. Small local errors easily manifest as high-frequency distortion. This paper explores some data representations that help. The results are still not that great, though.

<https://magenta.tensorflow.org/gansynth>

# More on audio generation in the next lecture

[Submitted on 16 Nov 2018]

## Generating Albums with SampleRNN to Imitate Metal, Rock, and Punk Bands

CJ Carr, Zack Zukowski

This early example of neural synthesis is a proof-of-concept for how machine learning can drive new types of music software. Creating music can be as simple as specifying a set of music influences on which a model trains. We demonstrate a method for generating albums that imitate bands in experimental music genres previously unrealized by traditional synthesis techniques (e.g. additive, subtractive, FM, granular, concatenative). Raw audio is generated autoregressively in the time-domain using an unconditional SampleRNN. We create six albums this way. Artwork and song titles are also generated using materials from the original artists' back catalog as training data. We try a fully-automated method and a human-curated method. We discuss its potential for machine-assisted production.

Comments: 3 pages

Subjects: **Sound (cs.SD)**; Audio and Speech Processing (eess.AS)

Journal reference: Proceedings of the 6th International Workshop on Musical Metacreation (MUME 2018)

Cite as: [arXiv:1811.06633 \[cs.SD\]](https://arxiv.org/abs/1811.06633)

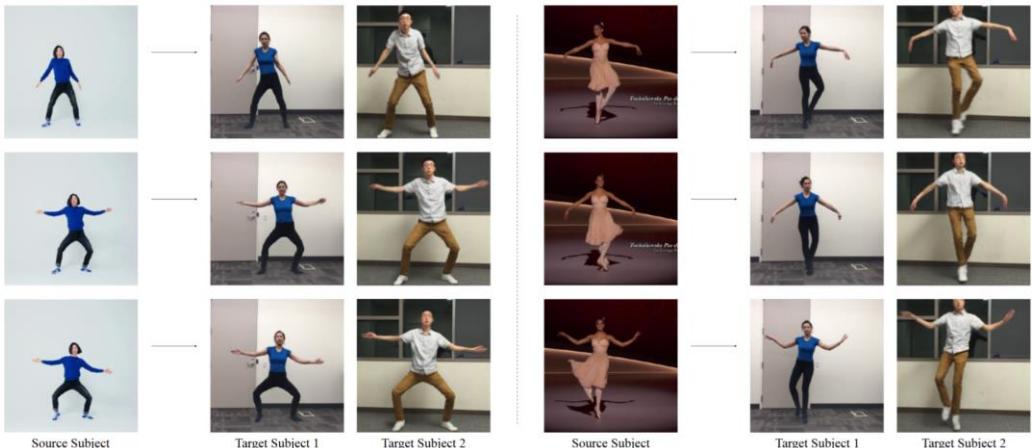
(or [arXiv:1811.06633v1 \[cs.SD\]](https://arxiv.org/abs/1811.06633v1) for this version)

<http://dadabots.com>

Audio can also be generated similar to text, using a recurrent model that generates new outputs based on its previous outputs.

## Everybody Dance Now (Chan et al. 2018)

- Conditioning GAN image synthesis with neural network motion tracking



<https://arxiv.org/abs/1808.07371>

# Glow: Generative Flow with Invertible $1 \times 1$ Convolutions

Diederik P. Kingma <sup>\*†</sup>, Prafulla Dhariwal<sup>\*</sup>  
<sup>\*</sup>OpenAI  
<sup>†</sup>Google AI

## Abstract

Flow-based generative models (Dinh et al., 2014) are conceptually attractive due to tractability of the exact log-likelihood, tractability of exact latent-variable inference, and parallelizability of both training and synthesis. In this paper we propose *Glow*, a simple type of generative flow using an invertible  $1 \times 1$  convolution. Using our method we demonstrate a significant improvement in log-likelihood on standard benchmarks. Perhaps most strikingly, we demonstrate that a flow-based generative model optimized towards the plain log-likelihood objective is capable of efficient realistic-looking synthesis and manipulation of large images. The code for our model is available at <https://github.com/openai/glow>.

## 1 Introduction

Two major unsolved problems in the field of machine learning are (1) data-efficiency: the ability to learn from few datapoints, like humans; and (2) generalization: robustness to changes of the task or its context. AI systems, for example, often do not work at all when given inputs that are different

<sup>\*</sup>Equal contribution.

32nd Conference on Neural Information Processing Systems (NeurIPS 2018), Montréal, Canada.



Figure 1: Synthetic celebrities sampled from our model; see Section 3 for architecture and method, and Section 8 for more results.

One problem of GANs is that there's no guarantee that the synthesized images actually cover the whole data instead of modeling only a part of it. So-called flow-based are the hot new thing that solves this, although GANs seem to still produce better visual quality. The flow-based models also give you a point-estimate of the probability density, i.e., how probable an image is in light of the training data. This can be useful in some applications.

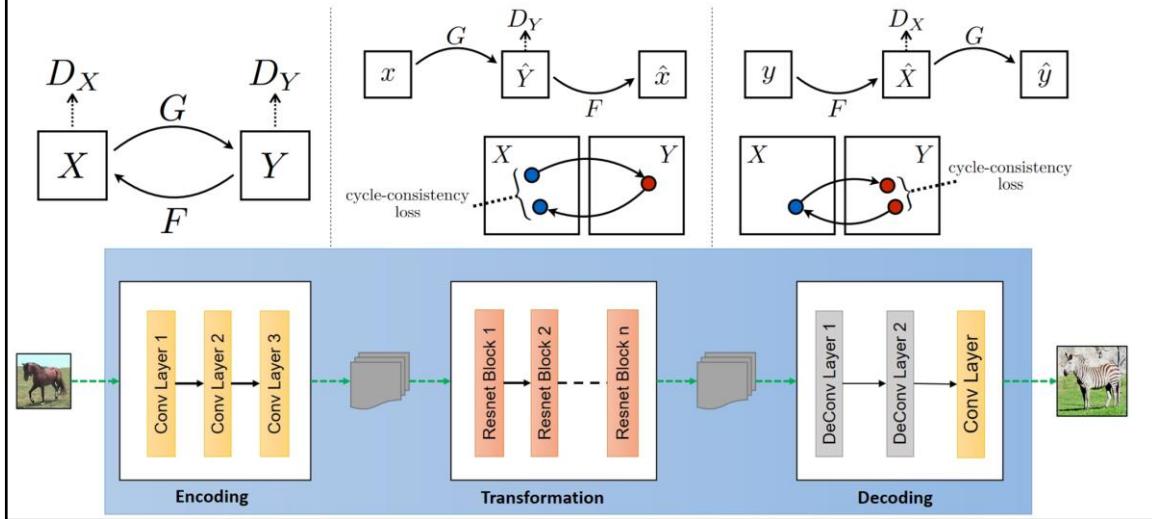
## Summary

- A *generative model* is needed when there are multiple possible outputs for a single input, and the outputs are not discrete-valued
- GANs are the dominant type of generative model
- Training GANs may be unstable, but things are improving rapidly
- StyleGAN 2 and BigGAN have been quickly adopted by artists and designers

For discrete-valued outputs, one can train a discriminative model that outputs the probabilities of each possible value, with a separate output neuron for each value. This can then be used in 1) discriminative manner by finding the most probable value or 2) generative manner by sampling a value based on the probabilities. A practical example of this is training a game-playing agent with a discrete action set from human player data.

Flow-based models are growing in popularity, and WAE also seems to have brought autoencoder-based models back to the spotlight.

A key takeaway: infinite ways to combine basic compute graph blocks



Instead of math and algorithms, a lot of the innovation has recently been on finding new architectures that combine common building blocks in a novel way.

Key principles:

- 1) Create a compute graph that is end-to-end differentiable, allowing gradient propagation and training/optimization.
- 2) Select or design a loss function
- 3) In some cases, it makes sense to separate the training process into phases where parts of the graph are trained while others are kept fixed (e.g., the discriminator vs. generator training)