

# COMP547

## DEEP UNSUPERVISED LEARNING

Lecture #8 - #9 – Generative Adversarial Networks



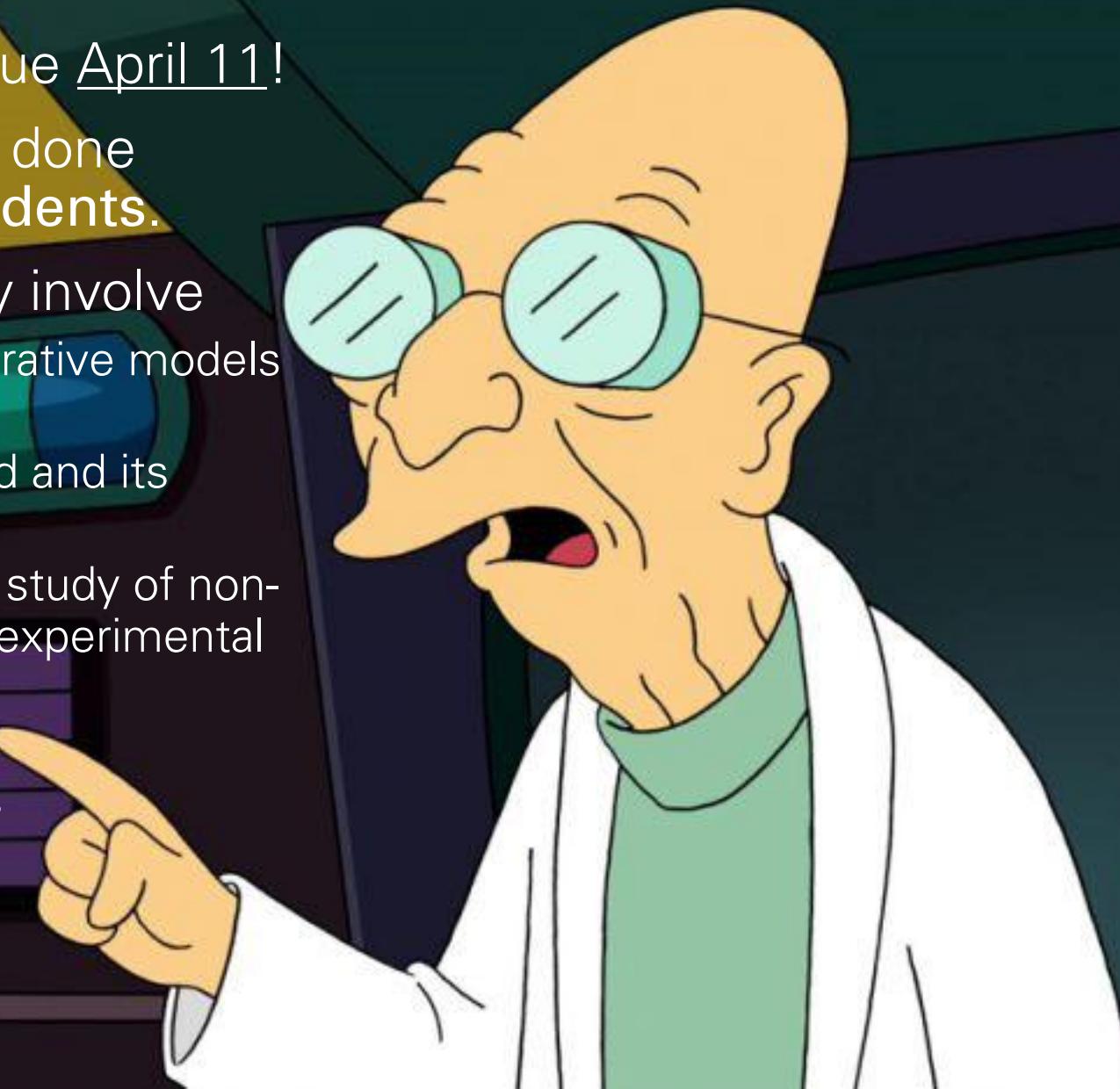
KOÇ  
UNIVERSITY

Aykut Erdem // Koç University // Spring 2021

# Good news, everyone!

- Project proposals are due April 11!
- The projects should be done in **groups of 2 to 3 students**.
- The course project may involve
  - Application of deep generative models on a novel task/dataset.
  - Design of a novel method and its experimental analysis,
  - An extension to a recent study of non-trivial complexity and its experimental analysis.
  - Reproduction of a work published in recent years

If you chose this particular path, participation to ML Reproducibility Challenge is strongly encouraged!



# Previously on COMP547

- Motivation
- Training Latent Variable Models  
(including VAE and IWAE)
- Variations
- Related ideas



Image: Synthetic faces sampled from NVAE model  
by Vahdat and Kautz

# Lecture overview

- Motivation & Definition of Implicit Models
- Original GAN (Goodfellow et al, 2014)
- Evaluation: Parzen, Inception, Frechet
- Theory of GANs
- GAN Progression
- Conditional GANs, Cycle-Consistent Adversarial Networks
- GANs and Representations
- Applications

**Disclaimer:** Much of the material and slides for this lecture were borrowed from

- Pieter Abbeel, Peter Chen, Jonathan Ho, Aravind Srinivas' Berkeley CS294-158 class
- Aaron Courville's IFT6135 class
- Bill Freeman, Antonio Torralba and Phillip Isola's MIT 6.869 class

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# Motivation: Evolution of GANs

- 5 years of GAN progress



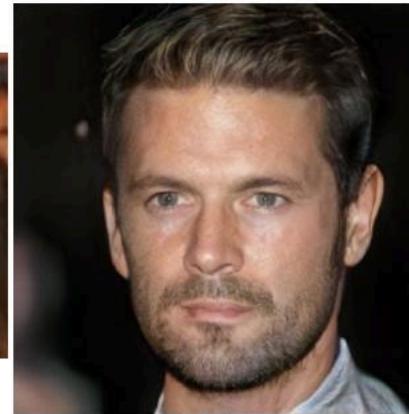
2014



2015



2016



2017



2018



2019

- GAN is most prominent of Implicit Models

I.J. Goodfellow, J. Pouget-Abadie, M. Mirza, B. Xu, D. Warde-Farley, S. Ozair, A. Courville, Y. Bengio. Generative Adversarial Networks. NIPS 2014.

A. Radford, L. Metz, S. Chintala. Unsupervised Representation Learning with Deep Convolutional Generative Adversarial Networks. ICLR 2016.

M.-Y. Liu, O. Tuzel. Coupled Generative Adversarial Networks. NIPS 2016.

T. Karras, T. Aila, S. Laine, J. Lehtinen. Progressive Growing of GANs for Improved Quality, Stability, and Variation. ICLR 2018.

T. Karras, S. Laine, T. Aila. A style-based generator architecture for generative adversarial networks. In CVPR 2018.

T. Karras, S. Laine, M. Aittala, J. Hellsten, J. Lehtinen, T. Aila. Analyzing and Improving the Image Quality of StyleGAN. CVPR 2020.

# Motivation: BigGAN



# So far...

- Autoregressive models
  - MADE, PixelRNN/CNN, Gated PixelCNN, PixelSNAIL
- Flow models
  - Autoregressive Flows, NICE, RealNVP, Glow, Flow++
- Latent Variable Models
  - VAE, IWAE, VQ-VAE, VLAE, PixelVAE
- **Common aspect:** Likelihood-based models
  - exact (autoregressive and flows)
  - approximate (VAE)

# Generative Models

- Sample
  - Evaluate likelihood
  - Train
  - Representation
- What if all we care about is sampling?

# Building a sampler

- How about this sampler?

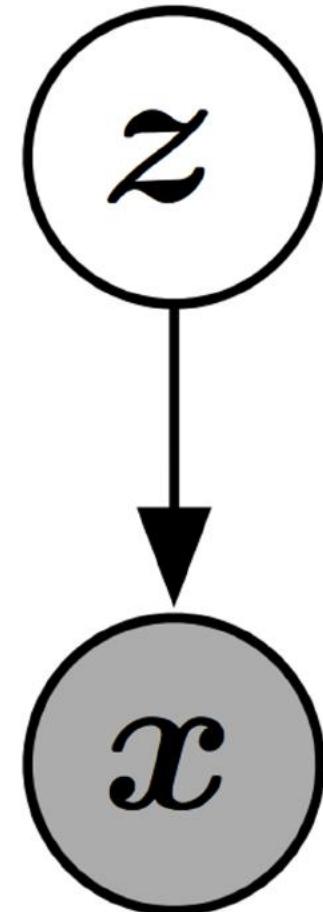
```
import glob, cv2, numpy as np
files = glob.glob('*.*jpg')
def _sample():
    idx = np.random.randint(len(files))
    return cv2.imread(files[idx])
def sample(*, n_samples):
    samples = np.array([\u033e_sample() for _ in range(n_samples)])
return samples
```

# Building a sampler

- You don't just want to sample the exact data points you have.
- You want to build a generative model that can understand the underlying distribution of data points and
  - smoothly interpolate across the training samples
  - output samples similar but not the same as training data samples
  - output samples representative of the underlying factors of variation in the training distribution.
  - Example: digits with unseen strokes, faces with unseen poses, etc.

# Implicit Models

- Sample  $z$  from a fixed noise source distribution (uniform or gaussian).
- Pass the noise through a deep neural network to obtain a sample  $x$ .
- Sounds familiar? Right:
  - Flow Models
  - VAE
- What's going to be different here?
  - Learning the deep neural network **without** explicit density estimation



# Implicit Models

Given samples from data distribution  $p_{data} : x_1, x_2, \dots, x_n$

Given a sampler  $q_\phi(z) = \text{DNN}(z; \phi)$  where  $z \sim p(z)$

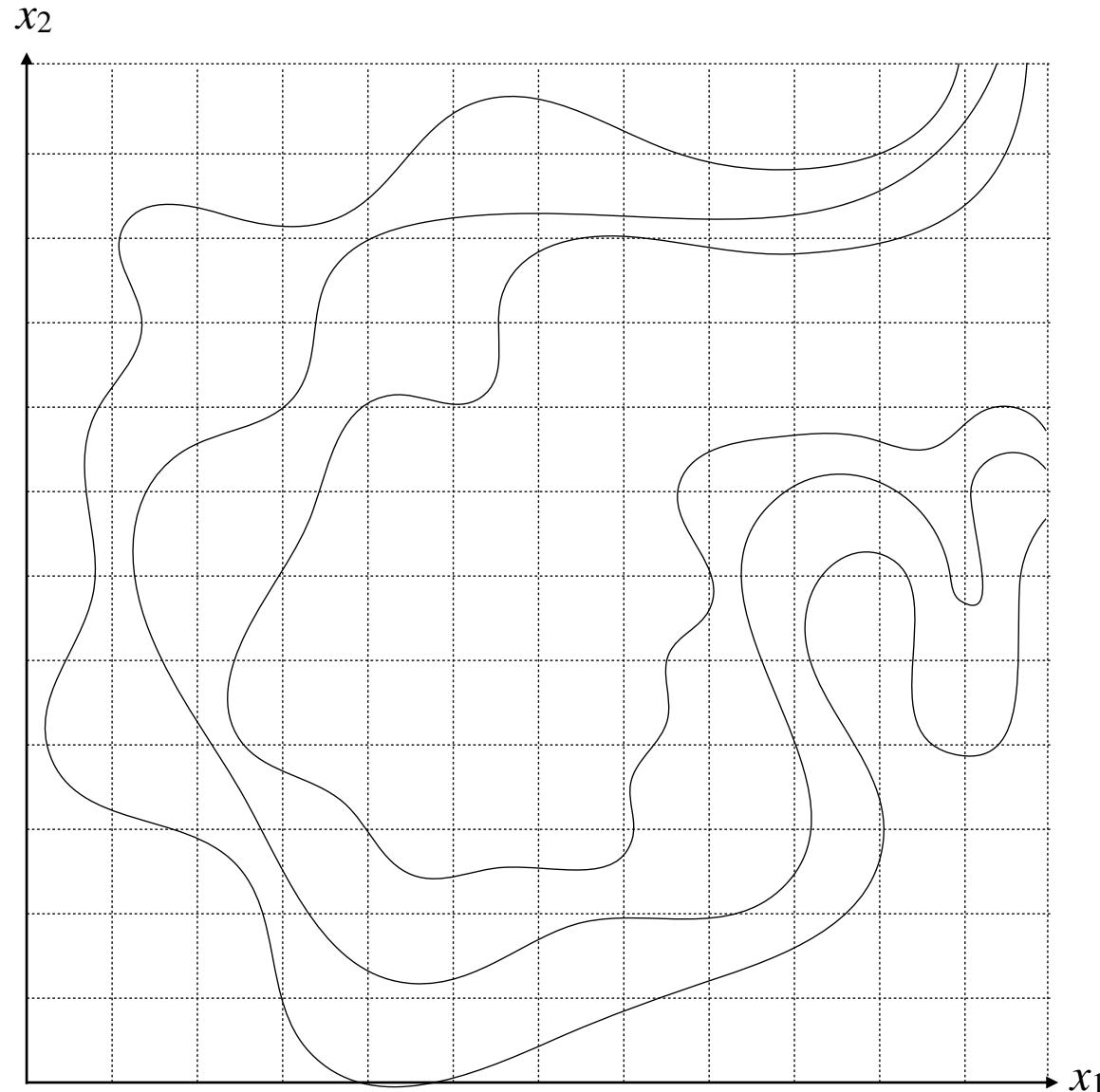
$x = q_\phi(z)$  induces a density function  $p_{model}$

- Do not have an explicit form for  $p_{data}$  or  $p_{model}$ ; can only draw samples
- Make  $p_{model}$  as close to  $p_{data}$  as possible by learning an appropriate  $\phi$

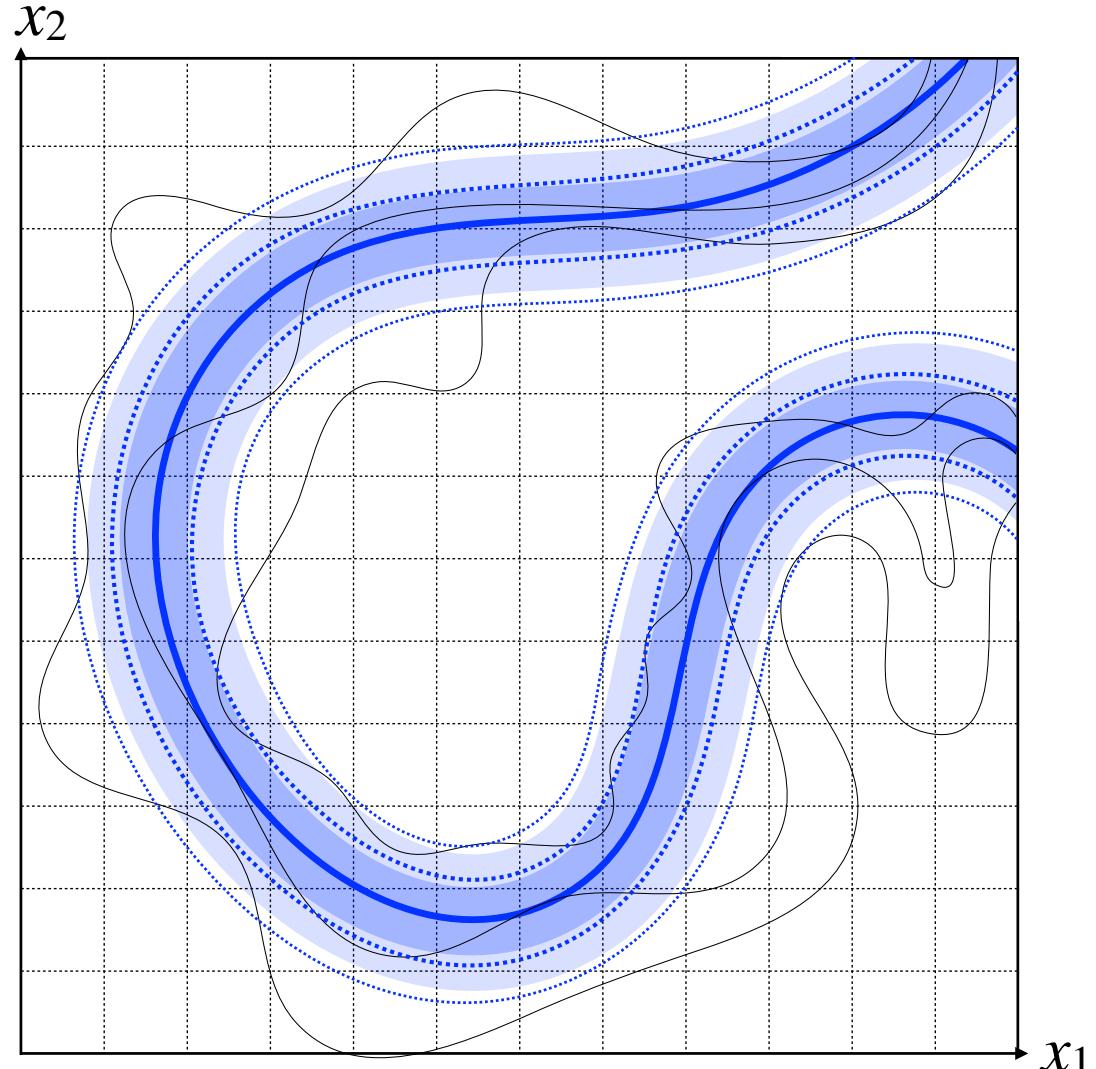
# Departure from maximum likelihood

- We need some measure of how far apart  $p_{data}$  and induces  $p_{model}$  are
- With density models, we used  $KL(p_{data} \parallel p_{model})$  which gave us the objective  $\mathbb{E}_{x \sim p_{data}} [\log p_\theta(x)]$  (discarding the term independent of  $\theta$ ) where we explicitly modeled  $p_{model}$  as  $p_\theta(x)$
- Not having an explicit  $p_\theta(x)$  requires us to come up distance measures that potentially behave differently from maximum likelihood.
- Example: Maximum Mean Discrepancy (MMD), Jensen Shannon Divergence (JSD), Earth Mover's Distance, etc.

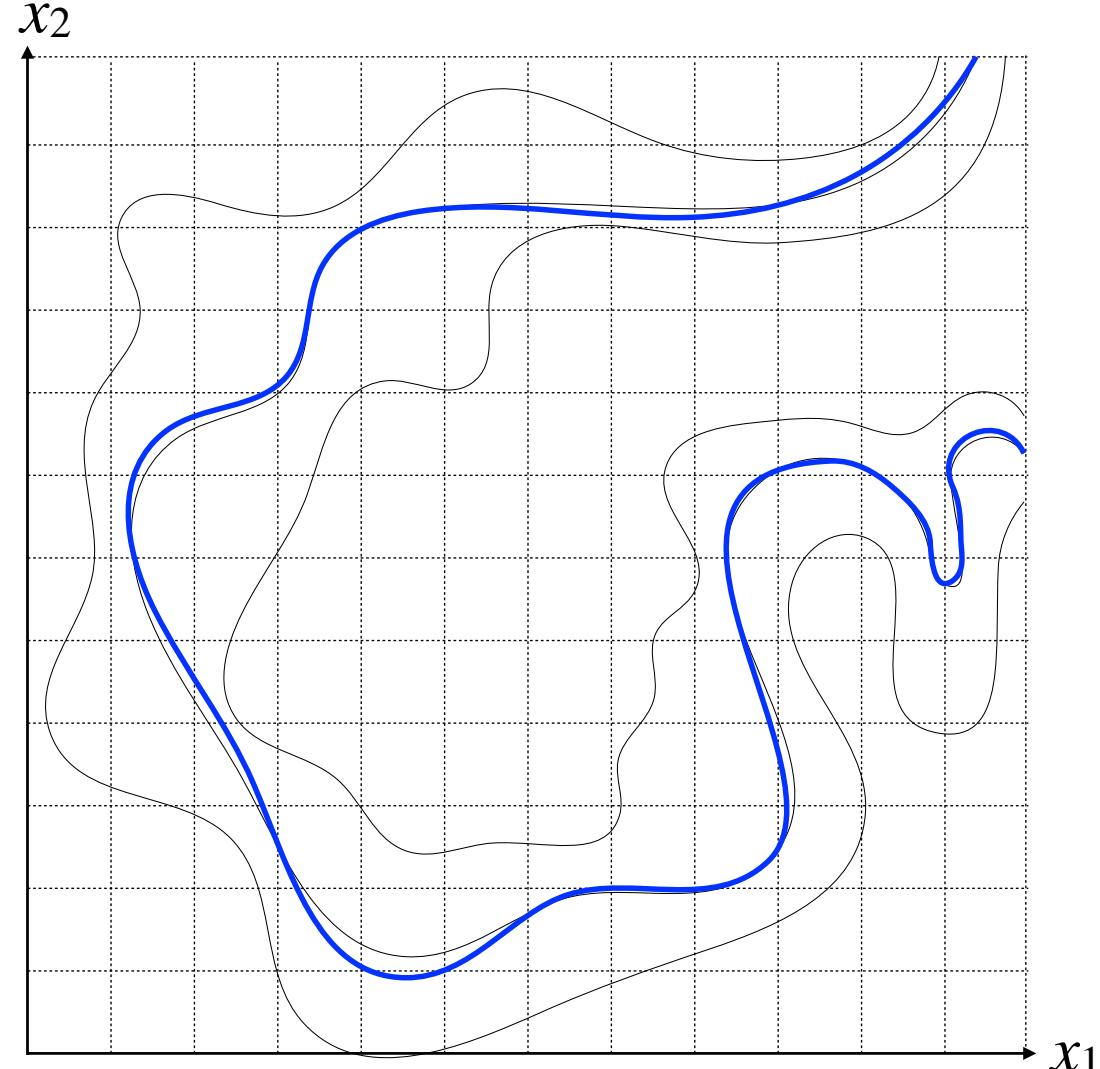
# Cartoon of the Image manifold



# What makes GANs special?



more traditional max-likelihood approach



GAN

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# Generative Adversarial Networks

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## Generative Adversarial Nets

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**Ian J. Goodfellow,<sup>\*</sup> Jean Pouget-Abadie,<sup>†</sup> Mehdi Mirza, Bing Xu, David Warde-Farley,  
Sherjil Ozair,<sup>‡</sup> Aaron Courville, Yoshua Bengio<sup>§</sup>**

Département d'informatique et de recherche opérationnelle

Université de Montréal

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### Abstract

We propose a new framework for estimating generative models via an adversarial process, in which we simultaneously train two models: a generative model  $G$  that captures the data distribution, and a discriminative model  $D$  that estimates the probability that a sample came from the training data rather than  $G$ . The training procedure for  $G$  is to maximize the probability of  $D$  making a mistake. This framework corresponds to a minimax two-player game. In the space of arbitrary functions  $G$  and  $D$ , a unique solution exists, with  $G$  recovering the training data distribution and  $D$  equal to  $\frac{1}{2}$  everywhere. In the case where  $G$  and  $D$  are defined by multilayer perceptrons, the entire system can be trained with backpropagation. There is no need for any Markov chains or unrolled approximate inference networks during either training or generation of samples. Experiments demonstrate the potential of the framework through qualitative and quantitative evaluation of the generated samples.

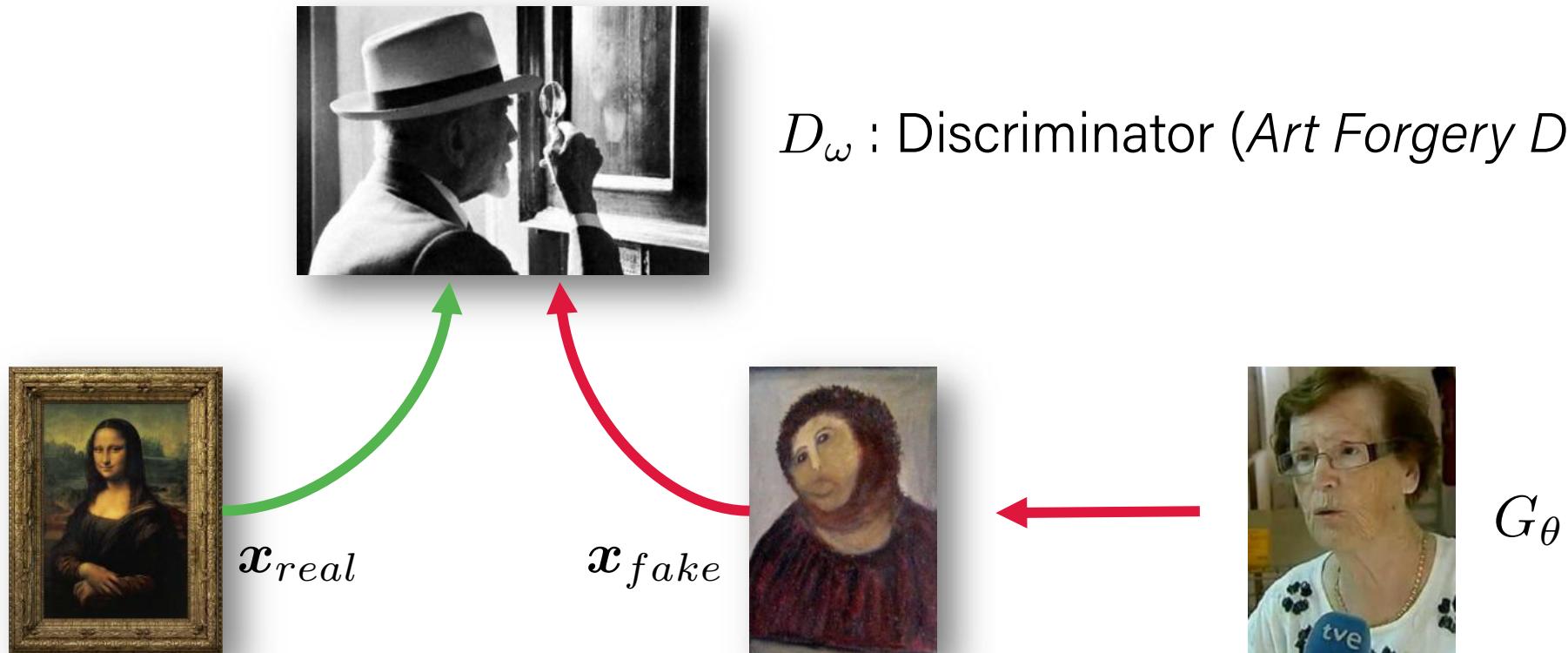
# Generative Adversarial Networks

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

- Two player minimax game between generator (G) and discriminator (D)
- (D) tries to maximize the log-likelihood for the binary classification problem
  - data: real (1)
  - generated: fake (0)
- (G) tries to minimize the log-probability of its samples being classified as “fake” by the discriminator (D)

# Intuition behind GANs

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



# Generative Adversarial Networks

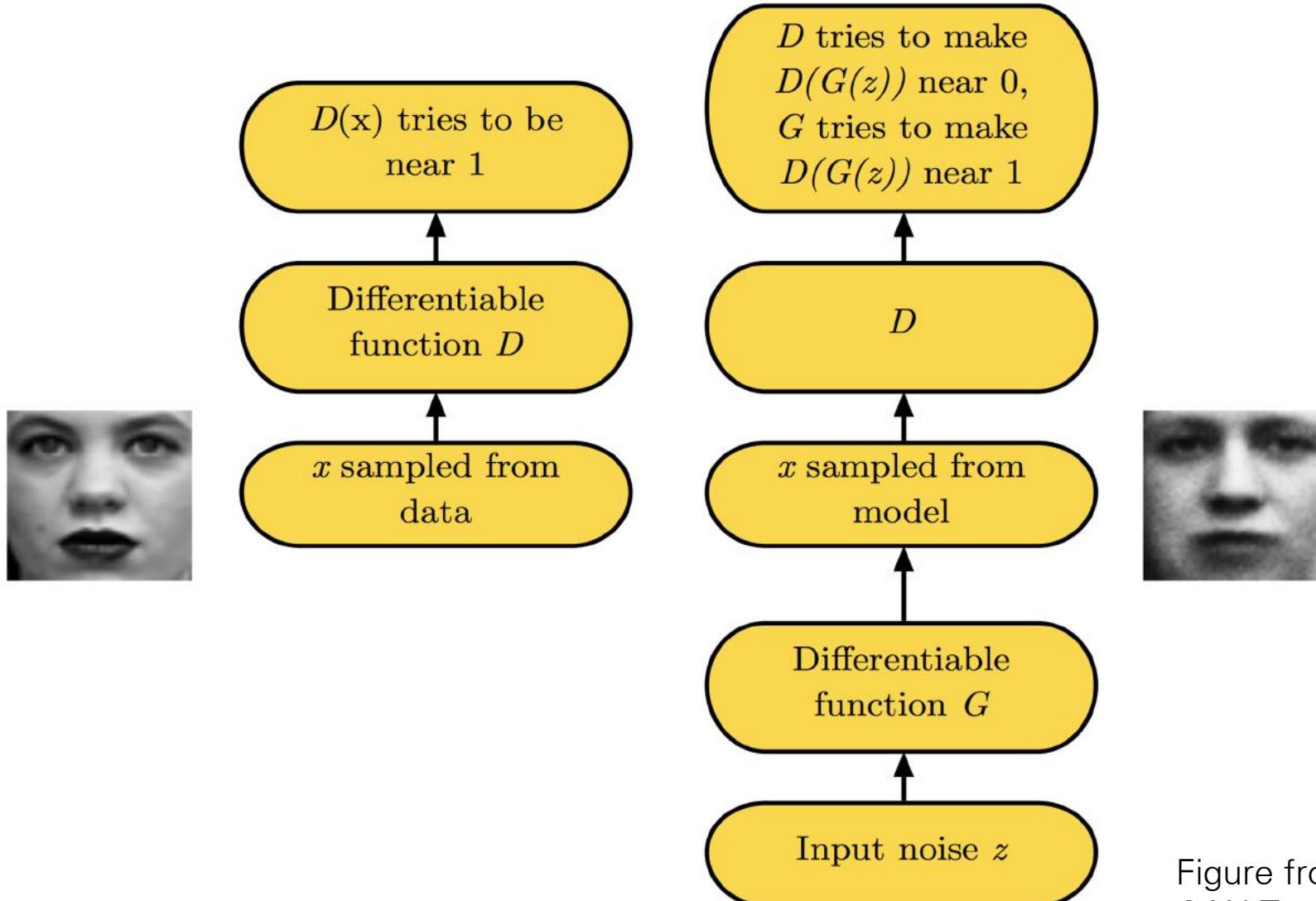


Figure from NeurIPS 2016  
GAN Tutorial (Goodfellow)

# GANs - Pseudocode

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**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  $\{\mathbf{z}^{(1)}, \dots, \mathbf{z}^{(m)}\}$  from noise prior  $p_g(\mathbf{z})$ .
        • Sample minibatch of  $m$  examples  $\{\mathbf{x}^{(1)}, \dots, \mathbf{x}^{(m)}\}$  from data generating distribution  $p_{\text{data}}(\mathbf{x})$ .
        • Update the discriminator by ascending its stochastic gradient:
```

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

```
end for
    • Sample minibatch of  $m$  noise samples  $\{\mathbf{z}^{(1)}, \dots, \mathbf{z}^{(m)}\}$  from noise prior  $p_g(\mathbf{z})$ .
    • Update the generator by descending its stochastic gradient:
```

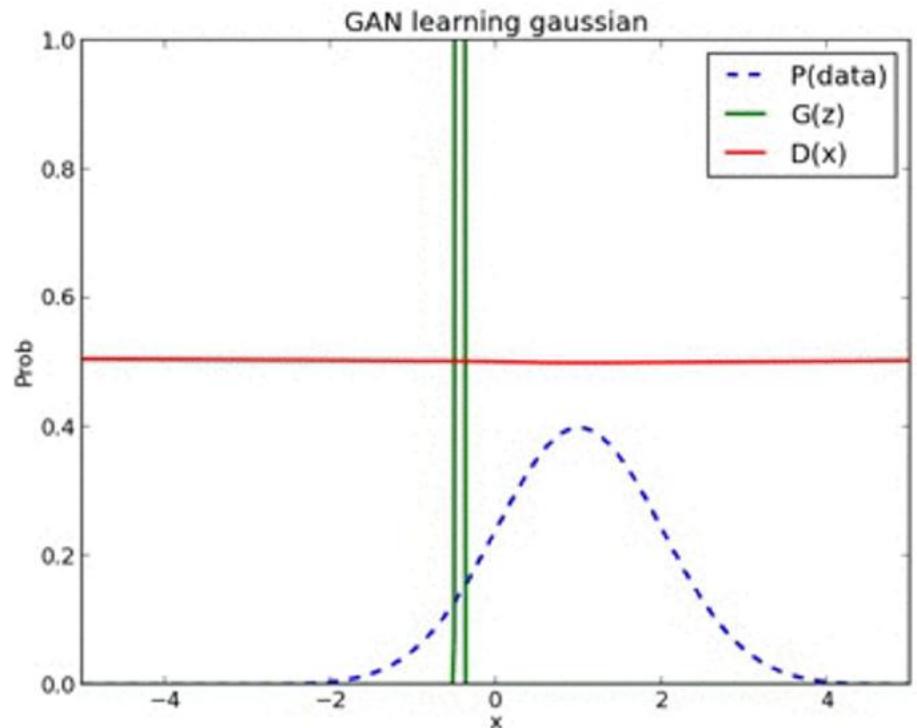
$$\nabla_{\theta_g} \frac{1}{m} \sum_{i=1}^m \log (1 - D(G(\mathbf{z}^{(i)}))).$$

```
end for
```

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

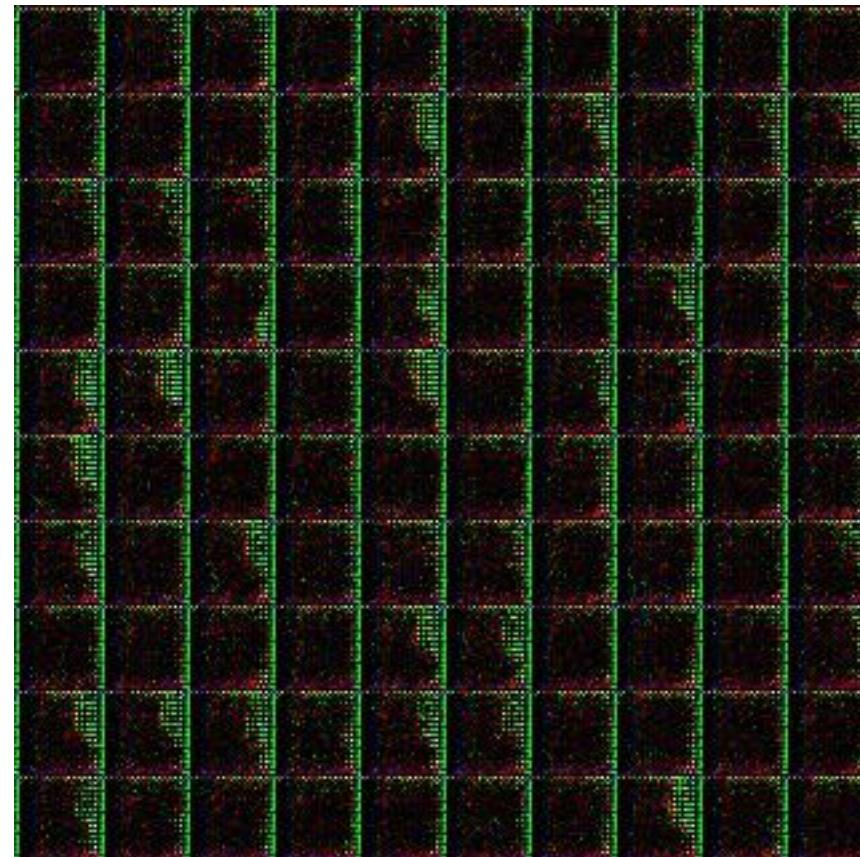
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# Training Procedure



Source: Alec Radford

Generating 1D points



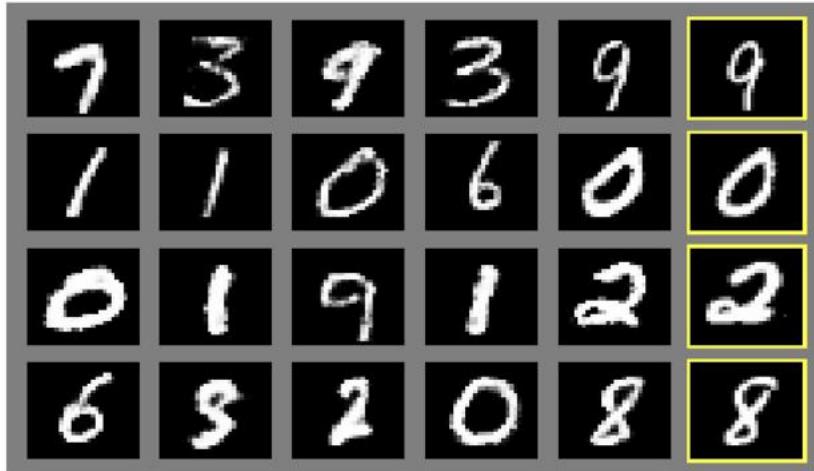
Source: OpenAI blog

Generating images

# GAN in Action

<https://poloclub.github.io/ganlab/>

# GAN samples from 2014



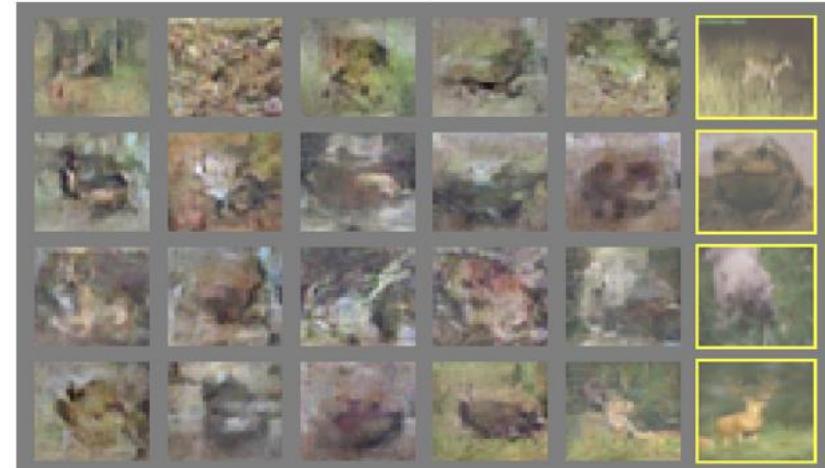
a)



b)



c)



d)

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# How to evaluate?

- Evaluation for GANs is still an open problem
- Unlike density models, you cannot report explicit likelihood estimates on test sets.

# Parzen-Window density estimator

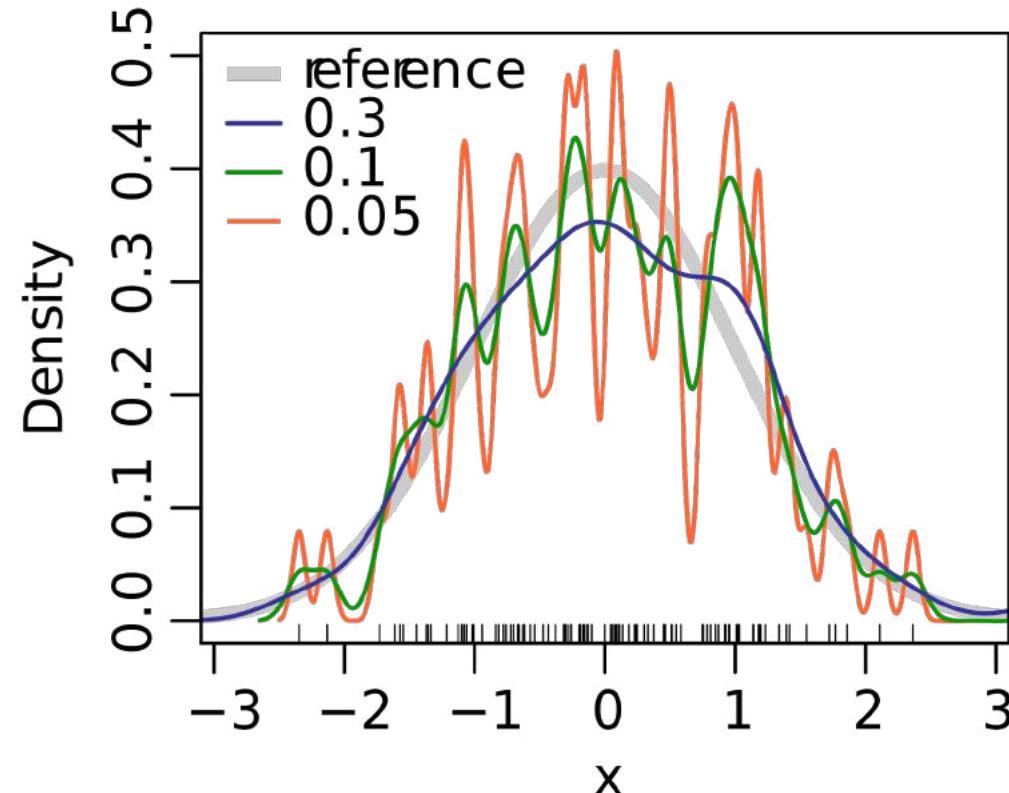
- Also known as Kernel Density Estimator (KDE)
- An estimator with kernel  $K$  and bandwidth  $h$ :

$$\hat{p}_h(x) = \frac{1}{nh} \sum_i K\left(\frac{x - x_i}{h}\right)$$

- In generative model evaluation,  $K$  is usually density function of standard Normal distribution

# Parzen-Window density estimator

- Bandwidth  $h$  matters
- Bandwidth  $h$  chosen according to validation set



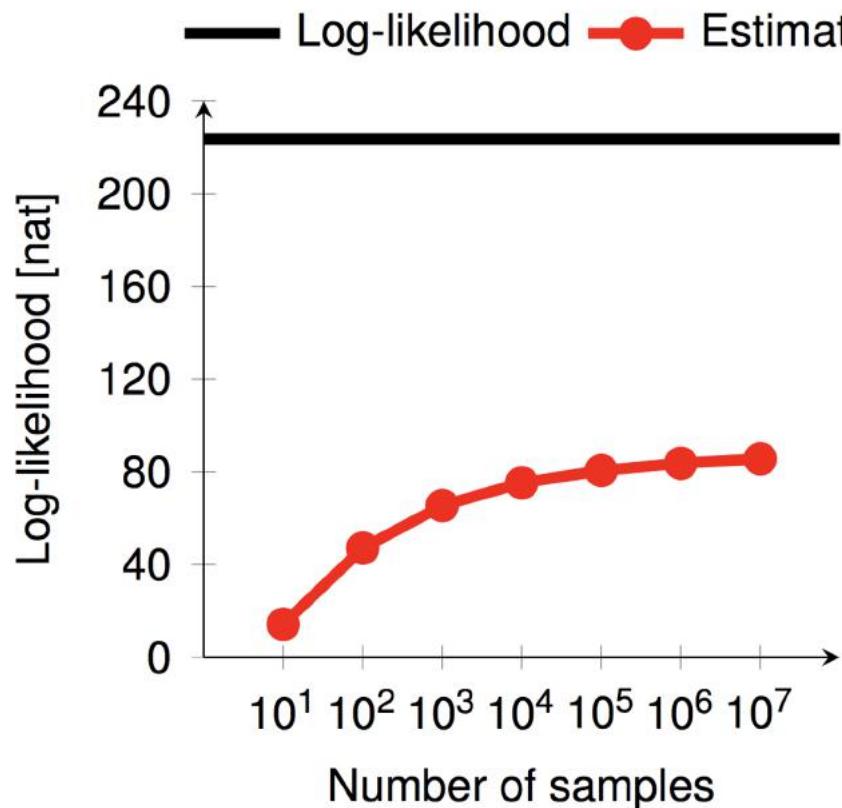
# Evaluation

Model	MNIST	TFD
DBN [3]	$138 \pm 2$	$1909 \pm 66$
Stacked CAE [3]	$121 \pm 1.6$	$2110 \pm 50$
Deep GSN [5]	$214 \pm 1.1$	$1890 \pm 29$
Adversarial nets	$225 \pm 2$	$2057 \pm 26$

Parzen Window density estimates (Goodfellow et al, 2014)

# Parzen-Window density estimator

- Parzen Window estimator can be unreliable



Model	Parzen est. [nat]
Stacked CAE	121
DBN	138
GMMN	147
Deep GSN	214
Diffusion	220
GAN	225
<b>True distribution</b>	<b>243</b>
GMMN + AE	282
<i>k</i> -means	313

# Inception Score

- Can we side-step high-dim density estimation?
- One idea: good generators generate samples that are semantically diverse
- Semantics predictor: trained Inception Network v3
  - $p(y|x)$ ,  $y$  is one of the [1000 ImageNet classes](#)
- Considerations:
  - each image  $x$  should have distinctly recognizable object ->  $p(y|x)$  should have low entropy
  - there should be as many classes generated as possible ->  $p(y)$  should have high entropy

# Inception Score

- Inception model:  $p(y|x)$
- Marginal label distribution:  $p(y) = \int_x p(y|x)p_g(x)$
- Inception Score:

$$\begin{aligned} \text{IS}(x) &= \exp(\mathbb{E}_{x \sim p_g} [D_{\text{KL}} [p(y|x) \parallel p(y)]]) \\ &= \exp(\mathbb{E}_{x \sim p_g, y \sim p(y|x)} [\log p(y|x) - \log p(y)]) \\ &= \exp(H(y) - H(y|x)) \end{aligned}$$

# Inception Score

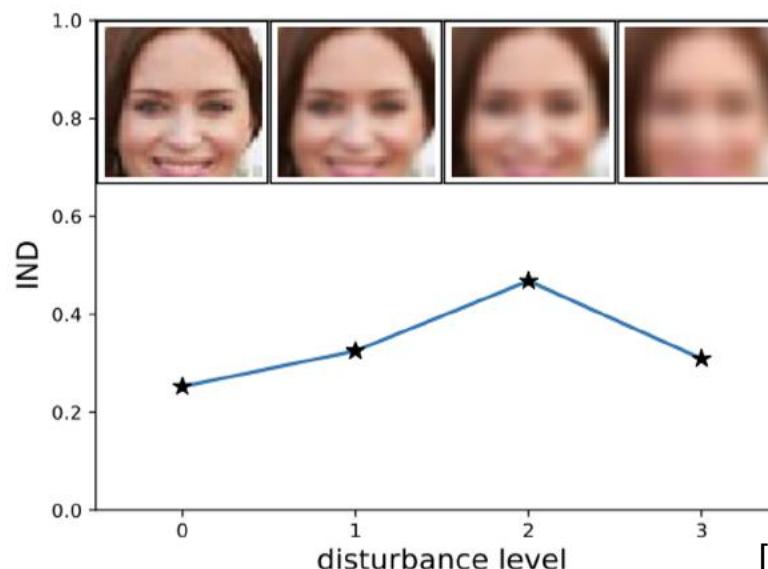
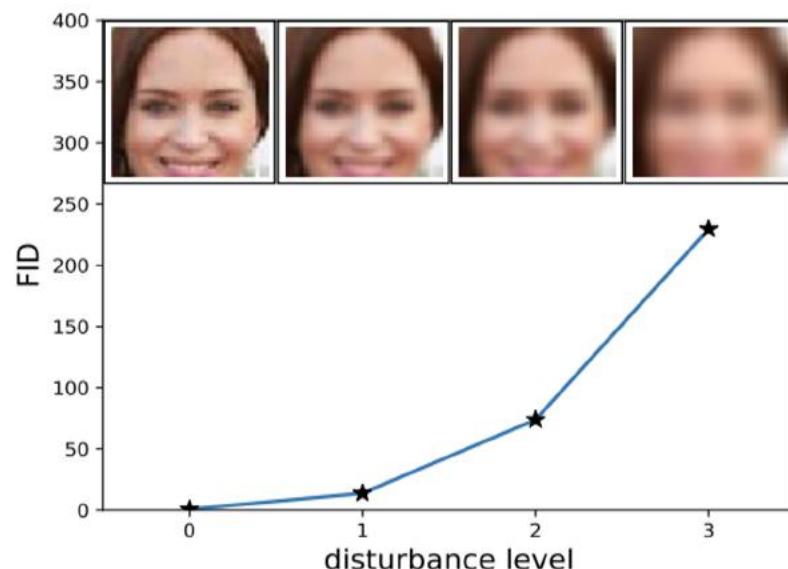
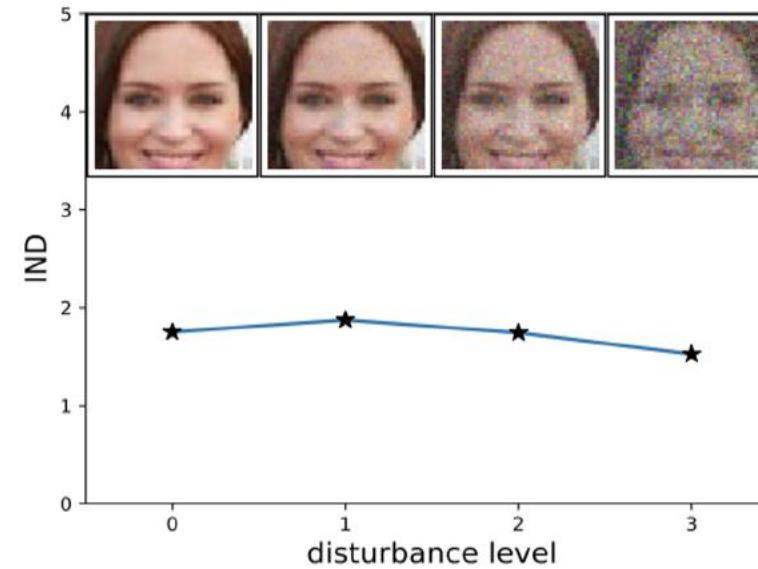
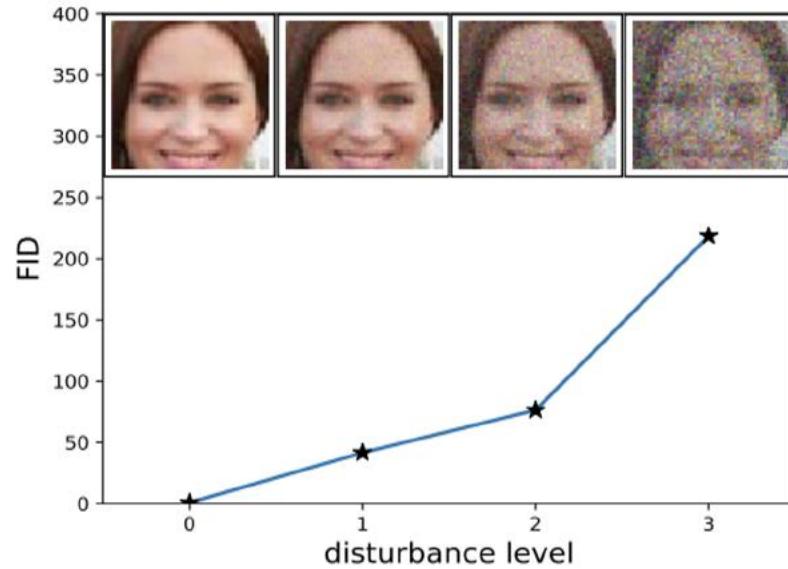
Samples				
Model	Real data	Our methods	-VBN+BN	-L+HA
Score $\pm$ std.	11.24 $\pm$ .12	8.09 $\pm$ .07	7.54 $\pm$ .07	6.86 $\pm$ .06

# Fréchet Inception Distance

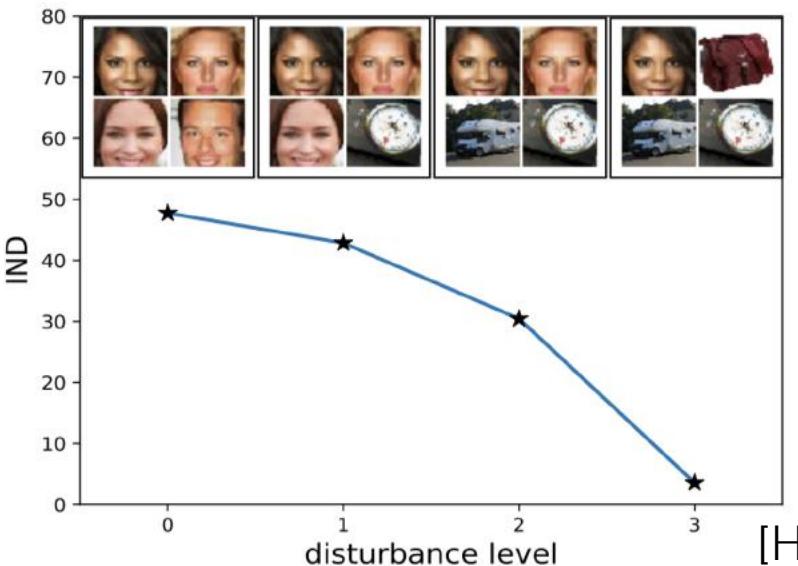
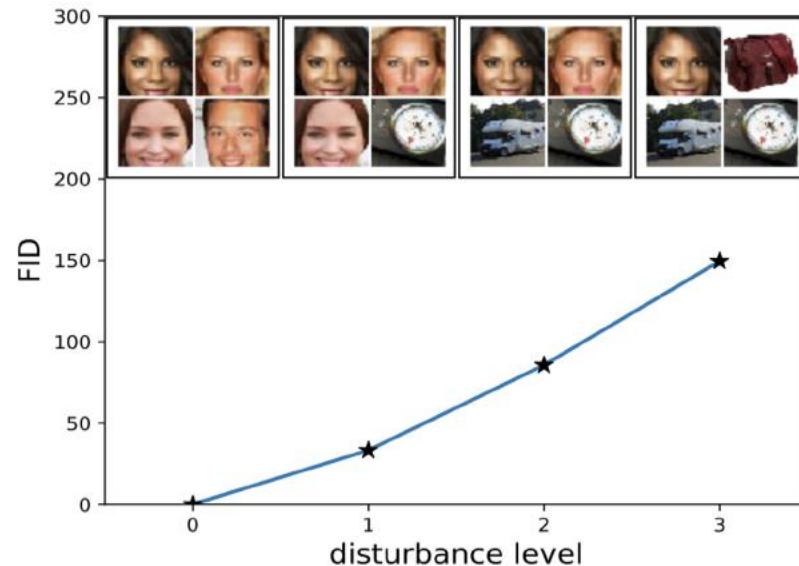
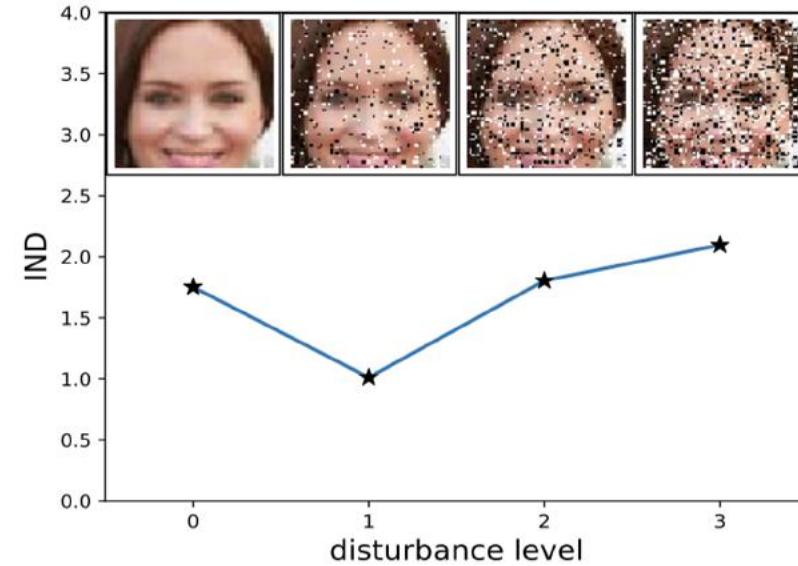
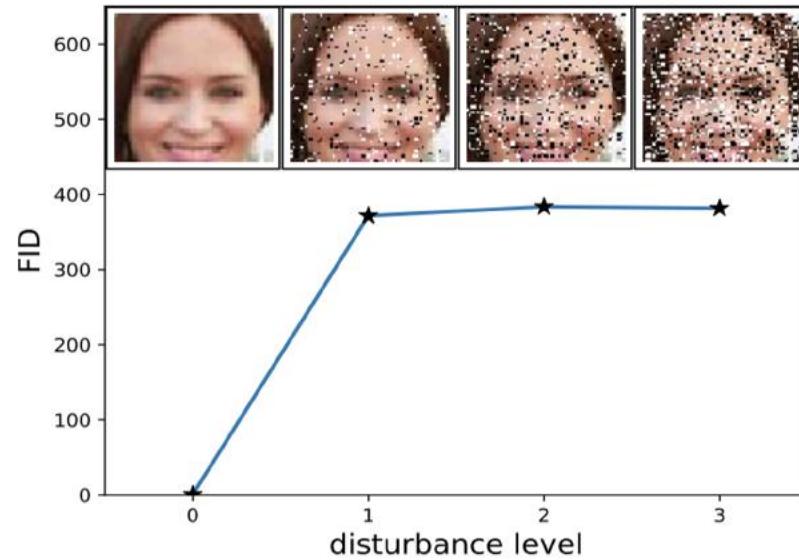
- Inception Score doesn't sufficiently measure diversity: a list of 1000 images (one of each class) can obtain perfect Inception Score
- FID was proposed to capture more nuances
- Embed image  $x$  into some feature space (2048-dimensional activations of the Inception-v3 pool3 layer), then compare mean ( $m$ ) & covariance ( $C$ ) of those random features

$$d^2((\mathbf{m}, \mathbf{C}), (\mathbf{m}_w, \mathbf{C}_w)) = \|\mathbf{m} - \mathbf{m}_w\|_2^2 + \text{Tr}(\mathbf{C} + \mathbf{C}_w - 2(\mathbf{C}\mathbf{C}_w)^{1/2})$$

# Fréchet Inception Distance



# Fréchet Inception Distance



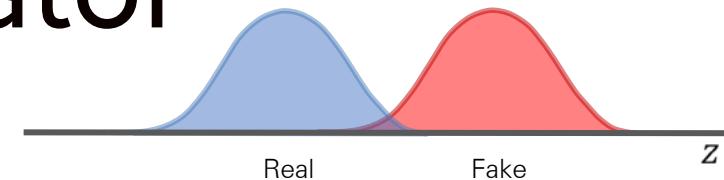
# Generative Adversarial Networks

- Key pieces of GAN
  - Fast sampling
  - No inference
  - Notion of optimizing directly for what you care about – perceptual samples

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# GAN: Bayes-Optimal Discriminator



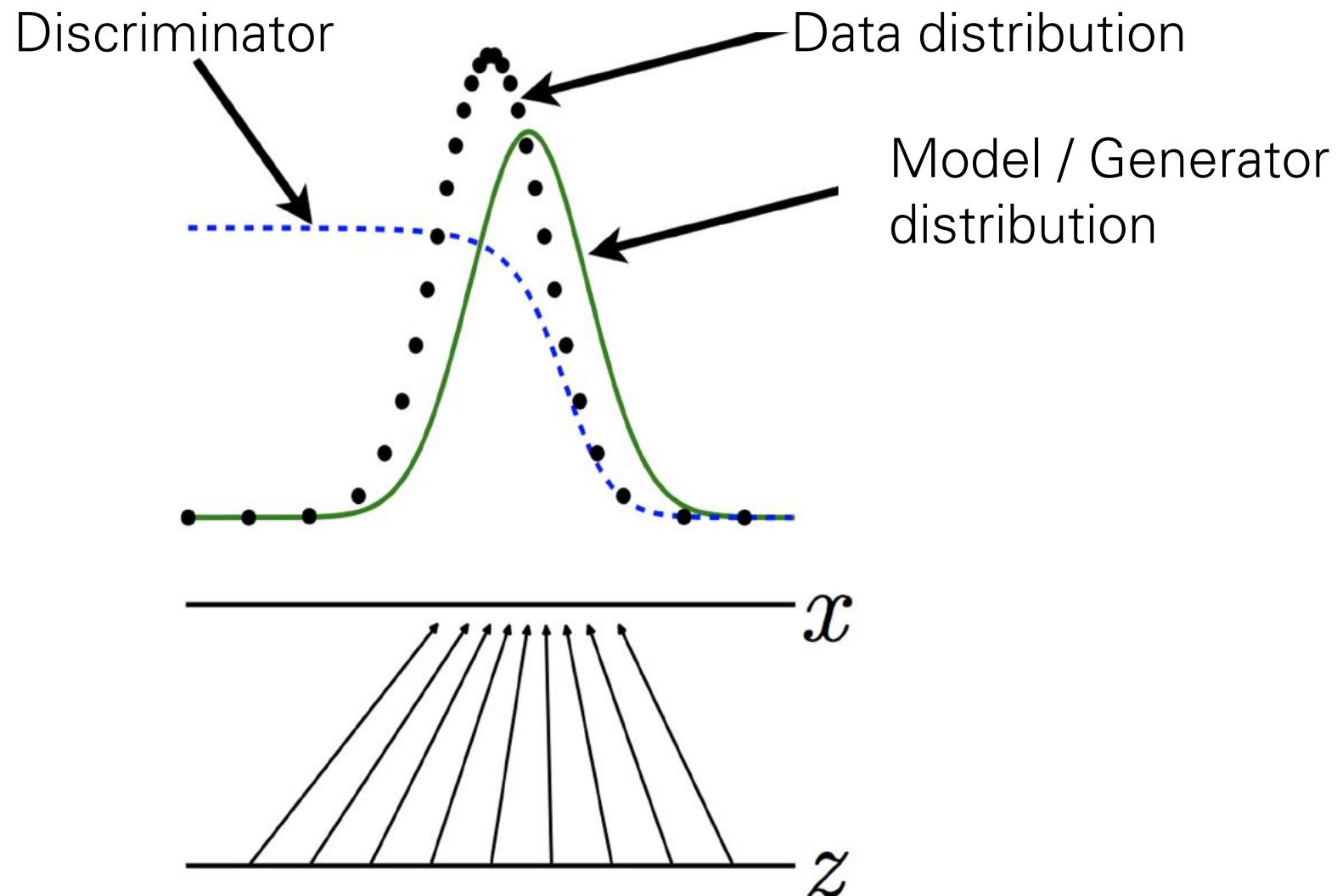
- What's the optimal discriminator given generated and true distributions?

$$\begin{aligned} V(G, D) &= \mathbb{E}_{x \sim p_{\text{data}}} [\log D(x)] + \mathbb{E}_{z \sim p(z)} [\log(1 - D(G(z)))] \\ &= \int_x p_{\text{data}}(x) \log D(x) dx + \int_z p(z) \log(1 - D(G(z))) dz \\ &= \int_x p_{\text{data}}(x) \log D(x) dx + \int_x p_g(x) \log(1 - D(x)) dx \\ &= \int_x [p_{\text{data}}(x) \log D(x) + p_g(x) \log(1 - D(x))] dx \end{aligned}$$

$$\nabla_y [a \log y + b \log(1 - y)] = 0 \implies y^* = \frac{a}{a+b} \quad \forall \quad [a, b] \in \mathbb{R}^2 \setminus [0, 0]$$

$$\implies D^*(x) = \frac{p_{\text{data}}(x)}{(p_{\text{data}}(x) + p_g(x))}$$

# GAN: Bayes-Optimal Discriminator



[Figure Source: Goodfellow  
NeurIPS 2016 Tutorial on GANs]

# GAN: Generator Objective under Bayes-Optimal Discriminator D\*?

$$\begin{aligned} V(G, D^*) &= \mathbb{E}_{x \sim p_{\text{data}}} [\log D^*(x)] + \mathbb{E}_{x \sim p_g} [\log(1 - D^*(x))] \\ &= \mathbb{E}_{x \sim p_{\text{data}}} \left[ \log \frac{p_{\text{data}}(x)}{p_{\text{data}}(x) + p_g(x)} \right] + \mathbb{E}_{x \sim p_g} \left[ \log \frac{p_g(x)}{p_{\text{data}}(x) + p_g(x)} \right] \\ &= \underbrace{-\log(4) + KL \left( p_{\text{data}} \parallel \left( \frac{p_{\text{data}} + p_g}{2} \right) \right) + KL \left( p_g \parallel \left( \frac{p_{\text{data}} + p_g}{2} \right) \right)}_{(\text{Jensen-Shannon Divergence (JSD) of } p_{\text{data}} \text{ and } p_g) \geq 0} \end{aligned}$$

$$V(G^*, D^*) = -\log(4) \text{ when } p_g = p_{\text{data}}$$

# Behaviors across divergence measures

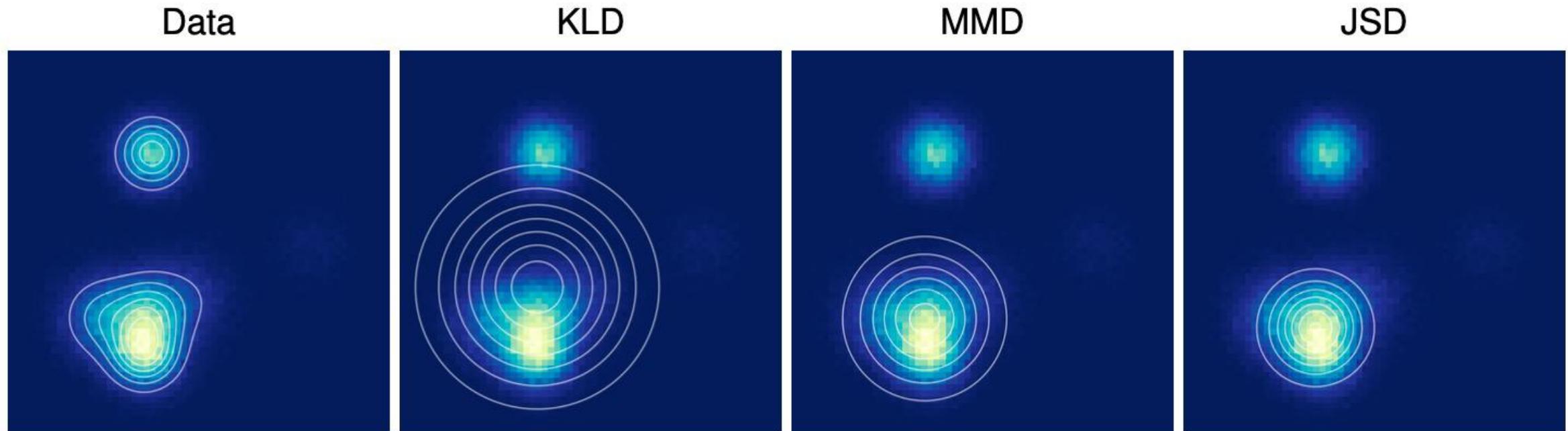
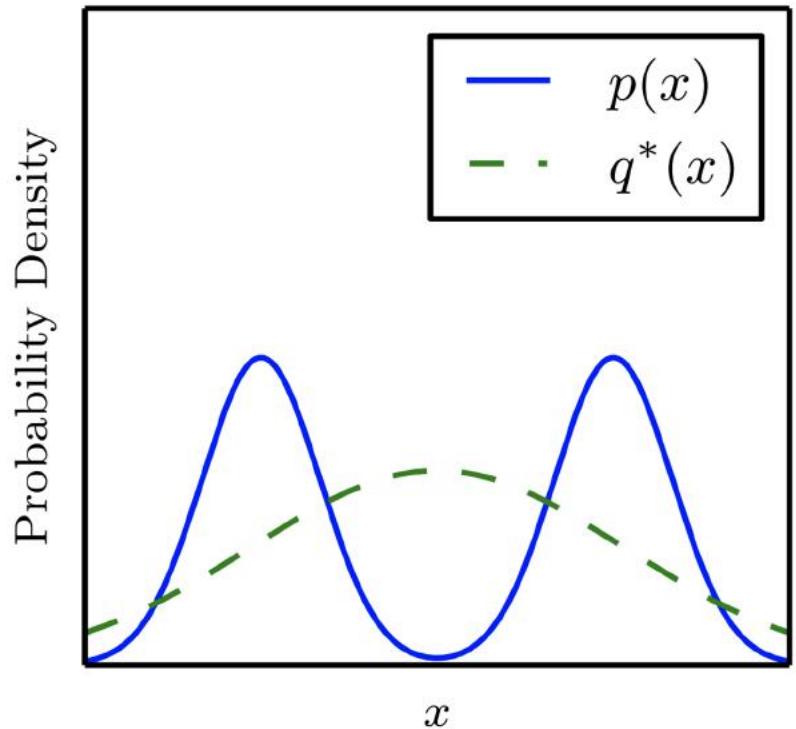


Figure 1: An isotropic Gaussian distribution was fit to data drawn from a mixture of Gaussians by either minimizing Kullback-Leibler divergence (KLD), maximum mean discrepancy (MMD), or Jensen-Shannon divergence (JSD). The different fits demonstrate different tradeoffs made by the three measures of distance between distributions.

[“A note on the evaluation of generative models” – Theis, Van den Oord, Bethge 2016]

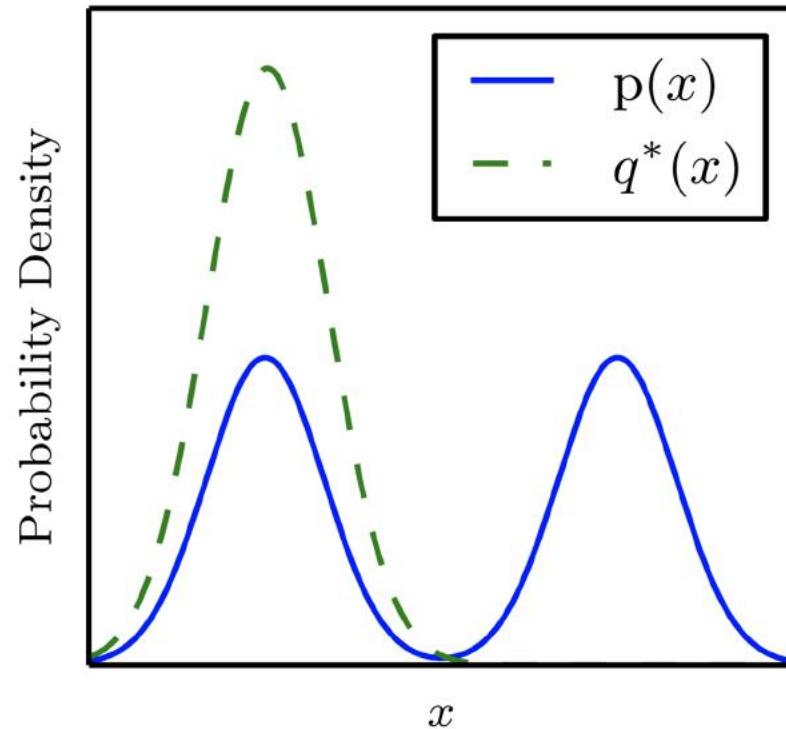
# Direction of KL divergence

$$q^* = \operatorname{argmin}_q D_{\text{KL}}(p\|q)$$



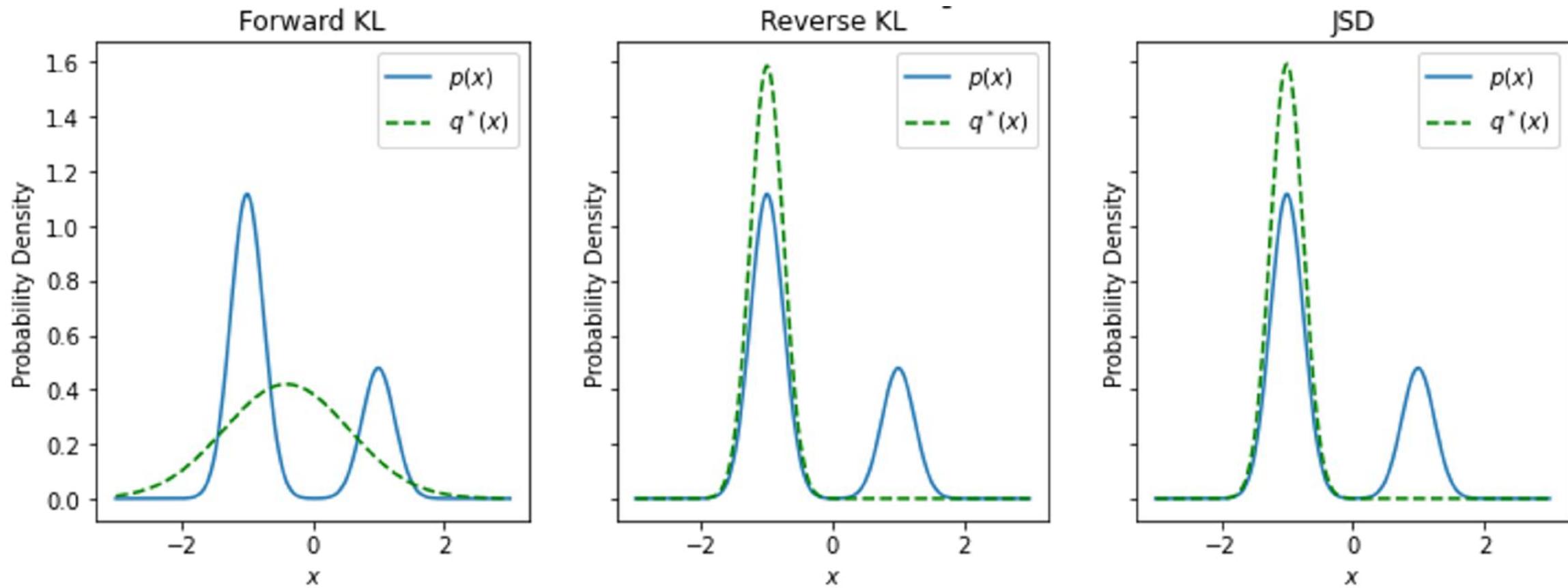
Maximum likelihood

$$q^* = \operatorname{argmin}_q D_{\text{KL}}(q\|p)$$



Reverse KL

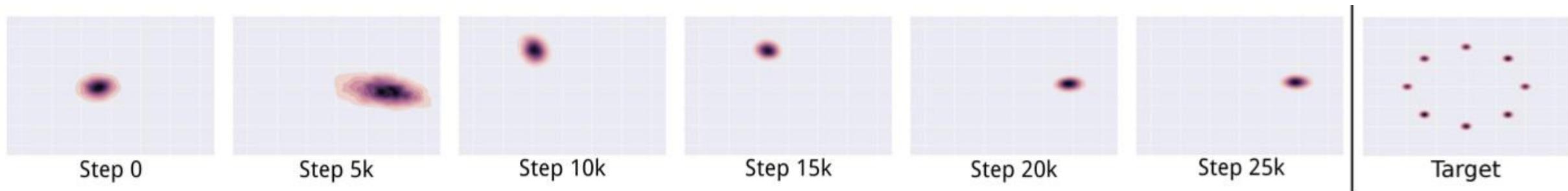
# KL and JSD



# Mode covering vs Mode seeking: Tradeoffs

- For compression, one would prefer to ensure all points in the data distribution are assigned probability mass.
- For generating good samples, blurring across modes spoils perceptual quality because regions outside the data manifold are assigned non-zero probability mass.
- Picking one mode without assigning probability mass on points outside can produce “better-looking” samples.
- **Caveat:** More expressive density models can place probability mass more accurately. For example, using mixture of Gaussians as opposed to a single isotropic gaussian.

# Mode Collapse



- Standard GAN training collapses when the true distribution is a mixture of gaussians!

(Figure from Metz et al. 2016)

# Back to GANs

## Recall

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


Discriminator

## Mini-Exercise

- Is it feasible to run the inner optimization to completion?
- For this specific objective, would it create problems if we were able to do so?

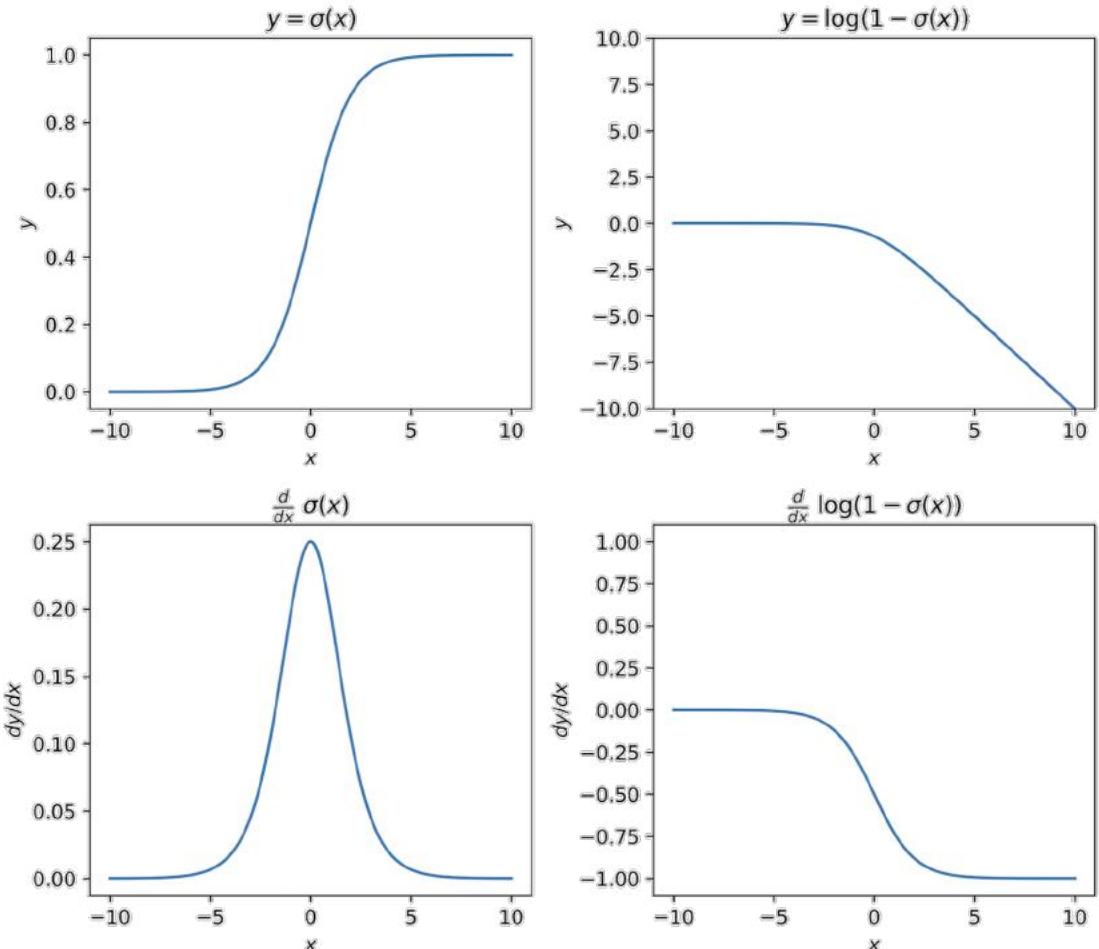
# Discriminator Saturation

- Generator samples confidently classified as fake by the discriminator receive no gradient for the generator update.

$$\nabla_{G(z)} \log(1 - D(G(z))) \quad \text{where}$$

$$D(x) = \text{sigmoid}(x; \theta) = \sigma(x; \theta)$$

$$\nabla_x \sigma(x) = \sigma(x)(1 - \sigma(x))$$



# Avoiding Discriminator Saturation: (1) Alternating Optimization

- Alternate gradient steps on discriminator and generator objectives

$$L^{(D)}(\theta_D, \theta_G) = -\mathbb{E}_{x \sim p_{\text{data}}} [\log D(x; \theta_D)] - \mathbb{E}_{z \sim p(z)} [\log(1 - D(G(z; \theta_G), \theta_D))]$$

$$L^{(G)}(\theta_D, \theta_G) = \mathbb{E}_{z \sim p(z)} [\log(1 - D(G(z; \theta_G), \theta_D))]$$

$$\theta_D := \theta_D - \alpha^{(D)} \nabla_{\theta_D} L^{(D)}(\theta_D, \theta_G)$$

$$\theta_G := \theta_G - \beta^{(G)} \nabla_{\theta_G} L^{(G)}(\theta_D, \theta_G)$$

- Balancing these two updates is hard for the zero-sum game

# Avoiding Discriminator Saturation: (2) Non-Saturating Formulation

$$L^{(D)} = -\mathbb{E}_{x \sim p_{\text{data}}} [\log D(x)] - \mathbb{E}_{z \sim p(z)} [\log(1 - D(G(z)))]$$

$$L^{(G)} = -L^D \equiv \min_G \mathbb{E}_{z \sim p(z)} \log(1 - D(G(z)))$$



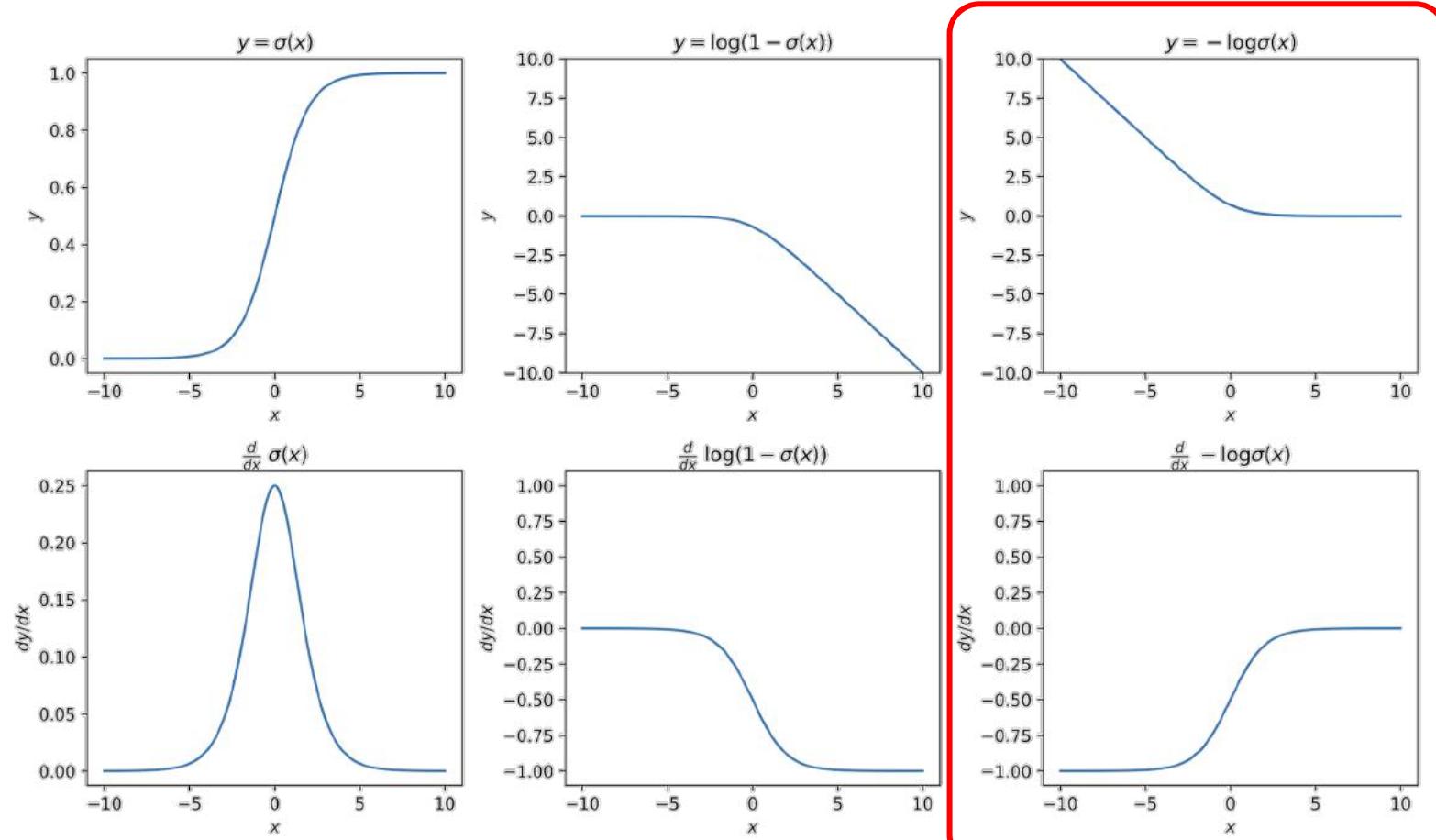
→ Not zero-sum

$$L^{(D)} = -\mathbb{E}_{x \sim p_{\text{data}}} [\log D(x)] - \mathbb{E}_{z \sim p(z)} [\log(1 - D(G(z)))]$$

$$L^{(G)} = -\mathbb{E}_{z \sim p(z)} \log(D(G(z))) \equiv \max_G \mathbb{E}_{z \sim p(z)} \log(D(G(z)))$$

# Avoiding Discriminator Saturation: (2) Non Saturating Formulation

- ORIGINAL ISSUE:  
Generator samples confidently classified as fake by the discriminator receive no gradient for the generator update.
- FIX: non-saturating loss for when discriminator confident about fake



# Lecture overview

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- Applications

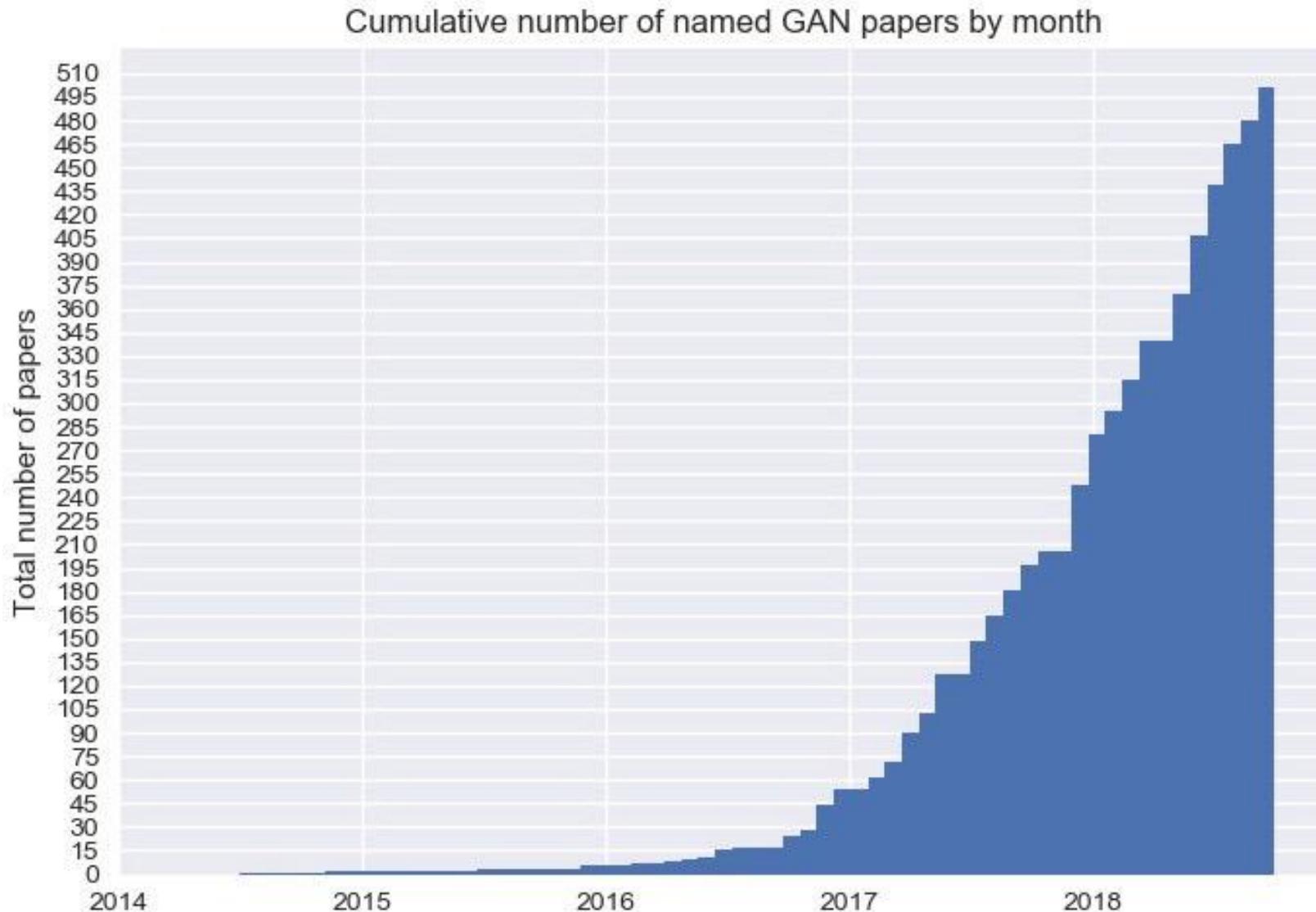
# GAN Zoo

- AN — Generative Adversarial Networks  
3D-GAN — Learning a Probabilistic Latent Space of Object Shapes via 3D Generative-Adversarial Modeling acGAN — Face Aging With Conditional Generative Adversarial Networks  
AC-GAN — Conditional Image Synthesis With Auxiliary Classifier GANs  
AdaGAN — AdaGAN: Boosting Generative Models  
AEGAN — Learning Inverse Mapping by Autoencoder based Generative Adversarial Nets  
AffGAN — Amortised MAP Inference for Image Super-resolution  
AL-CGAN — Learning to Generate Images of Outdoor Scenes from Attributes and Semantic Layouts  
ALI — Adversarially Learned Inference  
AMGAN — Generative Adversarial Nets with Labeled Data by Activation Maximization  
AnoGAN — Unsupervised Anomaly Detection with Generative Adversarial Networks to Guide Marker Discovery  
ArtGAN — ArtGAN: Artwork Synthesis with Conditional Categorical GANs  
b-GAN — b-GAN: Unified Framework of Generative Adversarial Networks  
Bayesian GAN — Deep and Hierarchical Implicit Models  
BEGAN — BEGAN: Boundary Equilibrium Generative Adversarial Networks  
BiGAN — Adversarial Feature Learning  
BS-GAN — Boundary-Seeking Generative Adversarial Networks  
CGAN — Conditional Generative Adversarial Nets  
CCGAN — Semi-Supervised Learning with Context-Conditional Generative Adversarial Networks  
CatGAN — Unsupervised and Semi-supervised Learning with Categorical Generative Adversarial Networks  
CoGAN — Coupled Generative Adversarial Networks  
Context-RNN-GAN — Contextual RNN-GANs for Abstract Reasoning Diagram Generation  
C-RNN-GAN — C-RNN-GAN: Continuous recurrent neural networks with adversarial training  
CS-GAN — Improving Neural Machine Translation with Conditional Sequence Generative Adversarial Nets  
CVAE-GAN — CVAE-GAN: Fine-Grained Image Generation through Asymmetric Training  
CycleGAN — Unpaired Image-to-Image Translation using Cycle-Consistent Adversarial Networks  
DTN — Unsupervised Cross-Domain Image Generation  
DCGAN — Unsupervised Representation Learning with Deep Convolutional Generative Adversarial Networks  
DiscoGAN — Learning to Discover Cross-Domain Relations with Generative Adversarial Networks  
DR-GAN — Disentangled Representation Learning GAN for Pose-Invariant Face Recognition  
DualGAN — DualGAN: Unsupervised Dual Learning for Image-to-Image Translation  
EBGAN — Energy-based Generative Adversarial Network  
f-GAN — f-GAN: Training Generative Neural Samplers using Variational Divergence Minimization  
GAWWN — Learning What and Where to Draw  
GoGAN — Gang of GANs: Generative Adversarial Networks with Maximum Margin Ranking  
GP-GAN — GP-GAN: Towards Realistic High-Resolution Image Blending  
IAN — Neural Photo Editing with Introspective Adversarial Networks  
iGAN — Generative Visual Manipulation on the Natural Image Manifold  
IcGAN — Invertible Conditional GANs for image editing  
ID-CGAN — Image De-raining Using a Conditional Generative Adversarial Network  
Improved GAN — Improved Techniques for Training GANs  
InfoGAN — InfoGAN: Interpretable Representation Learning by Information Maximizing Generative Adversarial Networks  
LAGAN — Learning Particle Physics by Example: Location-Aware Generative Adversarial Networks for Physics Synthesis  
LAPGAN — Deep Generative Image Models using a Laplacian Pyramid of Adversarial Networks  
LR-GAN — LR-GAN: Layered Recursive Generative Adversarial Networks for Image Generation  
LSGAN — Least Squares Generative Adversarial Networks  
LS-GAN — Loss-Sensitive Generative Adversarial Networks on Lipschitz Densities  
MGAN — Precomputed Real-Time Texture Synthesis with Markovian Generative Adversarial Networks  
MAGAN — MAGAN: Margin Adaptation for Generative Adversarial Networks  
MAD-GAN — Multi-Agent Diverse Generative Adversarial Networks  
MalGAN — Generating Adversarial Malware Examples for Black-Box Attacks Based on GAN  
MaliGAN — Maximum-Likelihood Augmented Discrete Generative Adversarial Networks  
MARTA-GAN — Deep Unsupervised Representation Learning for Remote Sensing Images  
McGAN — McGan: Mean and Covariance Feature Matching GAN  
MDGAN — Mode Regularized Generative Adversarial Networks  
MedGAN — Generating Multi-label Discrete Electronic Health Records using Generative Adversarial Networks  
MIX+GAN — Generalization and Equilibrium in Generative Adversarial Nets (GANs)  
MPM-GAN — Message Passing Multi-Agent GANs  
MV-BiGAN — Multi-view Generative Adversarial Networks  
pix2pix — Image-to-Image Translation with Conditional Adversarial Networks  
PPGN — Plug & Play Generative Networks: Conditional Iterative Generation of Images in Latent Space  
PrGAN — 3D Shape Induction from 2D Views of Multiple Objects  
RenderGAN — RenderGAN: Generating Realistic Labeled Data  
RTT-GAN — Recurrent Topic-Transition GAN for Visual Paragraph Generation  
SGAN — Stacked Generative Adversarial Networks  
SGAN — Texture Synthesis with Spatial Generative Adversarial Networks  
SAD-GAN — SAD-GAN: Synthetic Autonomous Driving using Generative Adversarial Networks  
SalGAN — SalGAN: Visual Saliency Prediction with Generative Adversarial Networks  
SEGAN — SEGAN: Speech Enhancement Generative Adversarial Network  
SegGAN — SegGAN: Segmenting and Generating the Invisible  
SeqGAN — SeqGAN: Sequence Generative Adversarial Nets with Policy Gradient  
SimGAN — Learning from Simulated and Unsupervised Images through Adversarial Training  
SketchGAN — Adversarial Training For Sketch Retrieval  
SL-GAN — Semi-Latent GAN: Learning to generate and modify facial images from attributes  
Softmax-GAN — Softmax GAN  
SRGAN — Photo-Realistic Single Image Super-Resolution Using a Generative Adversarial Network  
S2GAN — Generative Image Modeling using Style and Structure Adversarial Networks  
SSL-GAN — Semi-Supervised Learning with Context-Conditional Generative Adversarial Networks  
StackGAN — StackGAN: Text to Photo-realistic Image Synthesis with Stacked Generative Adversarial Networks  
TGAN — Temporal Generative Adversarial Nets  
TAC-GAN — TAC-GAN — Text Conditioned Auxiliary Classifier Generative Adversarial Network  
TP-GAN — Beyond Face Rotation: Global and Local Perception GAN for Photorealistic and Identity Preserving Frontal View Synthesis  
Triple-GAN — Triple Generative Adversarial Nets  
Unrolled GAN — Unrolled Generative Adversarial Networks  
VGAN — Generating Videos with Scene Dynamics  
VGAN — Generative Adversarial Networks as Variational Training of Energy Based Models  
VAE-GAN — Autoencoding beyond pixels using a learned similarity metric  
VariGAN — Multi-View Image Generation from a Single-View  
VIGAN — Image Generation and Editing with Variational Info Generative Adversarial Networks  
WGAN — Wasserstein GAN  
WGAN-GP — Improved Training of Wasserstein GANs  
WaterGAN — WaterGAN: Unsupervised Generative Network to Enable Real-time Color Correction of Monocular Underwater Images

Deep Hunt, blog by Avinash Hindupur  
<https://deephunt.in/the-gan-zoo-79597dc8c347>

# GAN Zoo

# An explo-GAN of papers



Explosive growth — All the named GAN variants cumulatively since 2014.

Credit: Bruno Gavranović

Deep Hunt, blog by Avinash Hindupur

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# Deep Convolutional GAN (DCGAN)

## UNSUPERVISED REPRESENTATION LEARNING WITH DEEP CONVOLUTIONAL GENERATIVE ADVERSARIAL NETWORKS

**Alec Radford & Luke Metz**

indico Research

Boston, MA

{alec, luke}@indico.io

**Soumith Chintala**

Facebook AI Research

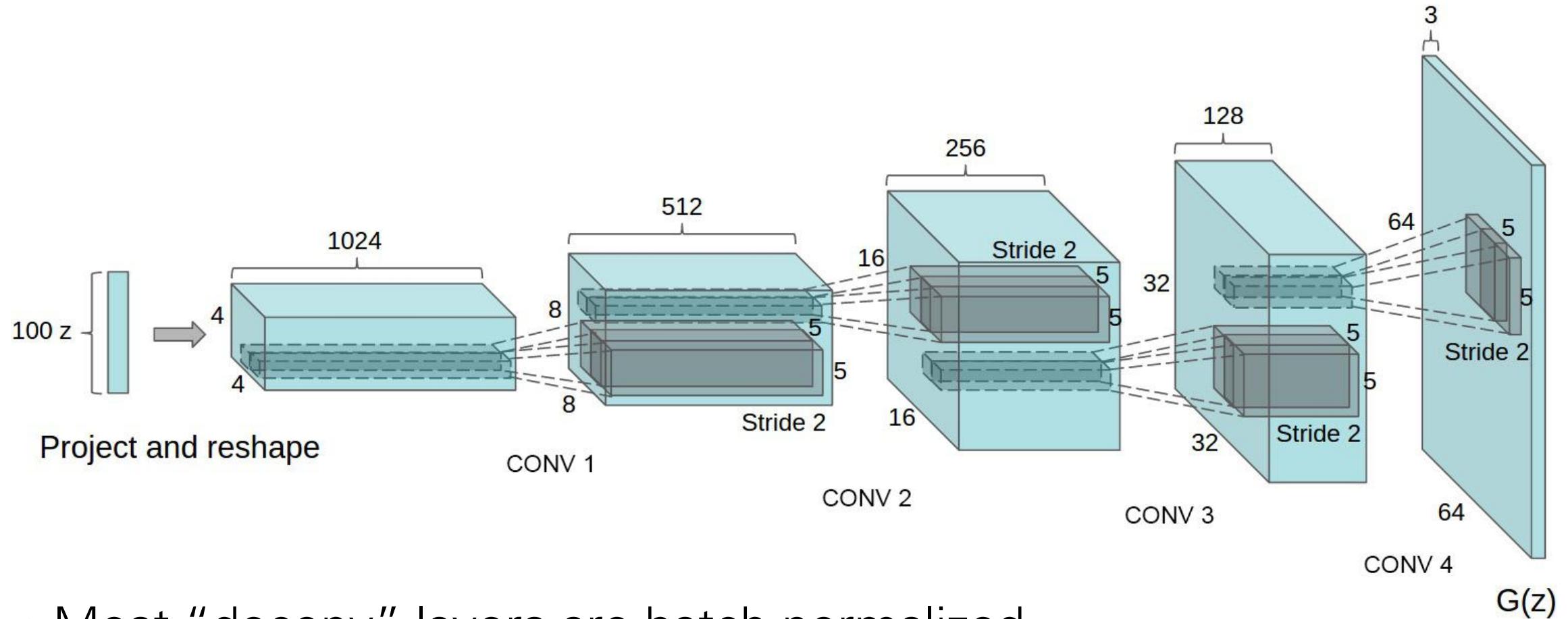
New York, NY

soumith@fb.com

### ABSTRACT

In recent years, supervised learning with convolutional networks (CNNs) has seen huge adoption in computer vision applications. Comparatively, unsupervised learning with CNNs has received less attention. In this work we hope to help bridge the gap between the success of CNNs for supervised learning and unsupervised learning. We introduce a class of CNNs called deep convolutional generative adversarial networks (DCGANs), that have certain architectural constraints, and demonstrate that they are a strong candidate for unsupervised learning. Training on various image datasets, we show convincing evidence that our deep convolutional adversarial pair learns a hierarchy of representations from object parts to scenes in both the generator and discriminator. Additionally, we use the learned features for novel tasks - demonstrating their applicability as general image representations.

# Deep Convolutional GAN (DCGAN)

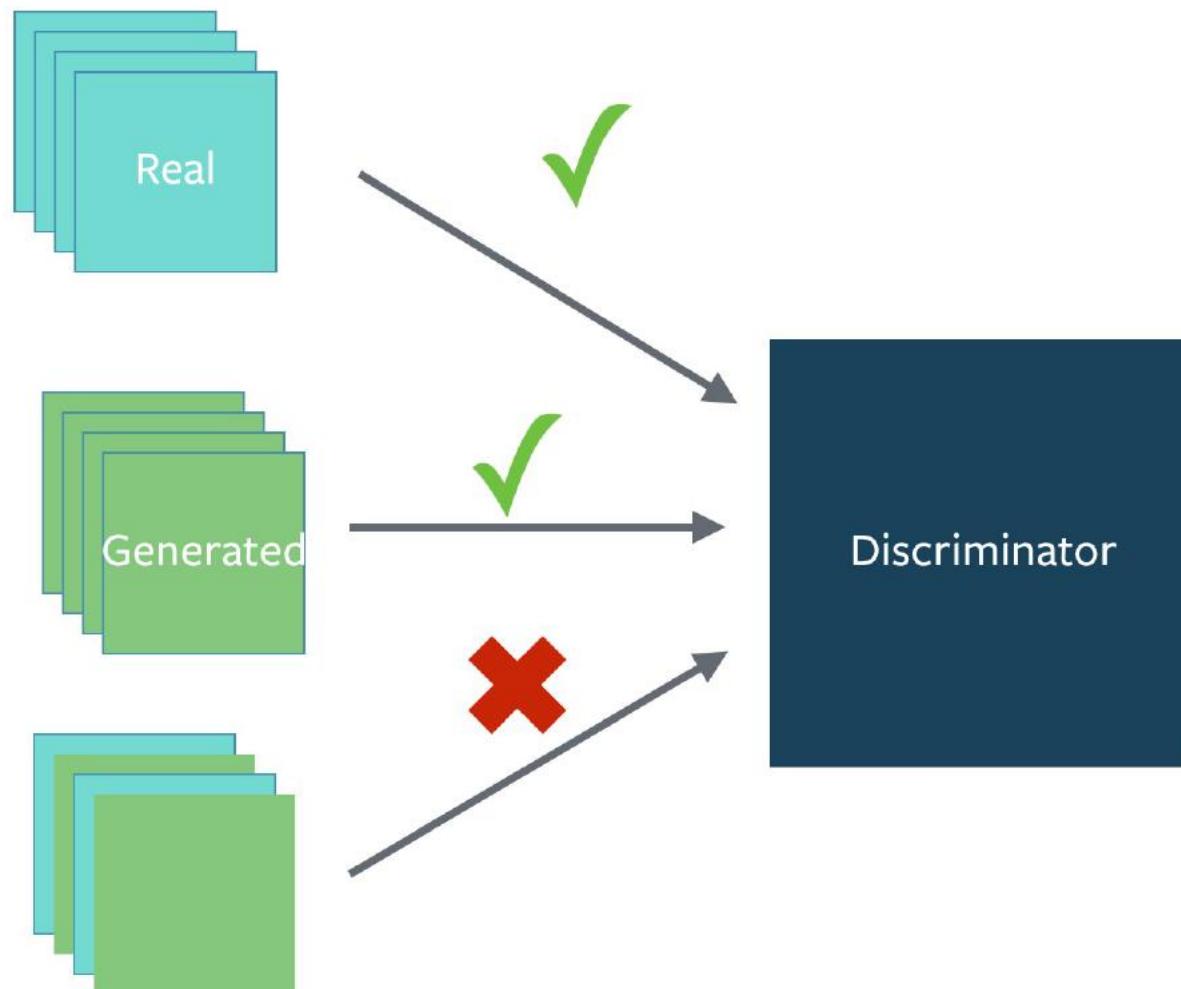


- Most “deconv” layers are batch normalized

# DCGAN - Architecture Design

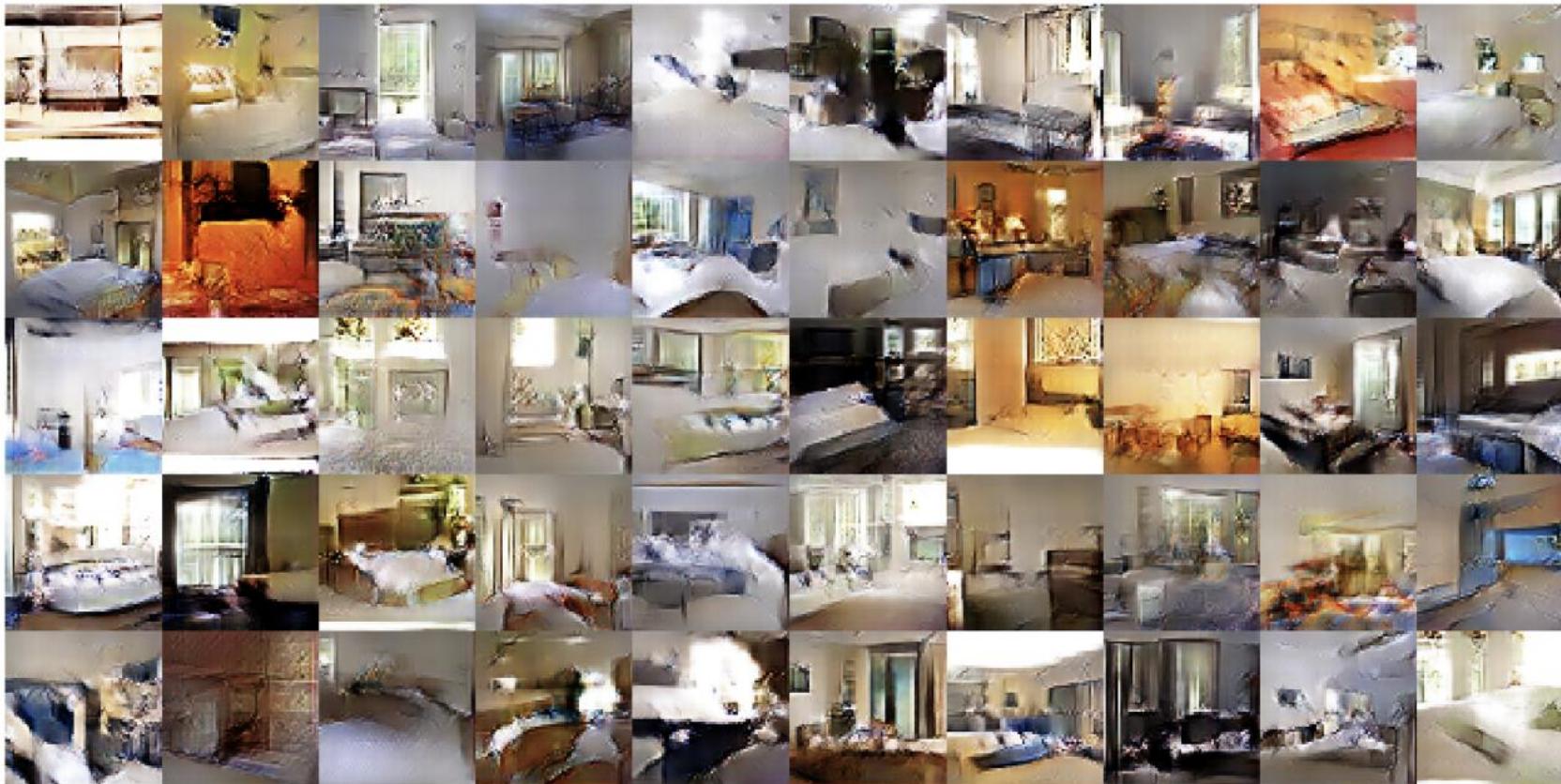
- Supervised Learning CNNs not directly usable
  - Remove max-pooling and mean-pooling
  - Upsample using transposed convolutions in the generator
  - Downsample with strided convolutions and average pooling
  - Non-Linearity: ReLU for generator, Leaky-ReLU (0.2) for discriminator
  - Output Non-Linearity: tanh for Generator, sigmoid for discriminator
  - Batch Normalization used to prevent mode collapse
  - Batch Normalization is not applied at the output of G and input of D
- Optimization details
  - Adam: small LR - 2e-4; small momentum: 0.5, batch-size: 128

# DCGAN Batch Norm



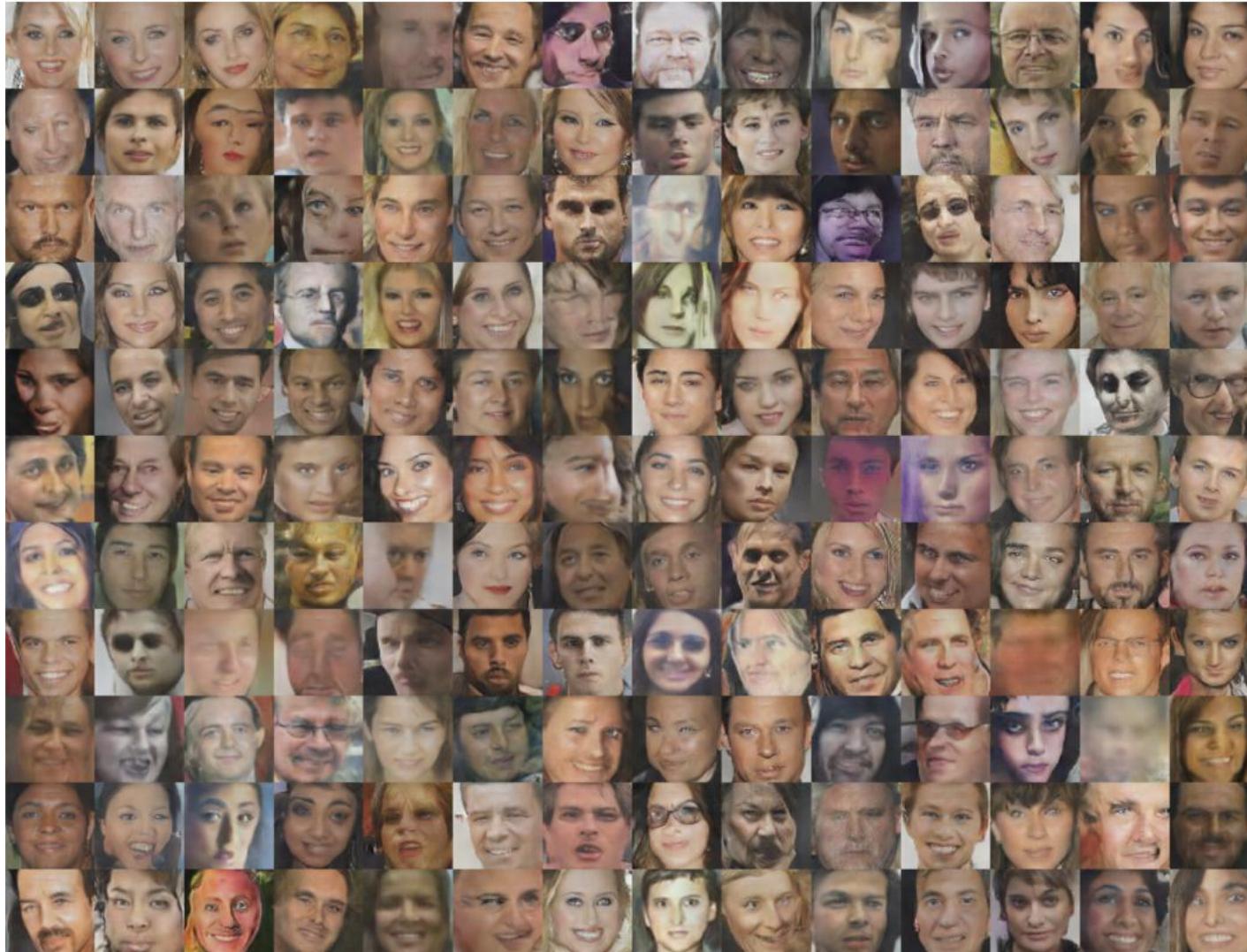
# DCGAN - Key Results

- Good samples on datasets with 3M images (Faces, Bedrooms) for the first time



[Radford et al 2016]

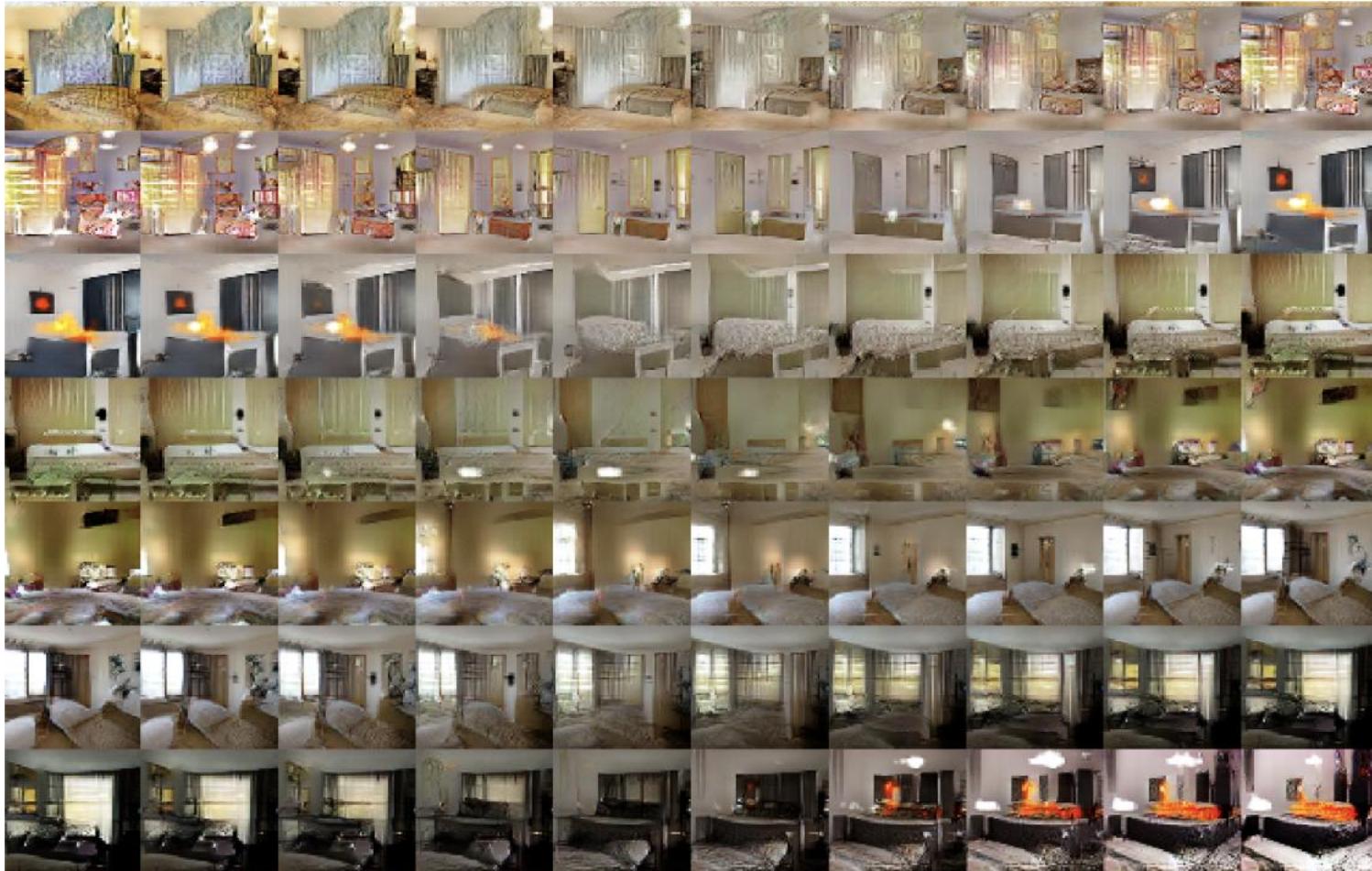
# DCGAN - Key Results



[Radford et al 2016]

# DCGAN - Key Results

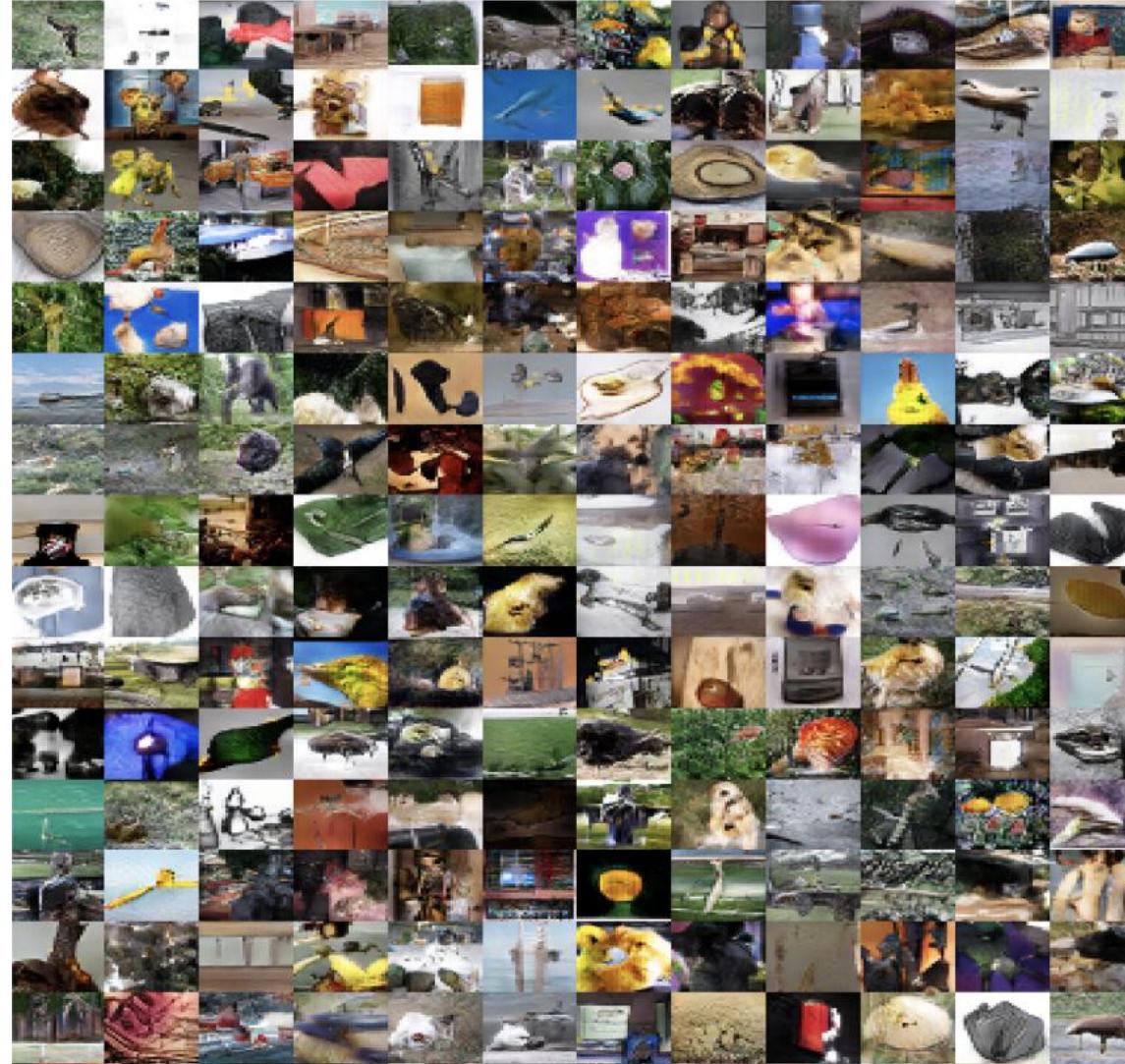
- Smooth interpolations in high dimensions



[Radford et al 2016]

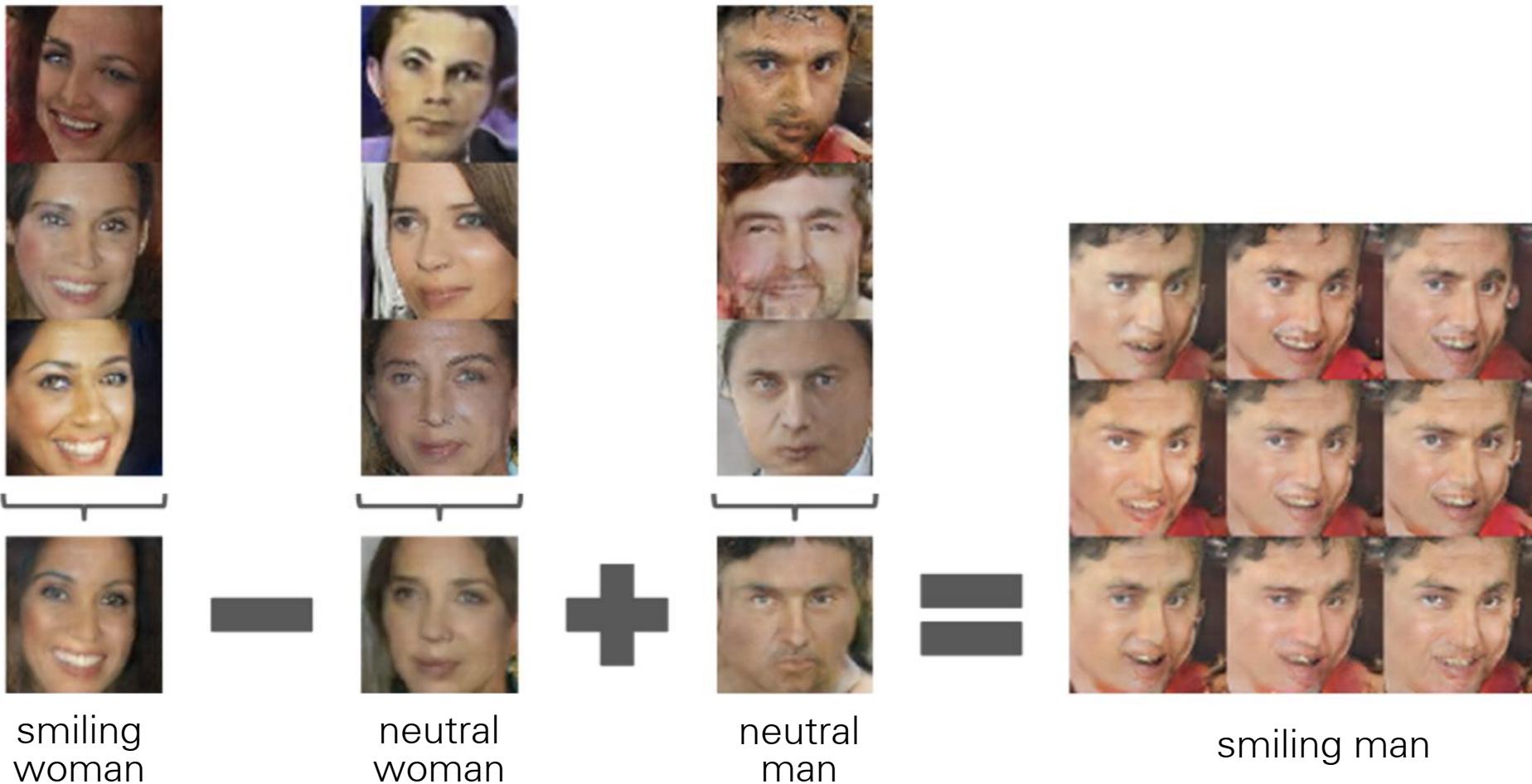
# DCGAN - Key Results

- Imagenet samples



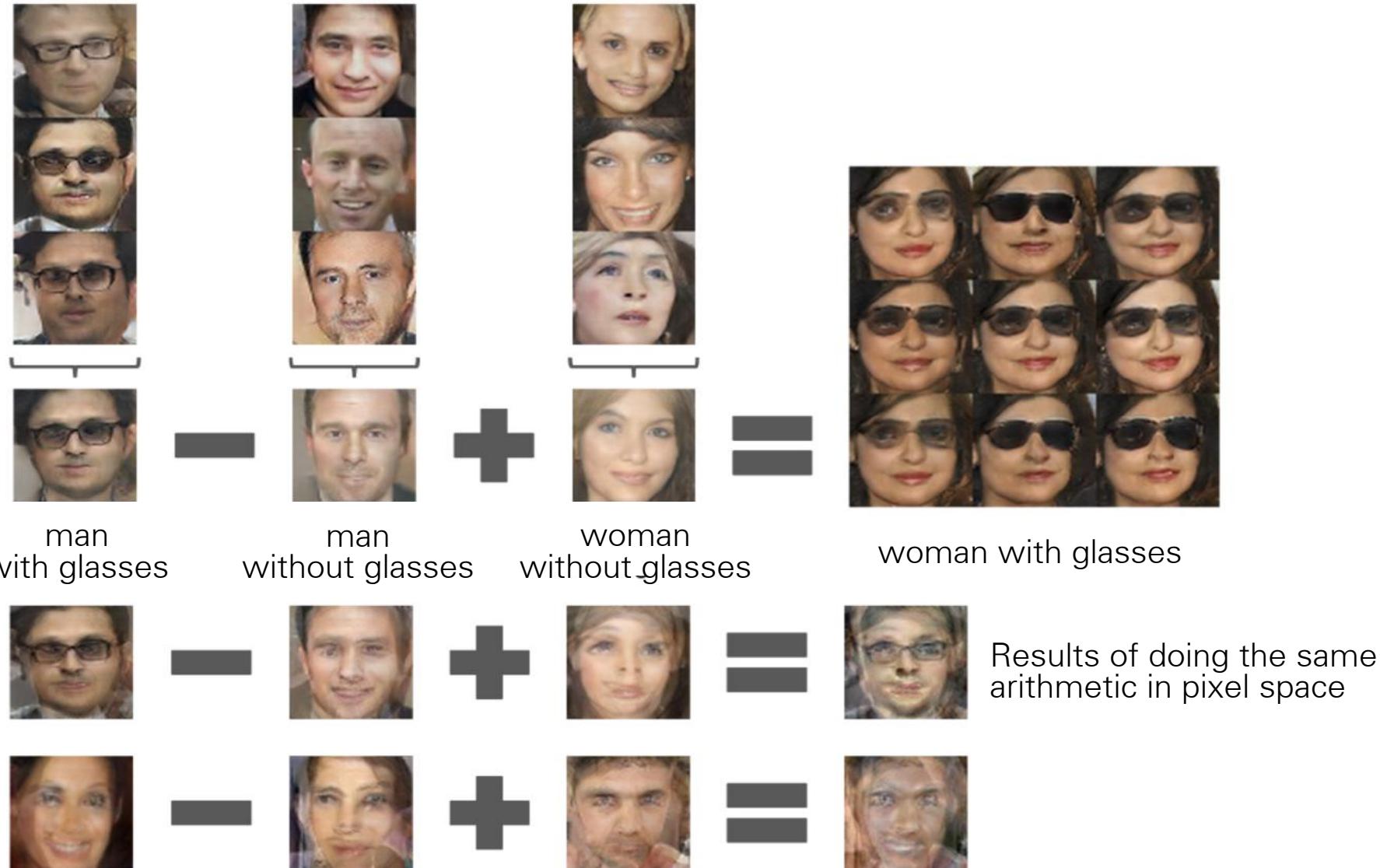
# DCGAN - Key Results

- Vector Arithmetic



[Radford et al 2016]

# DCGAN - Key Results



# DCGAN - Key Results



# DCGAN - Key Results

- Representation Learning

Model	Accuracy	Accuracy (400 per class)	max # of features units
1 Layer K-means	80.6%	63.7% ( $\pm 0.7\%$ )	4800
3 Layer K-means Learned RF	82.0%	70.7% ( $\pm 0.7\%$ )	3200
View Invariant K-means	81.9%	72.6% ( $\pm 0.7\%$ )	6400
Exemplar CNN	84.3%	77.4% ( $\pm 0.2\%$ )	1024
DCGAN (ours) + L2-SVM	82.8%	73.8% ( $\pm 0.4\%$ )	512

# DCGAN - Conclusions

- Incredible samples for any generative model
- GANs could be made to work well with architecture details
- Perceptually good samples and interpolations
- Representation Learning
- **Problems to address:**
  - Unstable training
  - Brittle architecture / hyperparameters

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# Improved training of GANs

- Feature Matching
- Minibatch discrimination
- Historical Averaging
- Virtual batch normalization
- One-sided label smoothing

---

## Improved Techniques for Training GANs

---

**Tim Salimans**  
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**Wojciech Zaremba**  
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**Vicki Cheung**  
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**Alec Radford**  
alec.radford@gmail.com

**Xi Chen**  
peter@openai.com

[Salimans 2016]

# Improved training of GANs

- Feature Matching

$$||\mathbb{E}_{x \sim p_{\text{data}}} f(x) - \mathbb{E}_{z \sim p(z)} f(G(z))||^2$$

Generator objective

[Salimans 2016]

# Improved training of GANs

- Minibatch discrimination

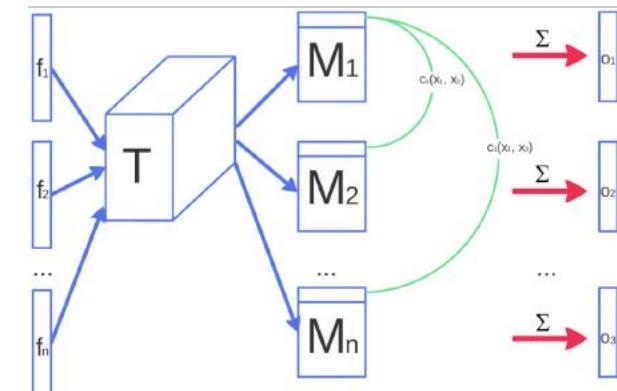
$$\mathbf{f}(\mathbf{x}_i) \in \mathbb{R}^A \quad T \in \mathbb{R}^{A \times B \times C} \quad M_i \in \mathbb{R}^{B \times C}$$

$$c_b(\mathbf{x}_i, \mathbf{x}_j) = \exp(-||M_{i,b} - M_{j,b}||_{L_1}) \in \mathbb{R}$$

$$o(\mathbf{x}_i)_b = \sum_{j=1}^n c_b(\mathbf{x}_i, \mathbf{x}_j) \in \mathbb{R}$$

$$o(\mathbf{x}_i) = [o(\mathbf{x}_i)_1, o(\mathbf{x}_i)_2, \dots, o(\mathbf{x}_i)_B] \in \mathbb{R}^B$$

$$o(\mathbf{X}) \in \mathbb{R}^{n \times B}$$



[Salimans 2016]

Allows to incorporate side information from other samples and is superior to feature matching in the unconditional setting.  
Helps addressing mode collapse by allowing discriminator to detect if the generated samples are too close to each other.

# Improved training of GANs

- Historical Averaging

$$\|\boldsymbol{\theta} - \frac{1}{t} \sum_{i=1}^t \boldsymbol{\theta}[i]\|^2$$

# Improved training of GANs

- One-sided label smoothing

Default discriminator cost:

```
cross_entropy(1., discriminator(data))  
+ cross_entropy(0., discriminator(samples))
```



One-sided label smoothed cost (Salimans et al 2016):

```
cross_entropy(.9, discriminator(data))  
+ cross_entropy(0., discriminator(samples))
```

# Improved training of GANs

- Why one-sided?

Reinforces current generator behavior

$$D(\mathbf{x}) = \frac{(1 - \alpha)p_{\text{data}}(\mathbf{x}) + \beta p_{\text{model}}(\mathbf{x})}{p_{\text{data}}(\mathbf{x}) + p_{\text{model}}(\mathbf{x})}$$

# Improved training of GANs

- Virtual Batch Normalization

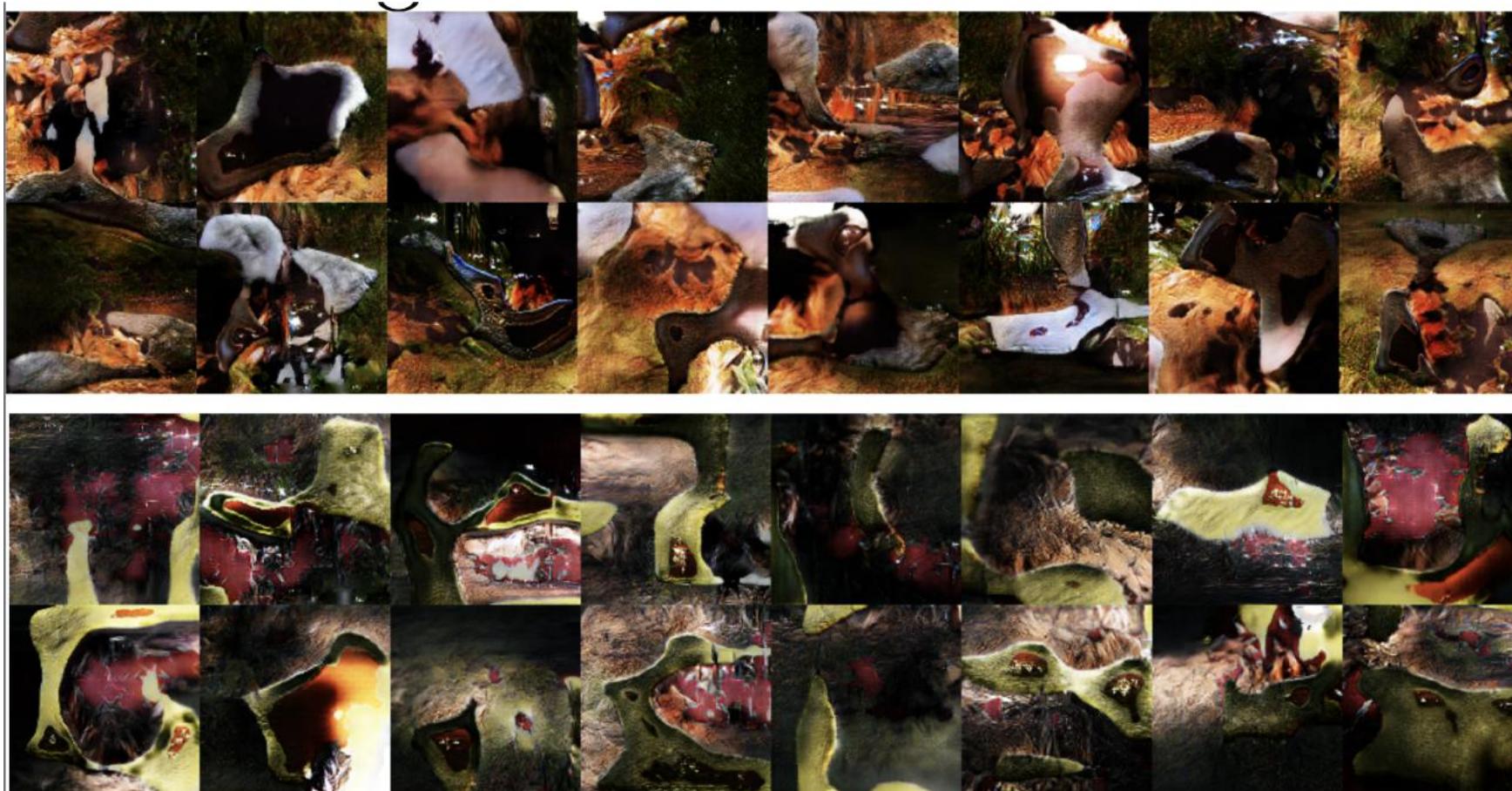


Figure source:  
NeurIPS tutorial  
Goodfellow 2016

# Improved training of GANs

- Virtual Batch Normalization
  - Use a reference batch (fixed) to compute normalization statistics
  - Construct a batch containing the sample and reference batch

# Improved training of GANs

- Semi-Supervised Learning
  - Predict labels in addition to fake/real in the discriminator
  - Approximate way of modeling  $p(x,y)$
  - Generator doesn't have to be made conditional  $p(x|y)$
  - Use a deeper architecture for the discriminator compared to generator

$$\begin{aligned} L &= -\mathbb{E}_{\substack{\mathbf{x}, y \sim p_{\text{data}}(\mathbf{x}, y)}} [\log p_{\text{model}}(y|\mathbf{x})] - \mathbb{E}_{\mathbf{x} \sim G} [\log p_{\text{model}}(y = K+1|\mathbf{x})] \\ &= L_{\text{supervised}} + L_{\text{unsupervised}}, \text{ where} \end{aligned}$$

$$L_{\text{supervised}} = -\mathbb{E}_{\substack{\mathbf{x}, y \sim p_{\text{data}}(\mathbf{x}, y)}} \log p_{\text{model}}(y|\mathbf{x}, y < K+1)$$

$$L_{\text{unsupervised}} = -\{\mathbb{E}_{\mathbf{x} \sim p_{\text{data}}(\mathbf{x})} \log[1 - p_{\text{model}}(y = K+1|\mathbf{x})] + \mathbb{E}_{\mathbf{x} \sim G} \log[p_{\text{model}}(y = K+1|\mathbf{x})]\}$$

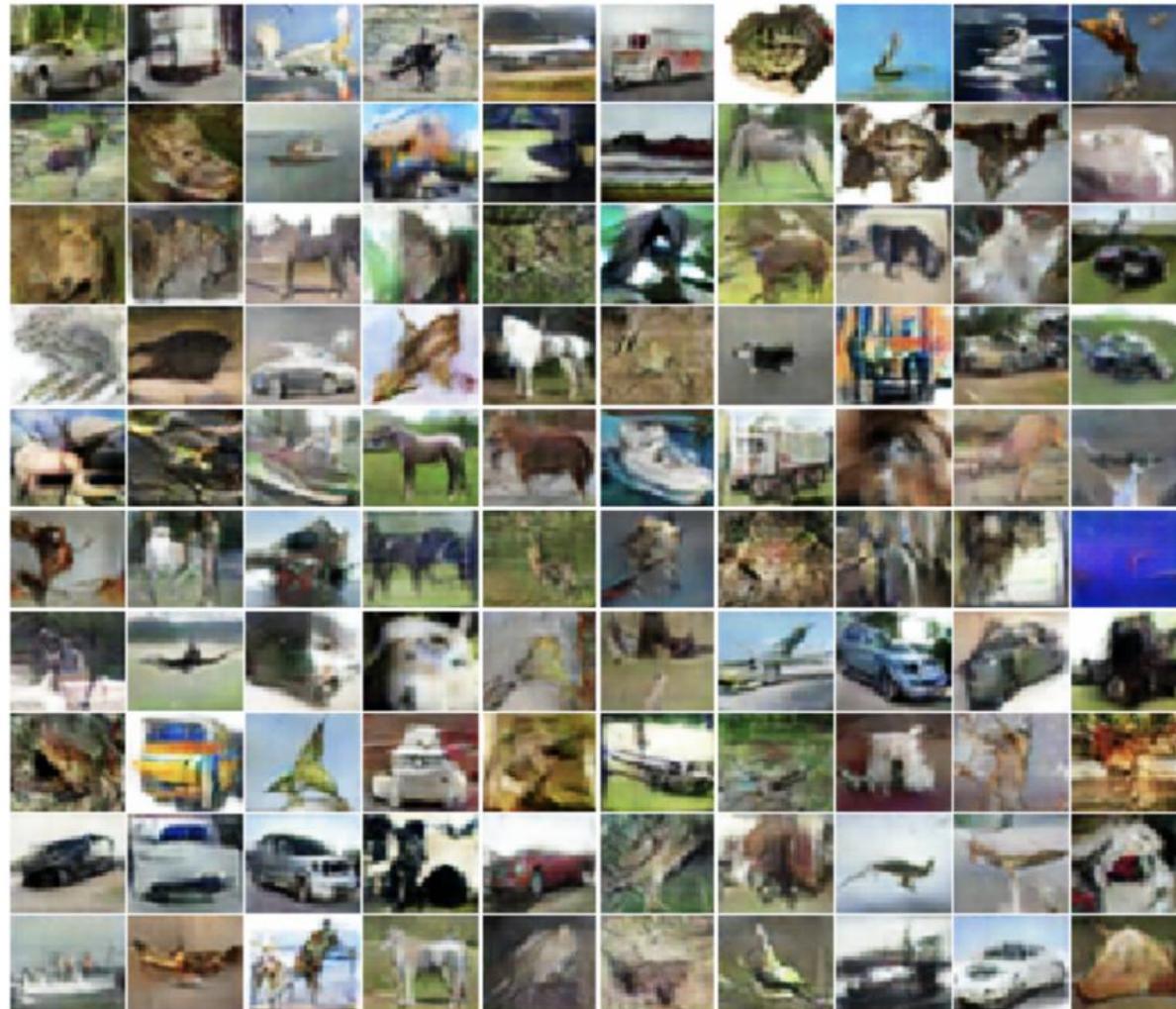
# Improved training of GANs

- Inception Score

$$\exp(\mathbb{E}_{\mathbf{x}} \text{KL}(p(y|\mathbf{x}) || p(y)))$$

- Approximate way of modeling  $p(x,y)$
- Correlates with human judgement
- Captures some necessity for diversity

# Improved training of GANs

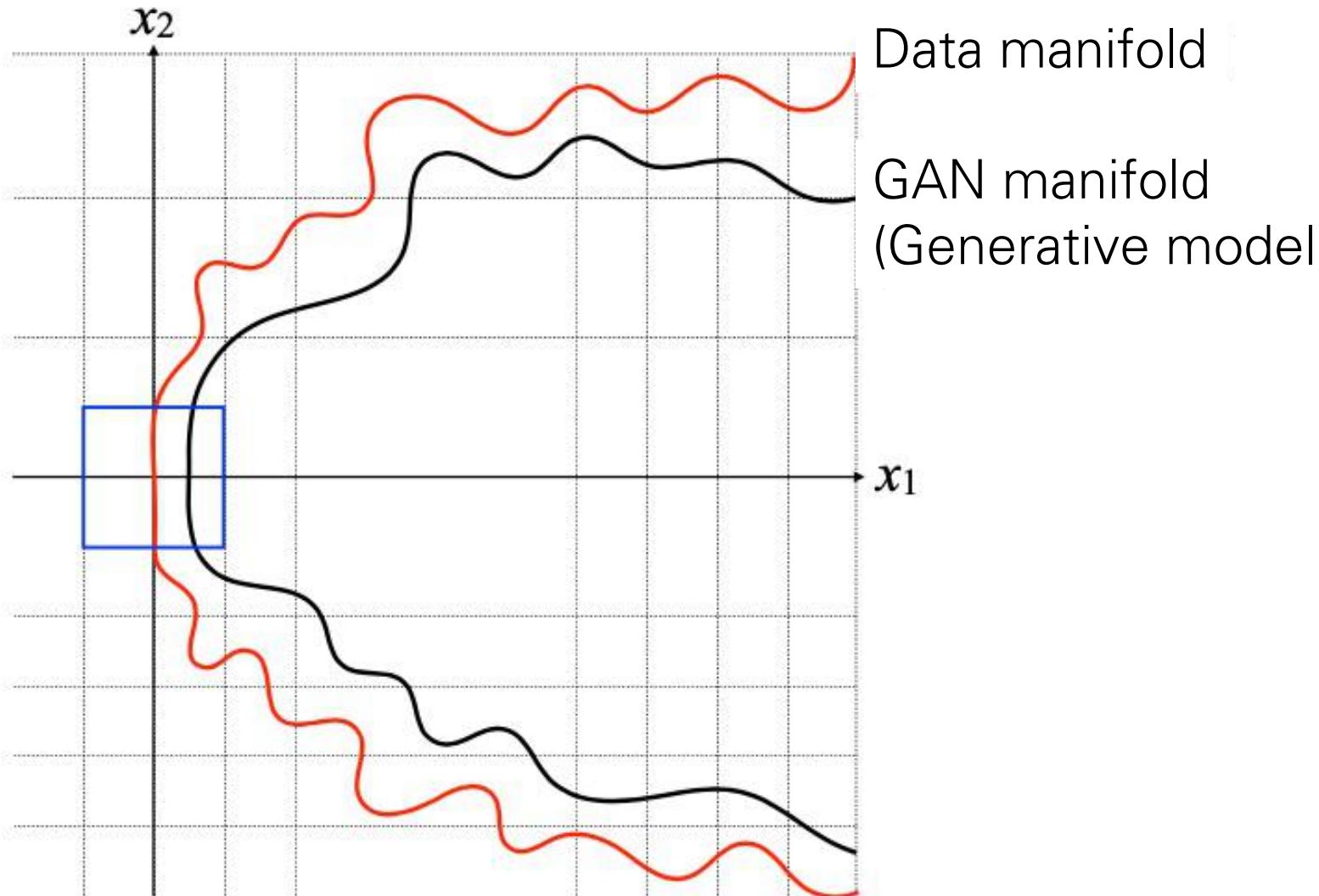


Salimans 2016

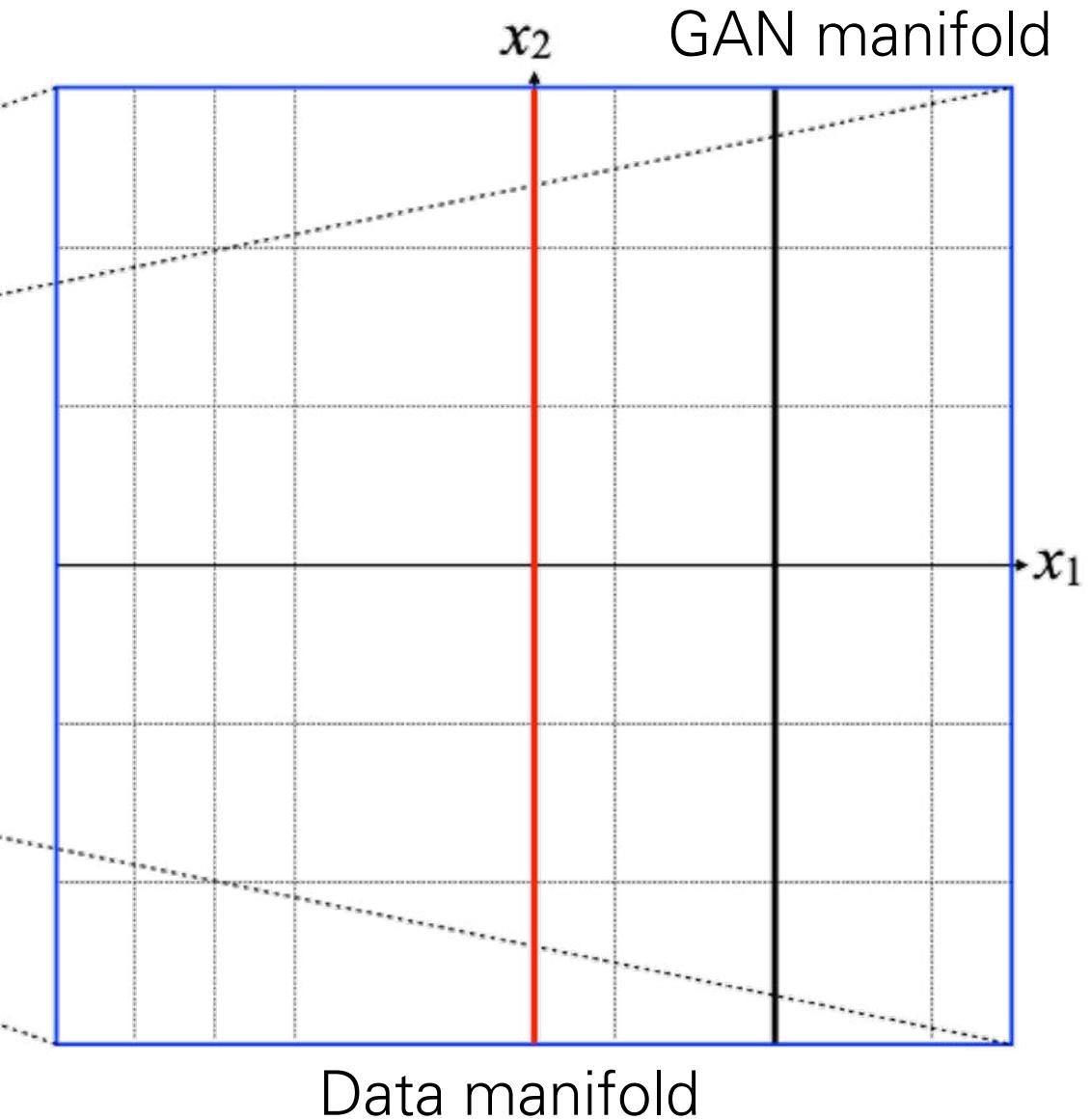
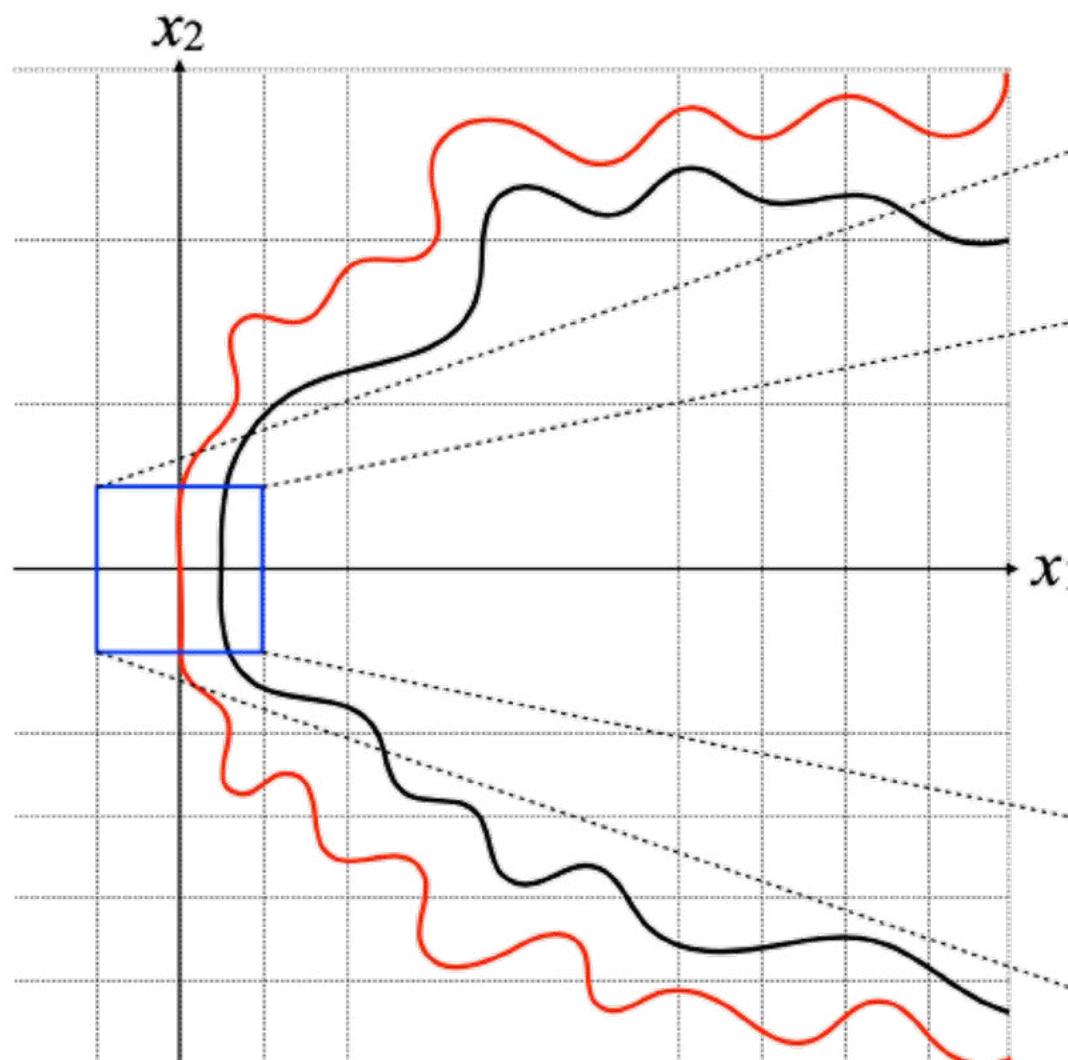
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# Training a GAN: Distances between Manifolds



# Training a GAN: Distances between Manifolds



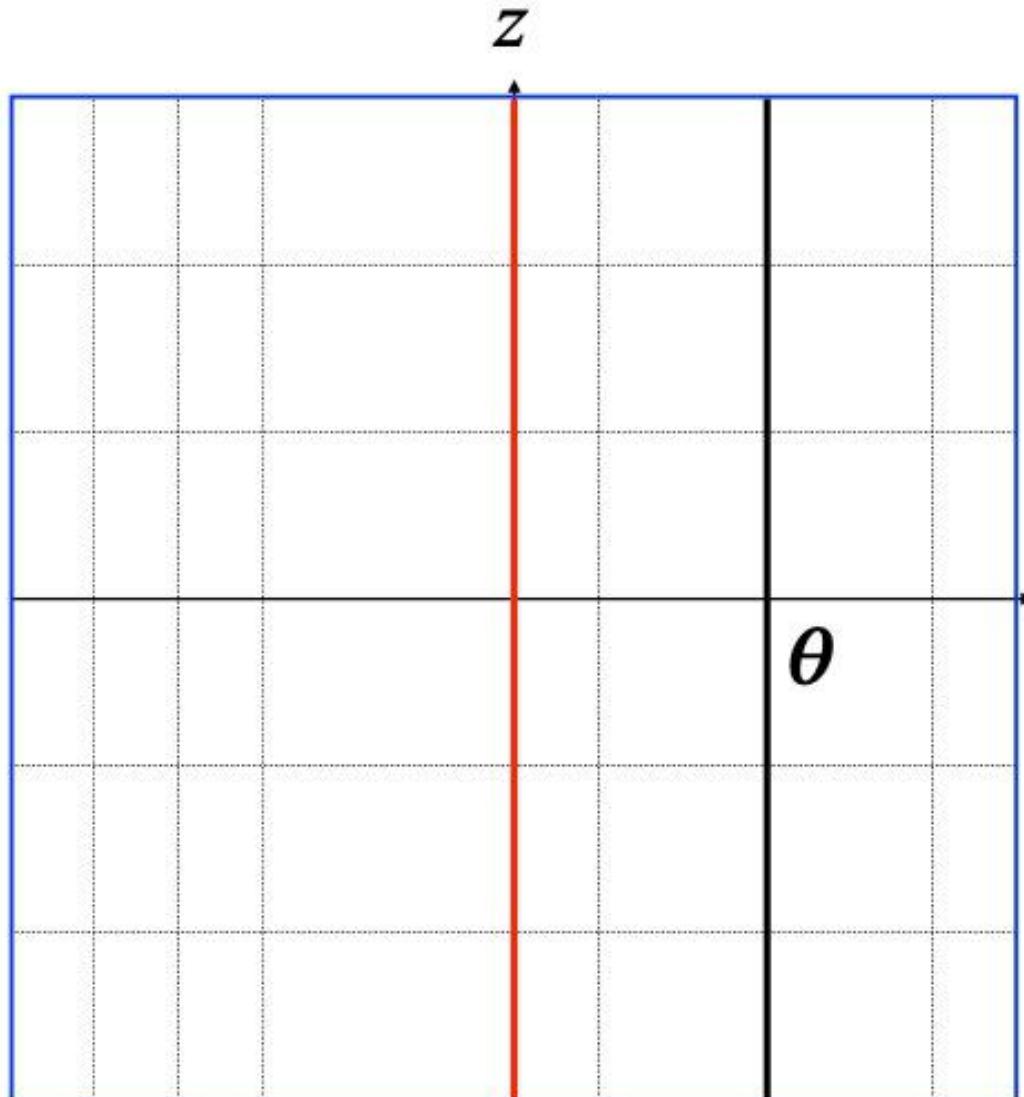
Data manifold

# Jensen-Shannon Divergence

$$\text{JS}(\mathbb{P}_r \parallel \mathbb{P}_g) = \text{KL}\left(\mathbb{P}_r \parallel \frac{\mathbb{P}_r + \mathbb{P}_g}{2}\right) + \text{KL}\left(\mathbb{P}_g \parallel \frac{\mathbb{P}_r + \mathbb{P}_g}{2}\right)$$

- What is the JS divergence in this simple case?

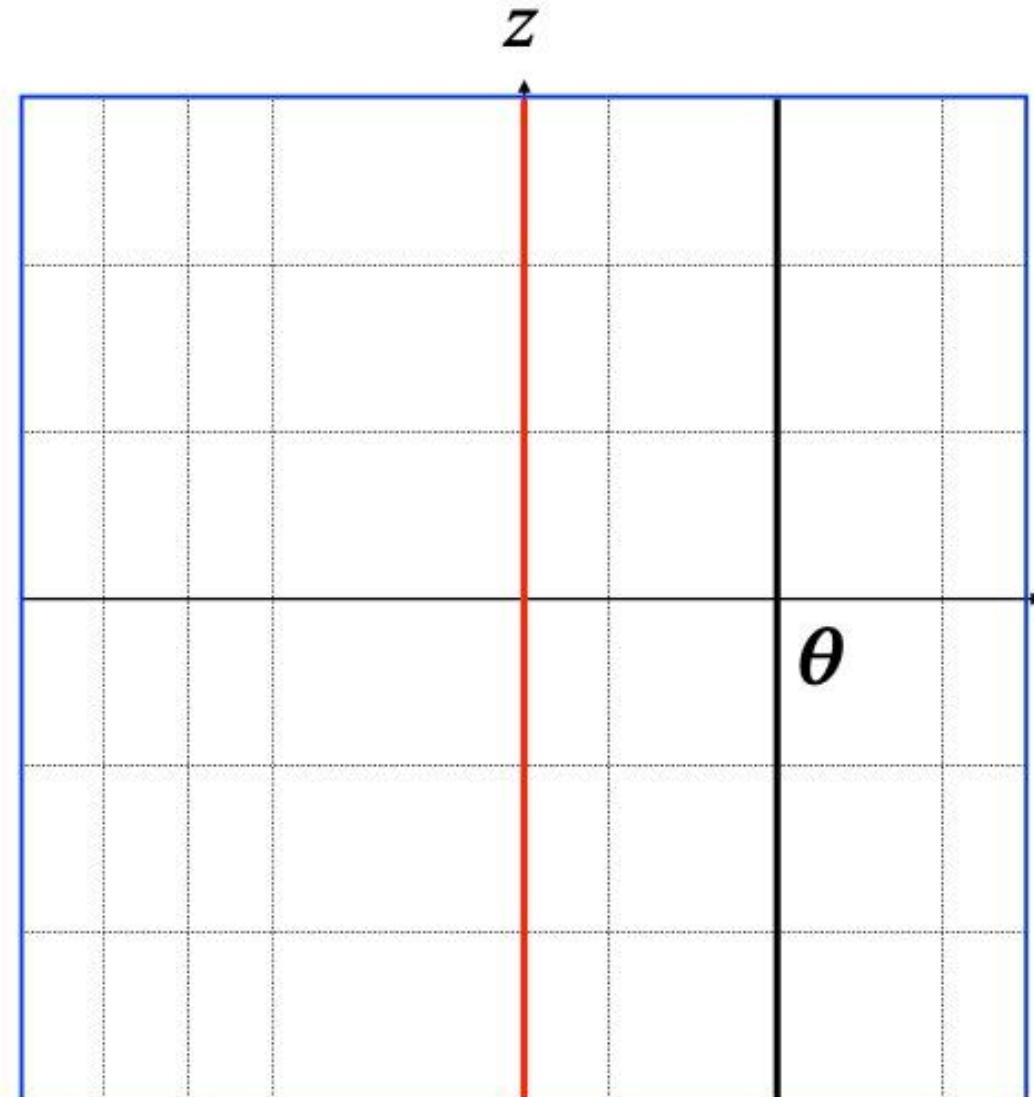
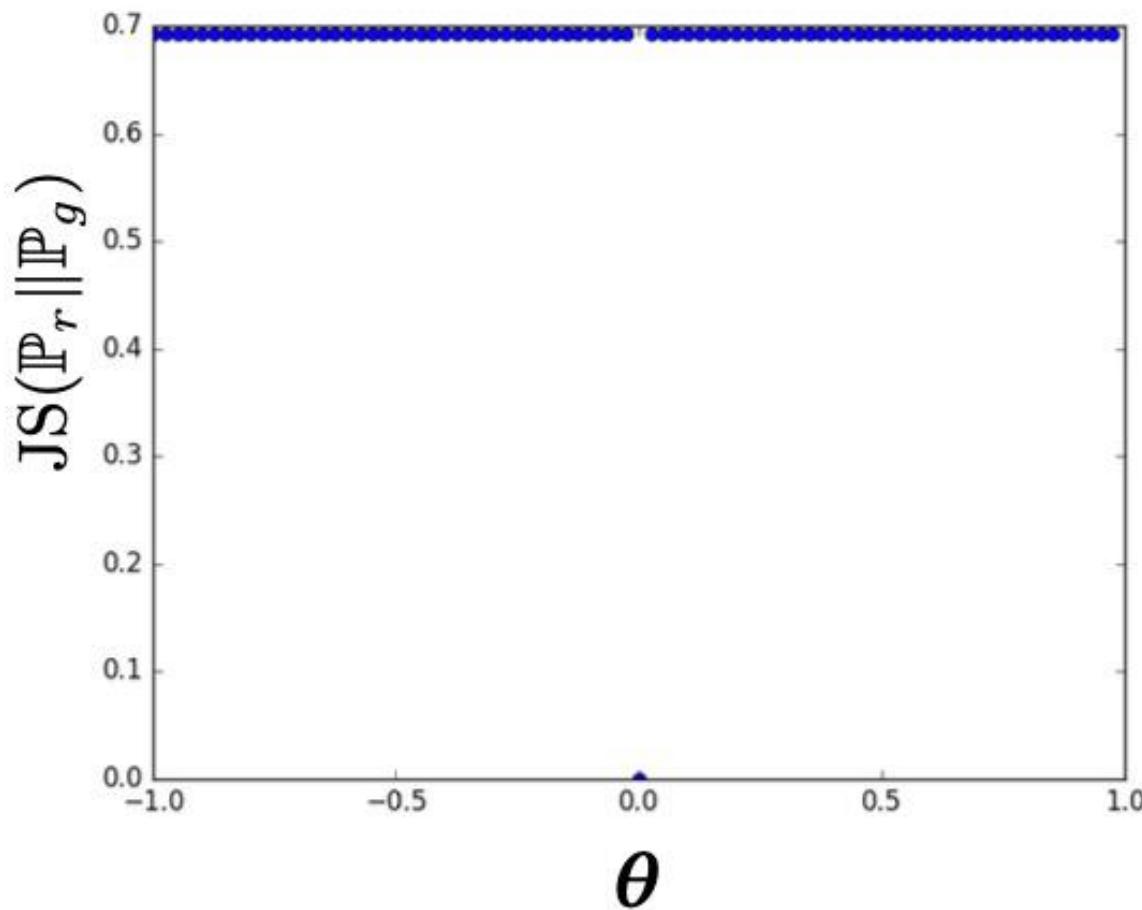
$$\text{JS}(\mathbb{P}_r \parallel \mathbb{P}_g) = \begin{cases} \log 2 & \text{if } \theta \neq 0 \\ 0 & \text{if } \theta = 0 \end{cases}$$



Example from (Arjovsky et al. 2017)

# Jensen-Shannon Divergence

$$\text{JS}(\mathbb{P}_r \parallel \mathbb{P}_g) = \begin{cases} \log 2 & \text{if } \theta \neq 0 \\ 0 & \text{if } \theta = 0 \end{cases}$$



Example from (Arjovsky et al. 2017)

# Wasserstein Distance

- JS divergence is not a useful learning signal to train GANs.
- Another distance measure inspired from Optimal Transport is the Earth Mover (EM) (also called Wasserstein-1 Distance) distance

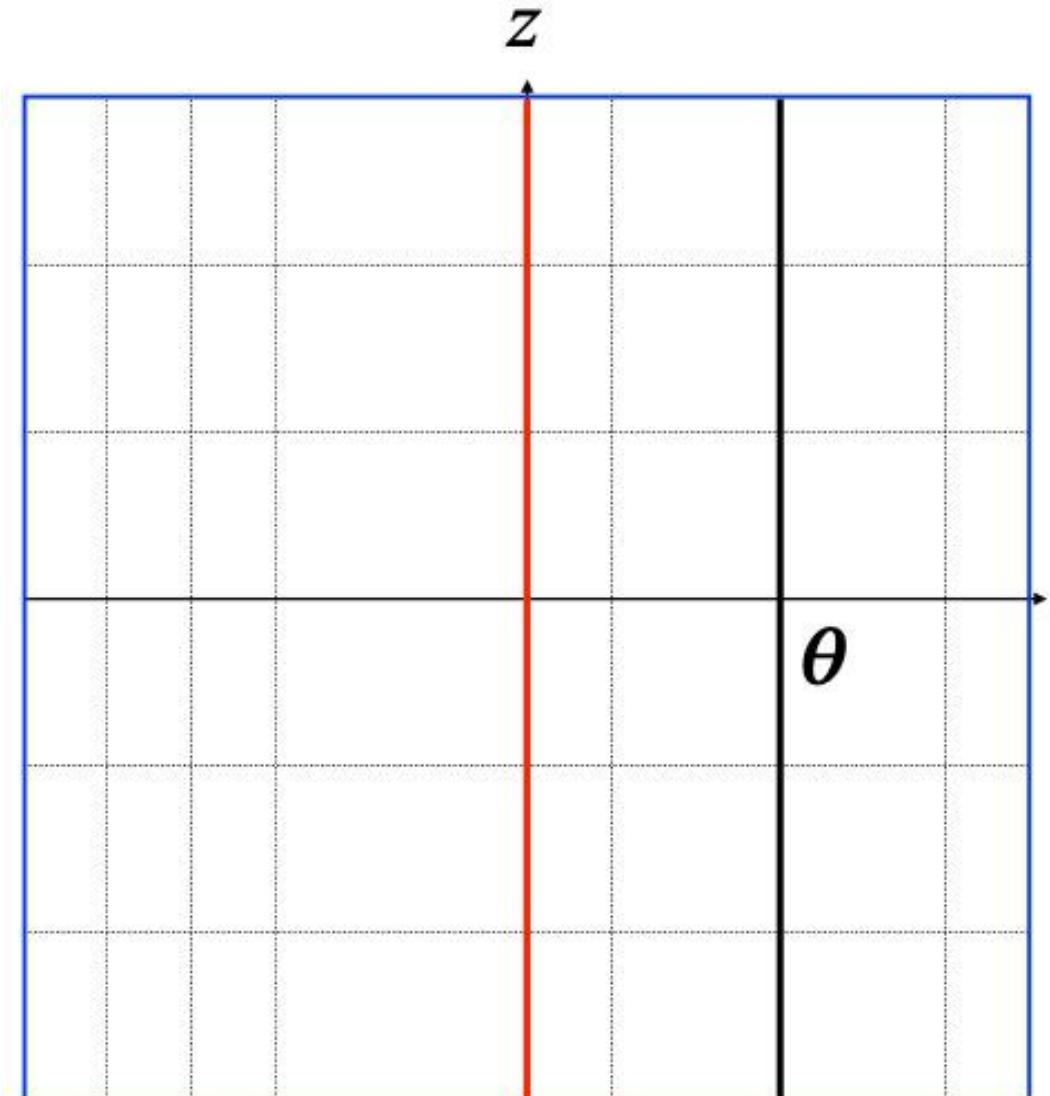
$$W(\mathbb{P}_r, \mathbb{P}_g) = \inf_{\gamma \in \Pi(\mathbb{P}_r, \mathbb{P}_g)} \mathbb{E}_{(x,y) \sim \gamma} [\|x - y\|]$$

- The EM distance is continuous everywhere and differentiable almost everywhere (under mild assumptions).

# Wasserstein Distance

$$W(\mathbb{P}_r, \mathbb{P}_g) = \inf_{\gamma \in \Pi(\mathbb{P}_r, \mathbb{P}_g)} \mathbb{E}_{(x,y) \sim \gamma} [\|x - y\|]$$

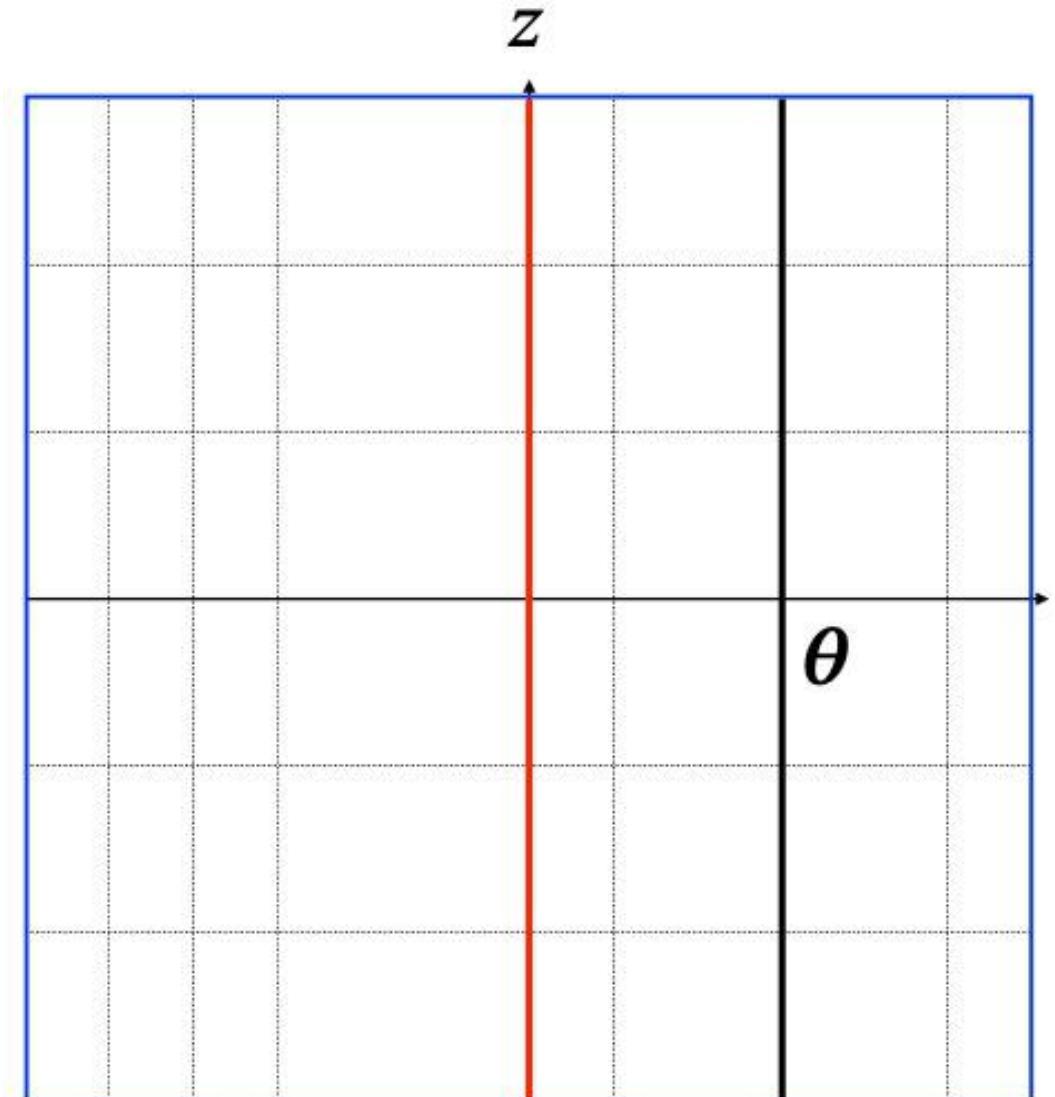
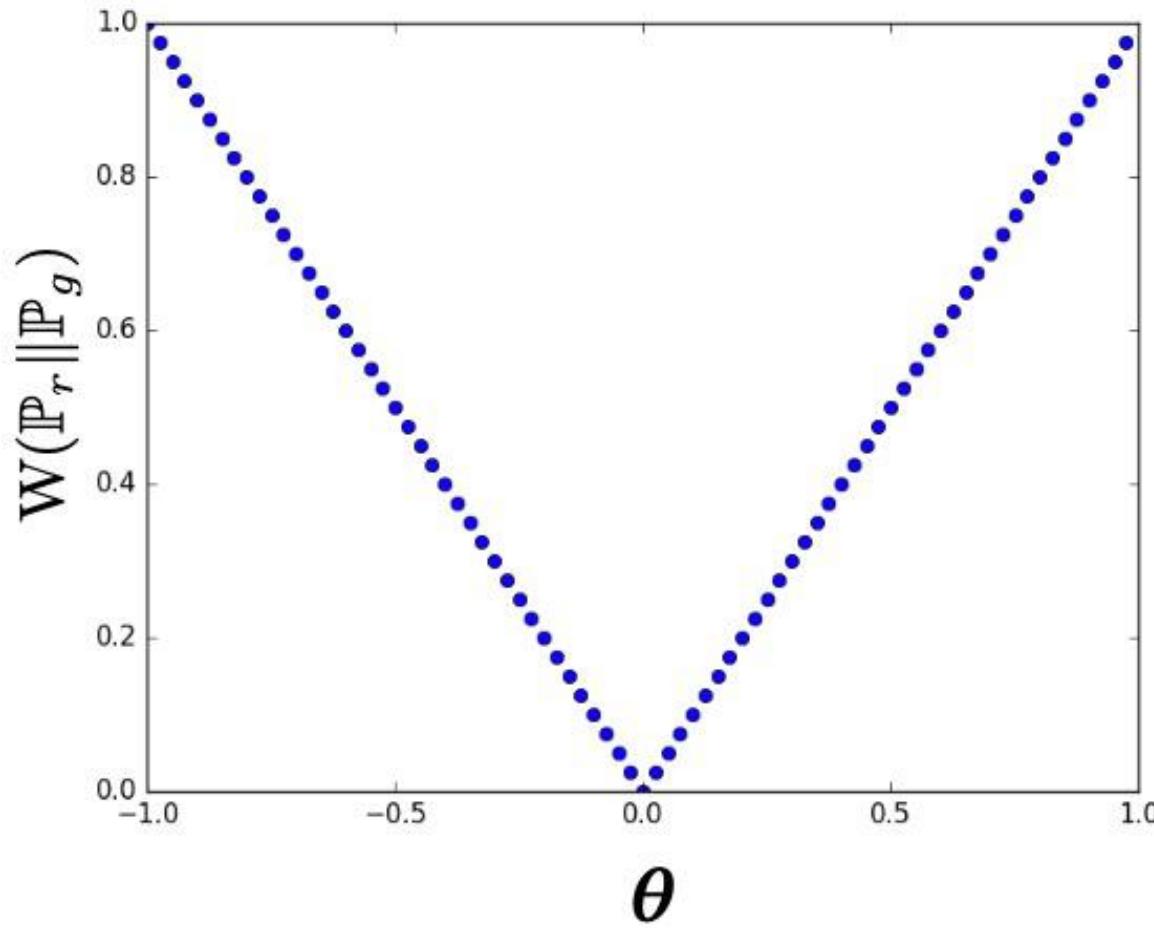
- What is the EM (or Wasserstein) distance in this simple case?



Example from (Arjovsky et al. 2017)

# Wasserstein Distance

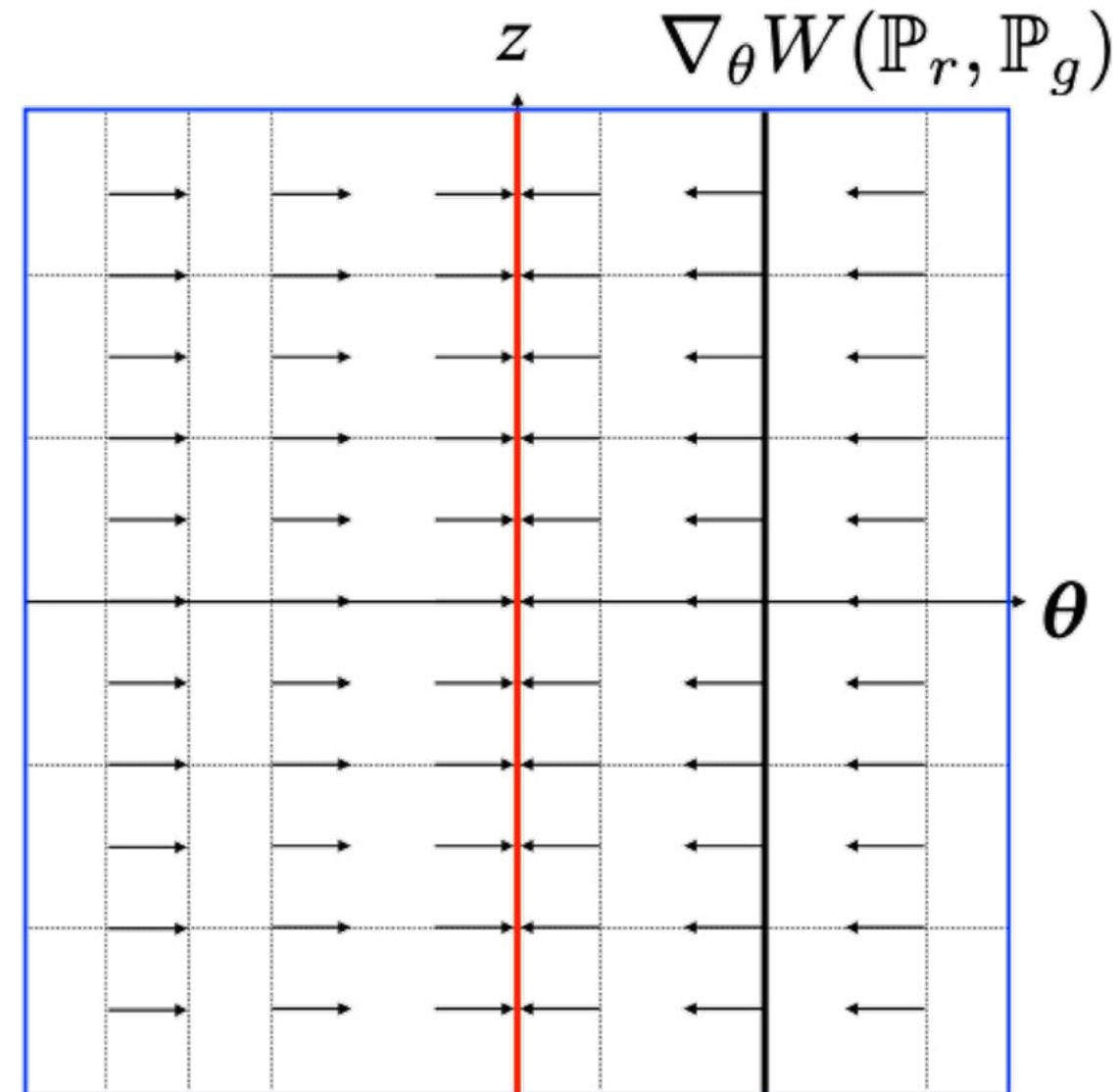
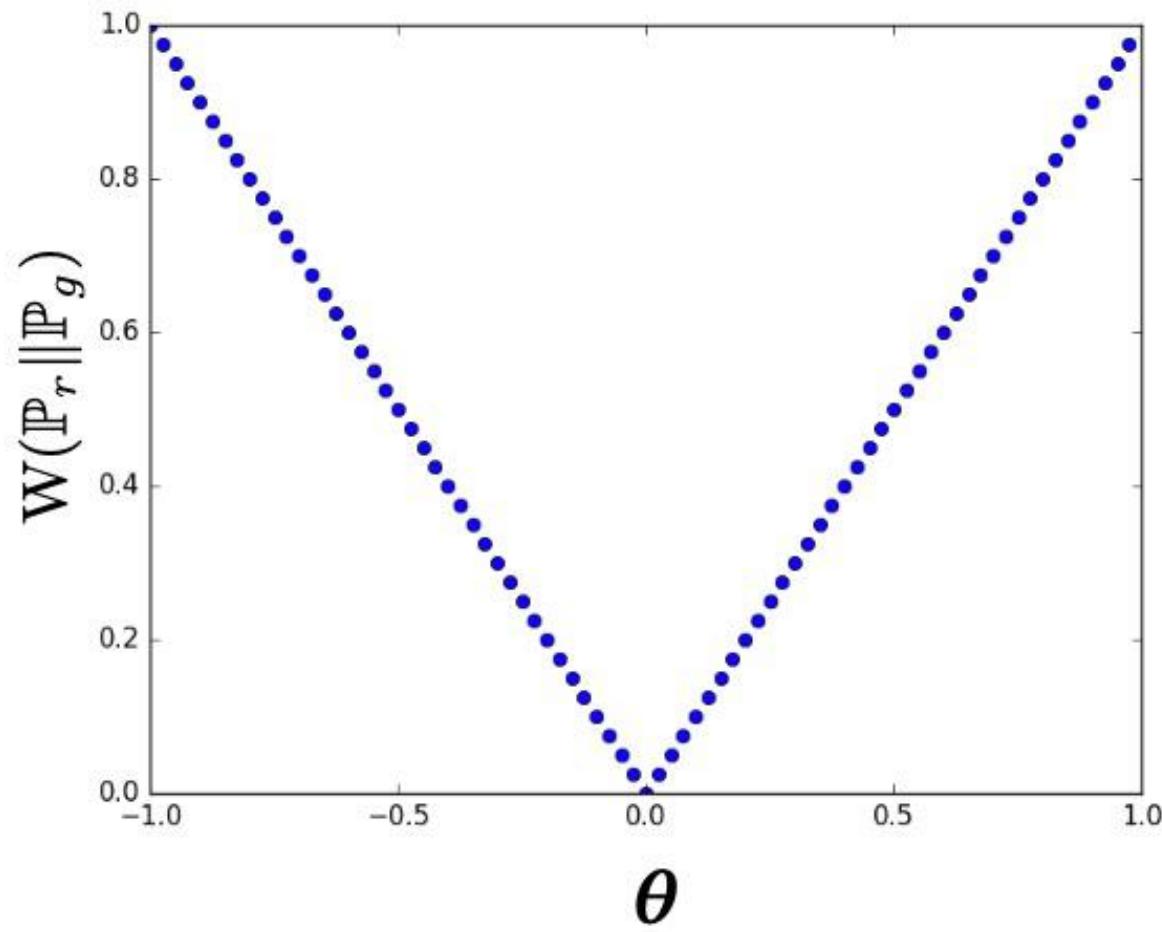
$$W(\mathbb{P}_r \parallel \mathbb{P}_g) = |\theta|$$



Example from (Arjovsky et al. 2017)

# Wasserstein Distance

$$W(\mathbb{P}_r \parallel \mathbb{P}_g) = |\theta|$$



Example from (Arjovsky et al. 2017)

# Wasserstein GAN

A real-valued function  $f: X \rightarrow Y$  is called  $K$ -Lipschitz continuous if there exists a real constant  $K \geq 0$  such that, for all  $x_1, x_2$ .  
 $|f(x_1) - f(x_2)| \leq K |x_1 - x_2|$   
Here  $K$  is known as a Lipschitz constant for function  $f(\cdot)$

- $W(\mathbb{P}_r \parallel \mathbb{P}_g)$  might have nice properties compared to  $\text{JS}(\mathbb{P}_r \parallel \mathbb{P}_g)$
- However, the infimum is intractable in:

$$W(\mathbb{P}_r, \mathbb{P}_g) = \inf_{\gamma \in \Pi(\mathbb{P}_r, \mathbb{P}_g)} \mathbb{E}_{(x,y) \sim \gamma} [\|x - y\|]$$

- Can exploit Kantorovich-Rubinstein duality:

$$W(\mathbb{P}_r, \mathbb{P}_g) = \sup_{\|f\|_L \leq 1} \mathbb{E}_{x \sim \mathbb{P}_r} [f(x)] - \mathbb{E}_{x \sim \mathbb{P}_g} [f(x)]$$

where the supremum is over all the 1-Lipschitz functions  $f: \mathcal{X} \rightarrow \mathbb{R}$

# Wasserstein GAN

- The WGAN Objective function:

$$\min_G \max_{D \in \mathcal{D}} \mathbb{E}_{x \sim \mathbb{P}_r} [D(x)] - \mathbb{E}_{\tilde{x} \sim \mathbb{P}_g} [D(\tilde{x})]$$

where  $\mathcal{D}$  is the set of 1-Lipschitz functions.

- Open question: how to effectively enforce the Lipschitz constraint on the critic  $D$ ?
  - Arjovsky et al. (2017) propose to clip the weights of the critic to lie within a compact space  $[-c, c]$ .
  - Results in a subset of the  $k$ -Lipschitz functions ( $k$  is a function of  $c$ ).

# Wasserstein GAN - Pseudocode

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**Algorithm 1** WGAN, our proposed algorithm. All experiments in the paper used the default values  $\alpha = 0.00005$ ,  $c = 0.01$ ,  $m = 64$ ,  $n_{\text{critic}} = 5$ .

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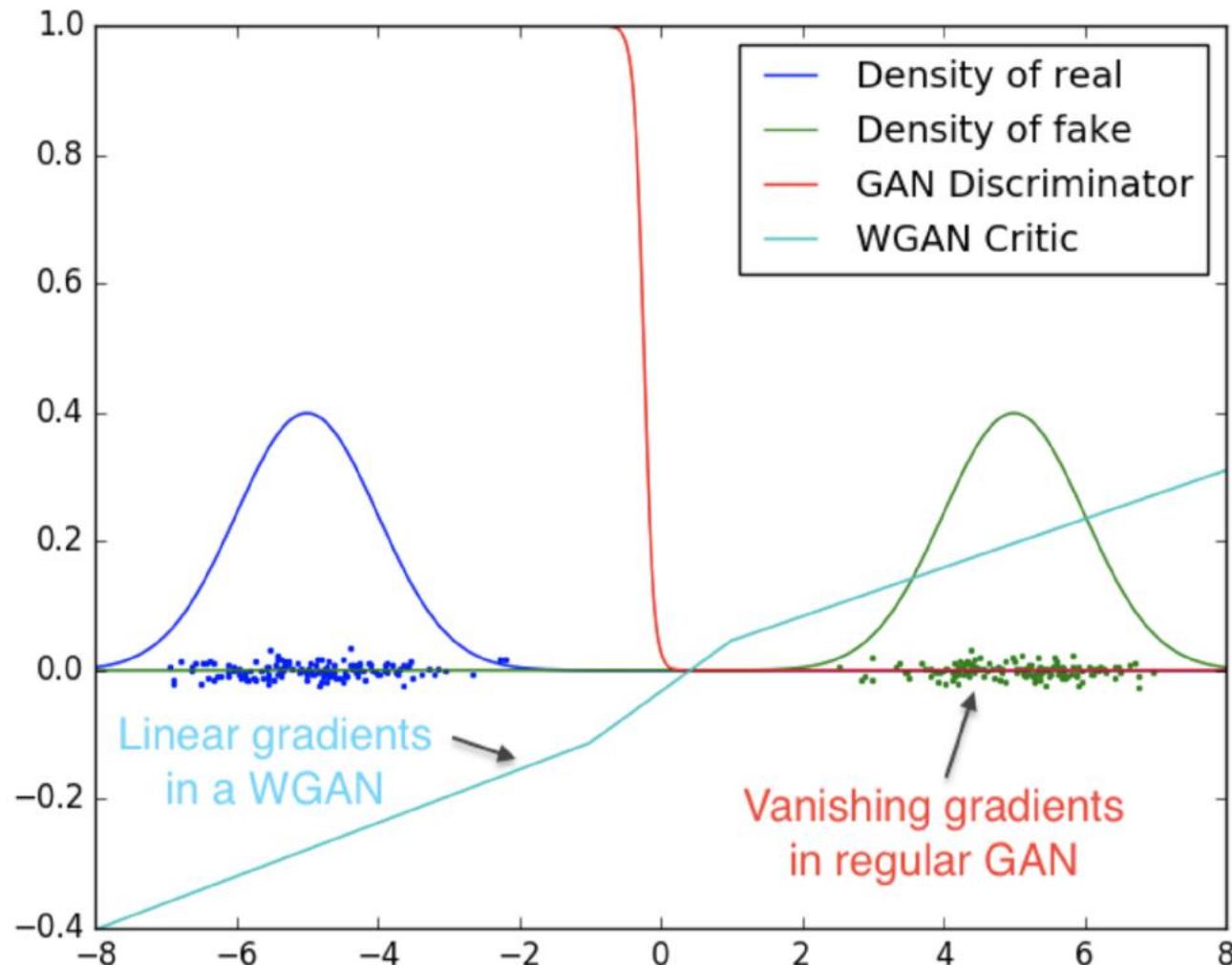
**Require:** :  $\alpha$ , the learning rate.  $c$ , the clipping parameter.  $m$ , the batch size.  $n_{\text{critic}}$ , the number of iterations of the critic per generator iteration.

**Require:** :  $w_0$ , initial critic parameters.  $\theta_0$ , initial generator's parameters.

```
1: while  $\theta$  has not converged do
2:   for  $t = 0, \dots, n_{\text{critic}}$  do
3:     Sample  $\{x^{(i)}\}_{i=1}^m \sim \mathbb{P}_r$  a batch from the real data.
4:     Sample  $\{z^{(i)}\}_{i=1}^m \sim p(z)$  a batch of prior samples.
5:      $g_w \leftarrow \nabla_w [\frac{1}{m} \sum_{i=1}^m f_w(x^{(i)}) - \frac{1}{m} \sum_{i=1}^m f_w(g_\theta(z^{(i)}))]$ 
6:      $w \leftarrow w + \alpha \cdot \text{RMSPProp}(w, g_w)$ 
7:      $w \leftarrow \text{clip}(w, -c, c)$ 
8:   end for
9:   Sample  $\{z^{(i)}\}_{i=1}^m \sim p(z)$  a batch of prior samples.
10:   $g_\theta \leftarrow -\nabla_\theta \frac{1}{m} \sum_{i=1}^m f_w(g_\theta(z^{(i)}))$ 
11:   $\theta \leftarrow \theta - \alpha \cdot \text{RMSPProp}(\theta, g_\theta)$ 
12: end while
```

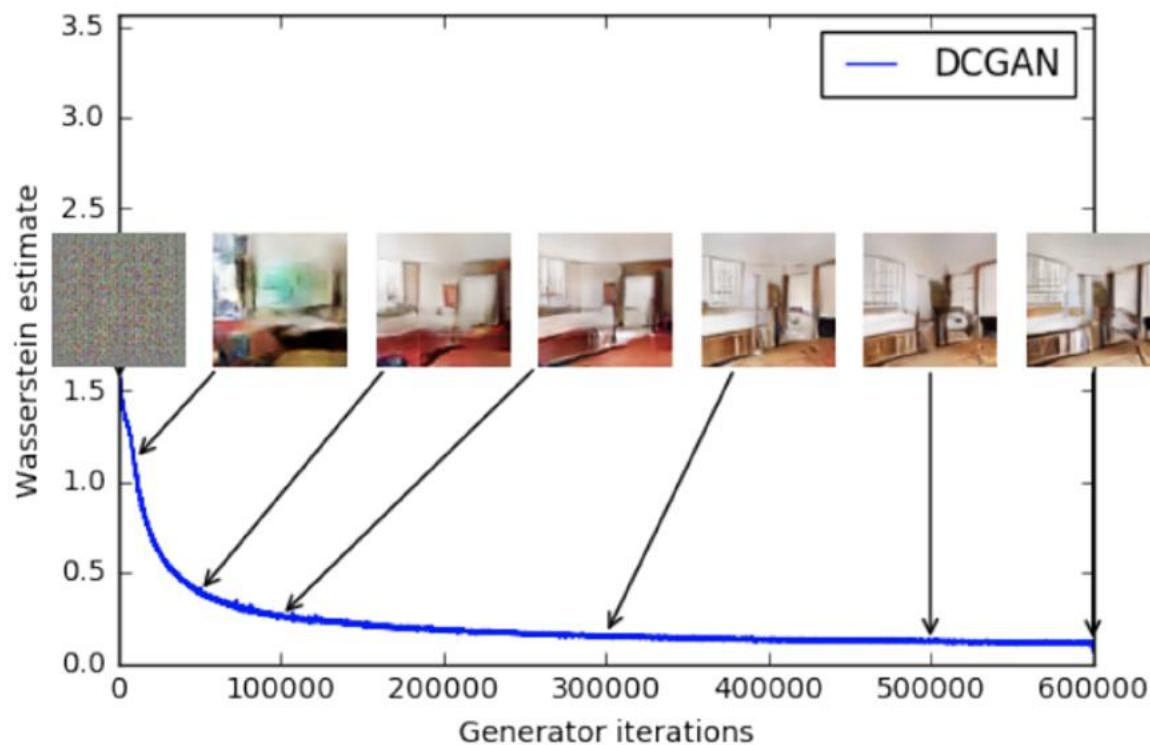
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# Wasserstein GAN - Training critic to converge

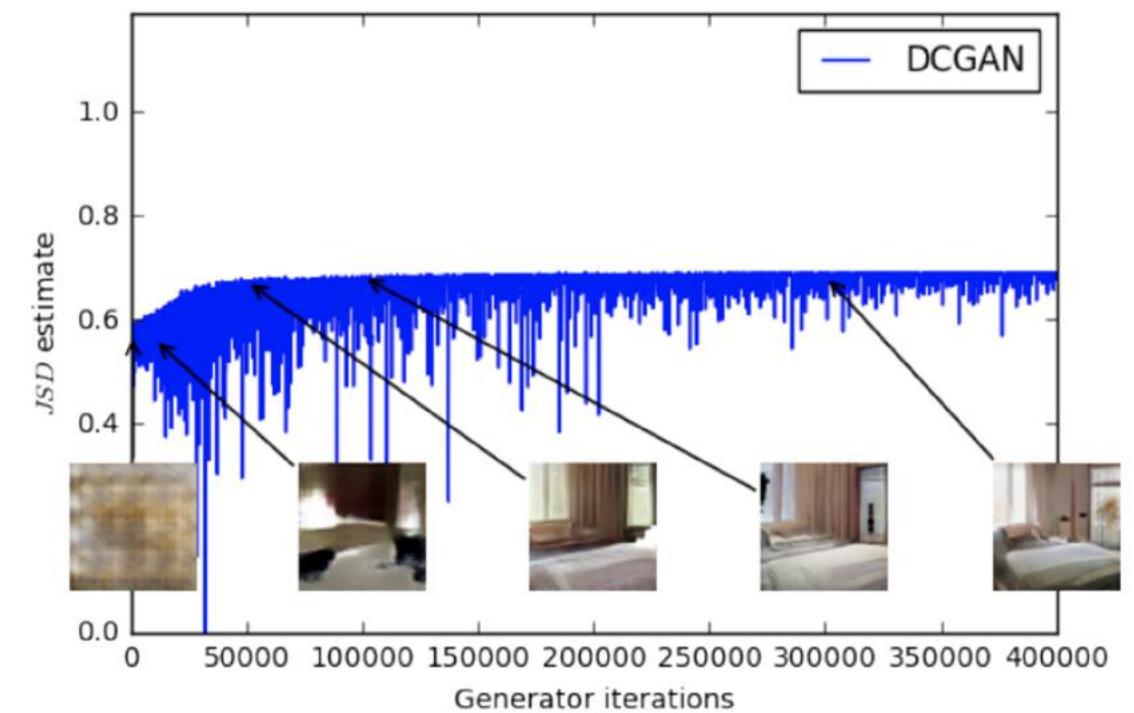


# Wasserstein distance correlates with sample quality

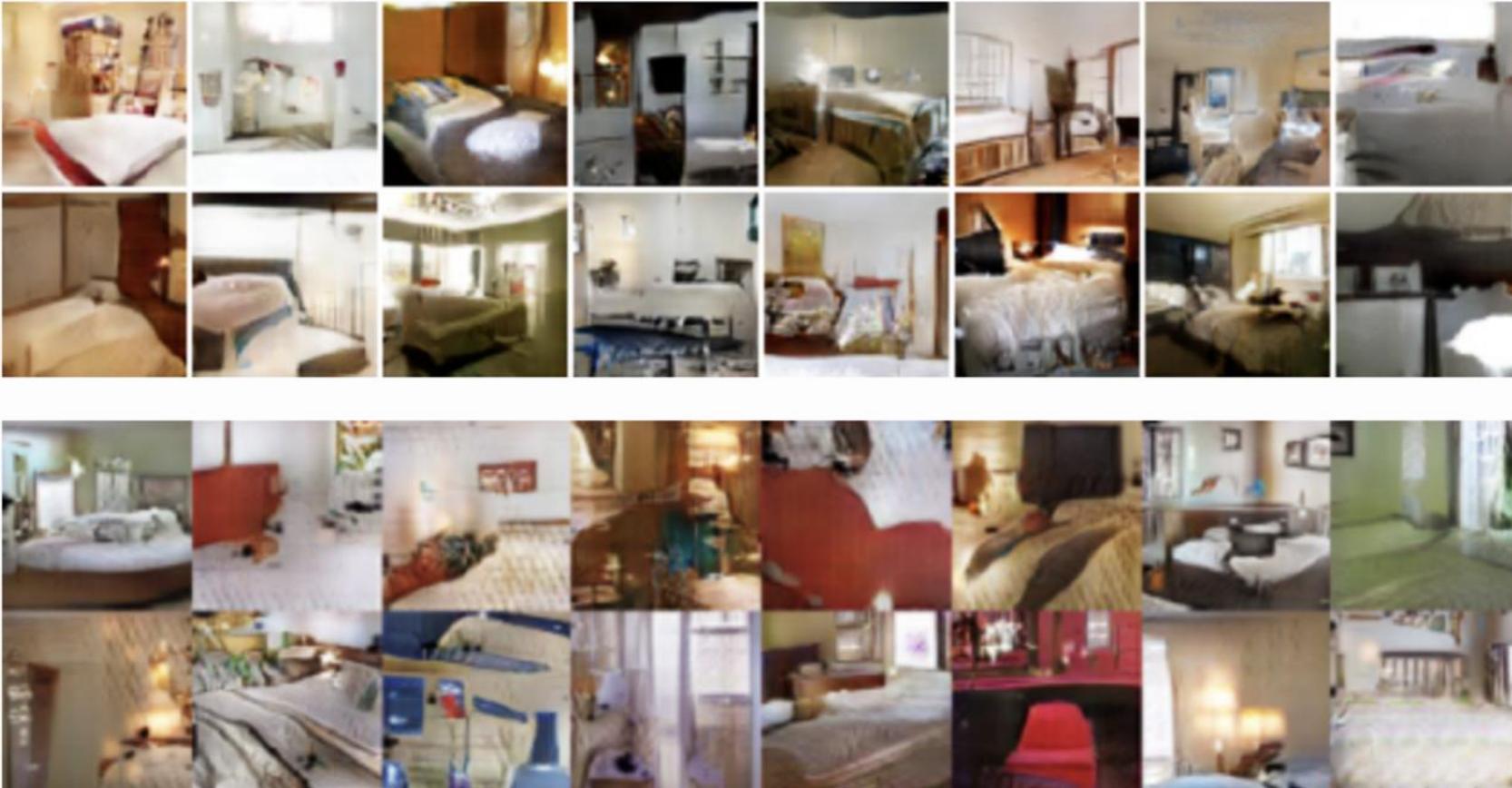
Wasserstein Estimate



JSD Estimate



# WGAN Samples on par with DCGAN



Top: WGAN with the same DCGAN architecture. Bottom: DCGAN

# WGAN robust to architecture choices



Top: WGAN with DCGAN architecture, no batch norm. Bottom: DCGAN, no batch norm

# WGAN robust to architecture choices



Top: WGAN with MLP architecture. Bottom: Standard GAN, same architecture

# WGAN Summary

Standard GAN

$$\min_G \max_D \mathbb{E}_{x \sim P_r} [\log D(x)] + \mathbb{E}_{\tilde{x} \sim P_g} [\log(1 - D(\tilde{x}))]$$



Wasserstein GAN

$$\min_G \max_{D \in \mathcal{D}} \mathbb{E}_{x \sim P_r} [D(x)] - \mathbb{E}_{\tilde{x} \sim P_g} [D(\tilde{x})]$$

# WGAN Summary

- New divergence measure for optimizing the generator
- Addresses instabilities with JSD version (sigmoid cross entropy)
- Robust to architectural choices
- Progress on mode collapse and stability of derivative wrt input
- Introduces the idea of using lipschitzness to stabilize GAN training
- **Negative:**

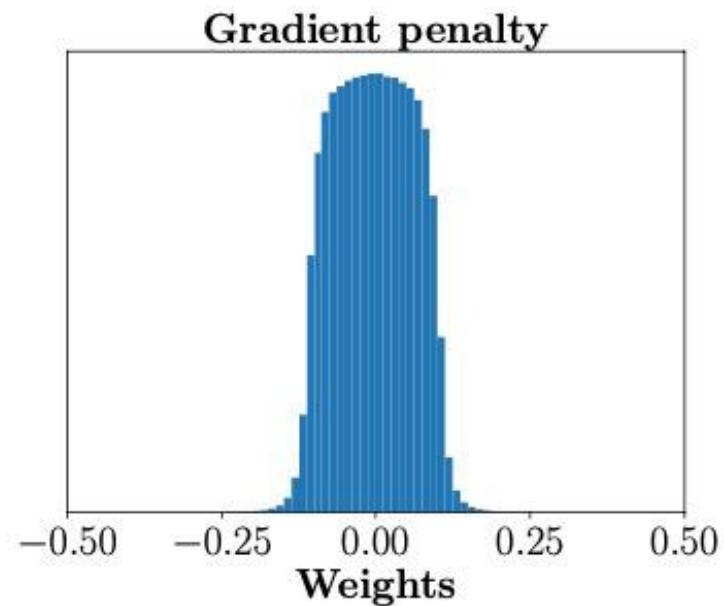
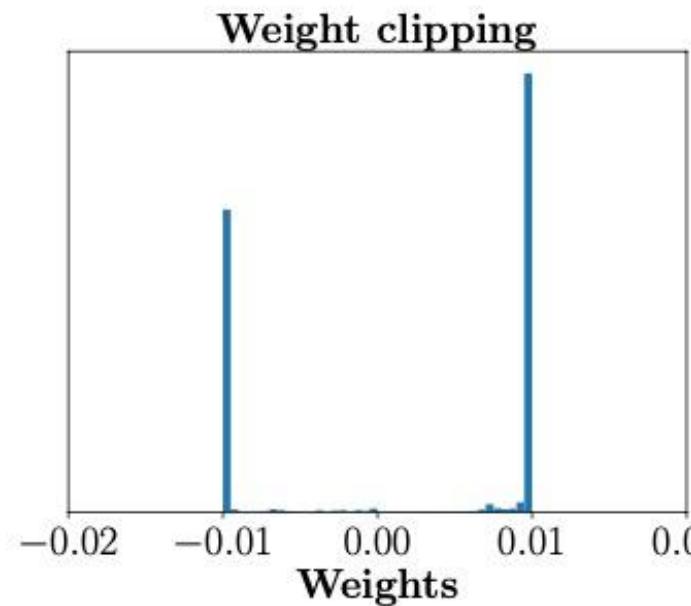
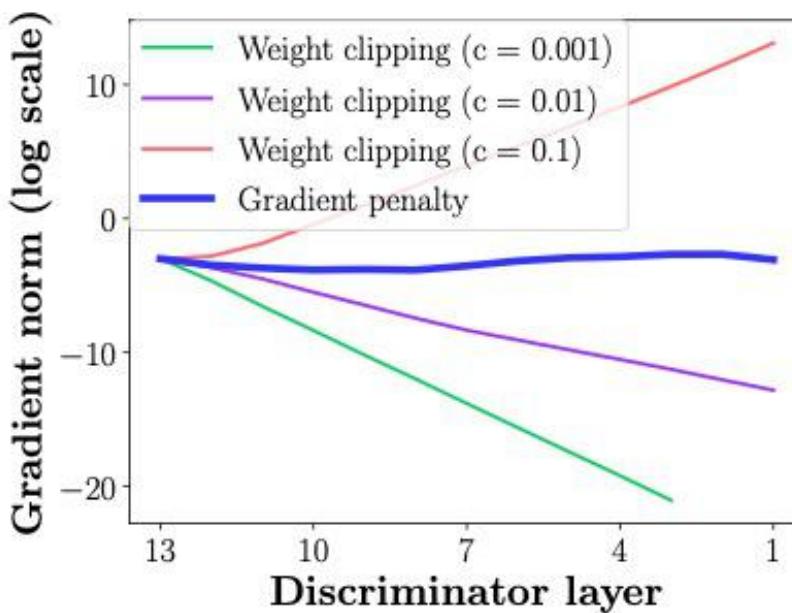
Weight clipping is a clearly terrible way to enforce a Lipschitz constraint. If the clipping parameter is large, then it can take a long time for any weights to reach their limit, thereby making it harder to train the critic till optimality. If the clipping is small, this can easily lead to vanishing gradients when the number of layers is big, or batch normalization is not used (such as in RNNs). We experimented with simple variants (such as projecting the weights to a sphere) with little difference, and we stuck with weight clipping due to its simplicity and already good performance. However, we do leave the topic of enforcing Lipschitz constraints in a neural network setting for further investigation, and we actively encourage interested researchers to improve on this method.

# Lecture overview

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- Evaluation: Parzen, Inception, Frechet
- Theory of GANs
- **GAN Progression**
  - DC GAN (Radford et al, 2016)
  - Improved Training of GANs (Salimans et al, 2016)
  - WGAN, **WGAN-GP**, Progressive GAN, SN-GAN, SAGAN
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- Applications

# Issues with Weight Clipping

1. Underuse capacity
2. Exploding and vanishing gradients



# WGAN-GP: Gradient Penalty Approach

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## Improved Training of Wasserstein GANs

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### Abstract

Generative Adversarial Networks (GANs) are powerful generative models, but suffer from training instability. The recently proposed Wasserstein GAN (WGAN) makes progress toward stable training of GANs, but sometimes can still generate only poor samples or fail to converge. We find that these problems are often due to the use of weight clipping in WGAN to enforce a Lipschitz constraint on the critic, which can lead to undesired behavior. We propose an alternative to clipping weights: penalize the norm of gradient of the critic with respect to its input. Our proposed method performs better than standard WGAN and enables stable training of a wide variety of GAN architectures with almost no hyperparameter tuning, including 101-layer ResNets and language models with continuous generators. We also achieve high quality generations on CIFAR-10 and LSUN bedrooms. <sup>†</sup>

# WGAN-GP: Gradient Penalty Approach

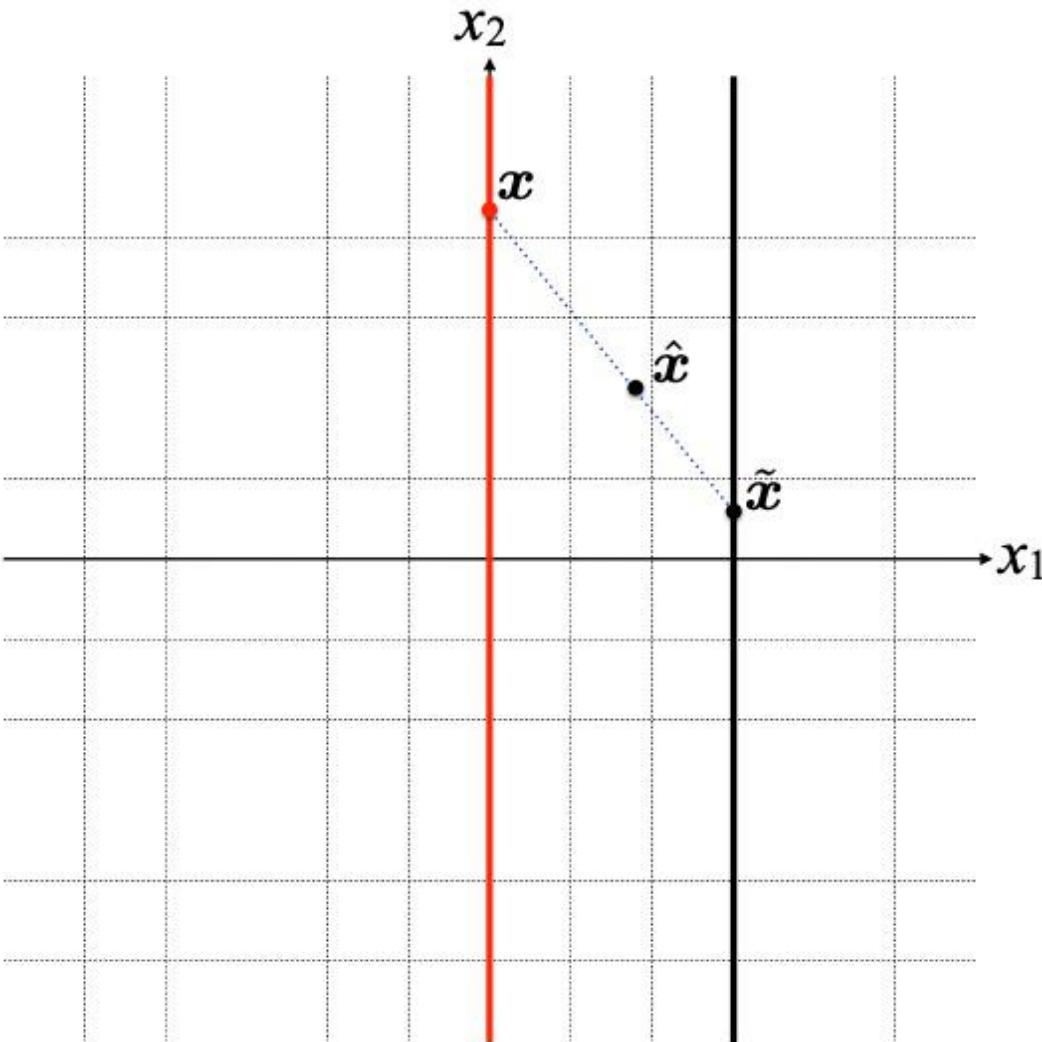
- A property of the optimal WGAN critic: If  $\tilde{\mathbf{x}} \sim \mathbb{P}_g$  then there is a point  $\mathbf{x} \sim \mathbb{P}_r$ , such that for all points  $\mathbf{x}_t = t\mathbf{x} + (1 - t)\tilde{\mathbf{x}}$  (on a straight line between  $\mathbf{x}$  and  $\tilde{\mathbf{x}}$ ) then:

$$\nabla D^*(\mathbf{x}_t) = \frac{\mathbf{x} - \mathbf{x}_t}{\|\mathbf{x} - \mathbf{x}_t\|}$$

- This implies the optimal WGAN critic has gradient norm 1 at  $\mathbf{x}_t$
- Gradient Penalty version of WGAN (i.e. WGAN-GP) objective

$$L = \underbrace{\mathbb{E}_{\tilde{\mathbf{x}} \sim \mathbb{P}_g} [D(\tilde{\mathbf{x}})] - \mathbb{E}_{\mathbf{x} \sim \mathbb{P}_r} [D(\mathbf{x})]}_{\text{Original critic loss}} + \lambda \underbrace{\mathbb{E}_{\hat{\mathbf{x}} \sim \mathbb{P}_{\hat{\mathbf{x}}}} \left[ (\|\nabla_{\hat{\mathbf{x}}} D(\hat{\mathbf{x}})\|_2 - 1)^2 \right]}_{\text{Our gradient penalty}}$$

# WGAN-GP: Gradient Penalty Approach



- Gradient penalty:

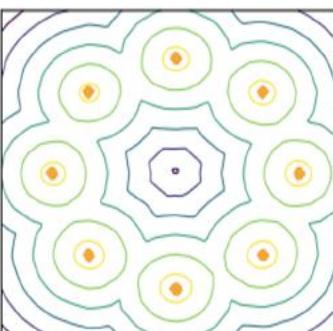
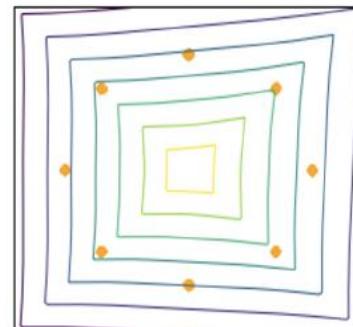
$$\mathbb{E}_{\hat{x} \sim \mathbb{P}_{\hat{x}}} \left[ (\|\nabla_{\hat{x}} D(\hat{x})\|_2 - 1)^2 \right]$$

Sample along straight lines:

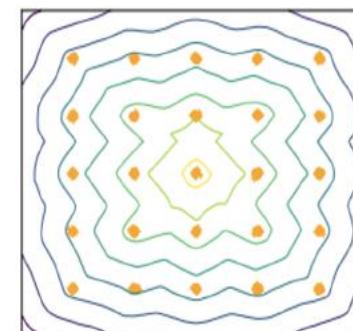
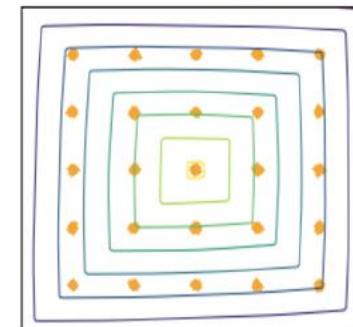
$$\begin{aligned}\epsilon &\sim U[0, 1], \mathbf{x} \sim \mathbb{P}_r, \tilde{\mathbf{x}} \sim \mathbb{P}_g \\ \hat{\mathbf{x}} &= \epsilon \mathbf{x} + (1 - \epsilon) \tilde{\mathbf{x}}\end{aligned}$$

# WGAN-GP: Gradient Penalty for Lipschitzness

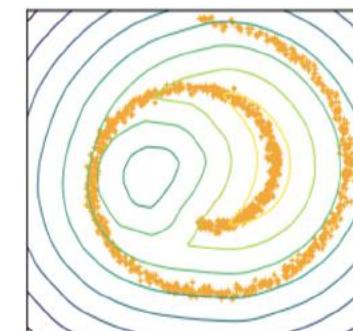
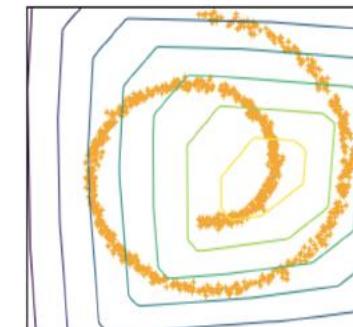
8 Gaussian



25 Gaussian



Swiss Roll



$$\max_D \underbrace{\mathbb{E}_{x \sim P_r} [D(x)] - \mathbb{E}_{\tilde{x} \sim P_g} [D(\tilde{x})]}_{\text{Wasserstein critic objective}} + \lambda \underbrace{\mathbb{E}_{\hat{x} \sim P_{\hat{x}}} \left[ (\|\nabla_{\hat{x}} D(\hat{x})\|_2 - 1)^2 \right]}_{\text{Gradient Penalty for Lipschitzness}}$$

$$\hat{x} \leftarrow \epsilon x + (1 - \epsilon)\tilde{x}$$

[Gulrajani et al 2017]

# WGAN-GP: Pseudocode

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**Algorithm 1** WGAN with gradient penalty. We use default values of  $\lambda = 10$ ,  $n_{\text{critic}} = 5$ ,  $\alpha = 0.0001$ ,  $\beta_1 = 0$ ,  $\beta_2 = 0.9$ .

---

**Require:** The gradient penalty coefficient  $\lambda$ , the number of critic iterations per generator iteration  $n_{\text{critic}}$ , the batch size  $m$ , Adam hyperparameters  $\alpha, \beta_1, \beta_2$ .

**Require:** initial critic parameters  $w_0$ , initial generator parameters  $\theta_0$ .

```
1: while  $\theta$  has not converged do
2:   for  $t = 1, \dots, n_{\text{critic}}$  do
3:     for  $i = 1, \dots, m$  do
4:       Sample real data  $\mathbf{x} \sim \mathbb{P}_r$ , latent variable  $\mathbf{z} \sim p(\mathbf{z})$ , a random number  $\epsilon \sim U[0, 1]$ .
5:        $\tilde{\mathbf{x}} \leftarrow G_\theta(\mathbf{z})$ 
6:        $\hat{\mathbf{x}} \leftarrow \epsilon \mathbf{x} + (1 - \epsilon) \tilde{\mathbf{x}}$ 
7:        $L^{(i)} \leftarrow D_w(\tilde{\mathbf{x}}) - D_w(\mathbf{x}) + \lambda (\|\nabla_{\hat{\mathbf{x}}} D_w(\hat{\mathbf{x}})\|_2 - 1)^2$ 
8:     end for
9:      $w \leftarrow \text{Adam}(\nabla_w \frac{1}{m} \sum_{i=1}^m L^{(i)}, w, \alpha, \beta_1, \beta_2)$ 
10:   end for
11:   Sample a batch of latent variables  $\{\mathbf{z}^{(i)}\}_{i=1}^m \sim p(\mathbf{z})$ .
12:    $\theta \leftarrow \text{Adam}(\nabla_\theta \frac{1}{m} \sum_{i=1}^m -D_w(G_\theta(\mathbf{z})), \theta, \alpha, \beta_1, \beta_2)$ 
13: end while
```

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# WGAN-GP: BatchNorm

**No critic batch normalization** Most prior GAN implementations [22, 23, 2] use batch normalization in both the generator and the discriminator to help stabilize training, but batch normalization changes the form of the discriminator’s problem from mapping a single input to a single output to mapping from an entire batch of inputs to a batch of outputs [23]. Our penalized training objective is no longer valid in this setting, since we penalize the norm of the critic’s gradient with respect to each input independently, and not the entire batch. To resolve this, we simply omit batch normalization in the critic in our models, finding that they perform well without it. Our method works with normalization schemes which don’t introduce correlations between examples. In particular, we recommend layer normalization [3] as a drop-in replacement for batch normalization.

# WGAN-GP: Robustness to architectures

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Nonlinearity ( $G$ )	[ReLU, LeakyReLU, $\frac{\text{softplus}(2x+2)}{2} - 1$ , tanh]
Nonlinearity ( $D$ )	[ReLU, LeakyReLU, $\frac{\text{softplus}(2x+2)}{2} - 1$ , tanh]
Depth ( $G$ )	[4, 8, 12, 20]
Depth ( $D$ )	[4, 8, 12, 20]
Batch norm ( $G$ )	[True, False]
Batch norm ( $D$ ; layer norm for WGAN-GP)	[True, False]
Base filter count ( $G$ )	[32, 64, 128]
Base filter count ( $D$ )	[32, 64, 128]

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Min. score	Only GAN	Only WGAN-GP	Both succeeded	Both failed
1.0	0	8	192	0
3.0	1	88	110	1
5.0	0	147	42	11
7.0	1	104	5	90
9.0	0	0	0	200

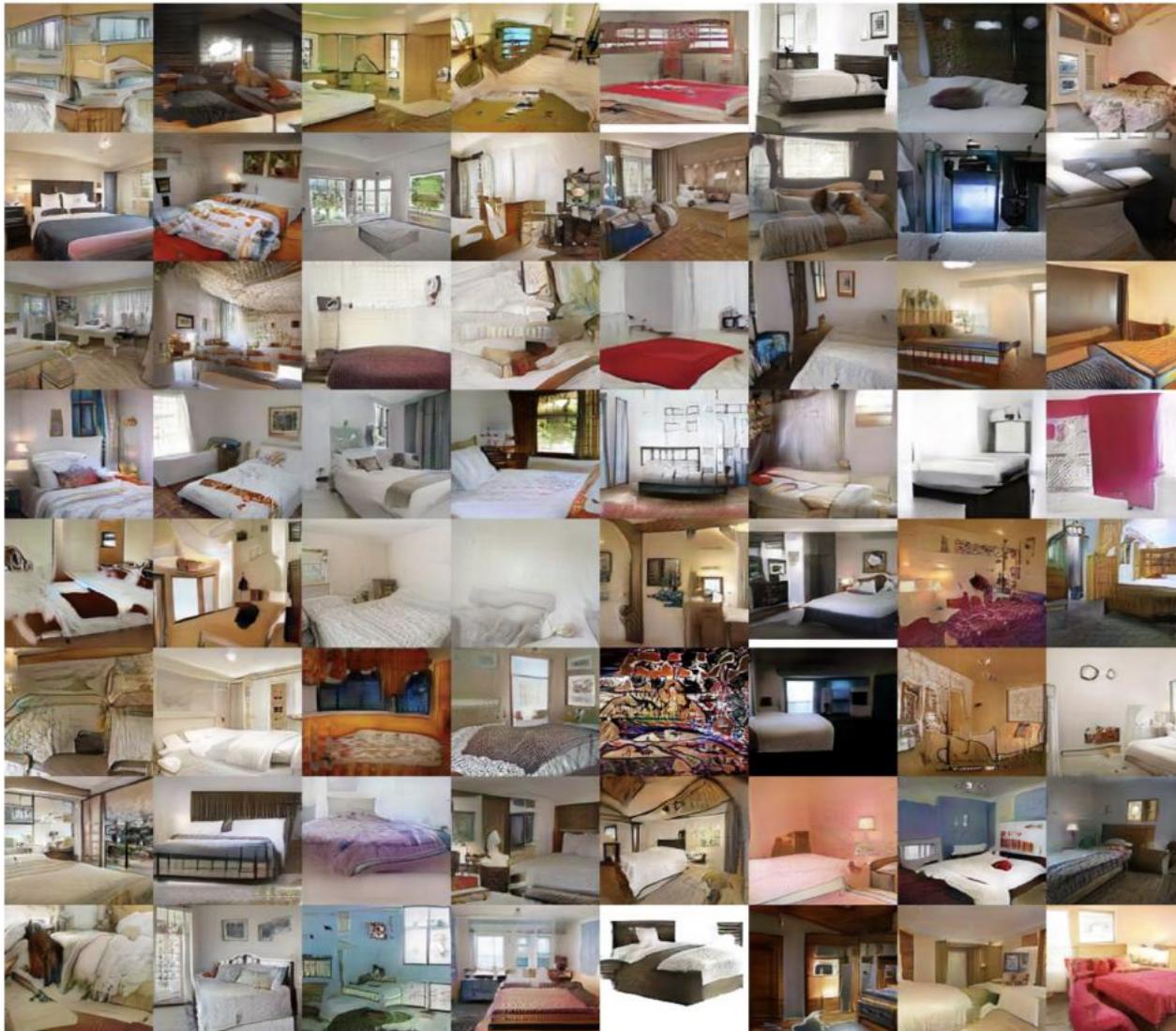
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# WGAN-GP: Robustness to architectures

DCGAN	LSGAN	WGAN (clipping)	WGAN-GP (ours)	
Baseline ( $G$ : DCGAN, $D$ : DCGAN)				
$G$ : No BN and a constant number of filters, $D$ : DCGAN				
$G$ : 4-layer 512-dim ReLU MLP, $D$ : DCGAN				
No normalization in either $G$ or $D$				
Gated multiplicative nonlinearities everywhere in $G$ and $D$				
tanh nonlinearities everywhere in $G$ and $D$				
101-layer ResNet $G$ and $D$				

[Gulrajani et al 2017]

# WGAN-GP: High quality samples



[Gulrajani et al 2017]

# WGAN-GP: High quality samples

Table 3: Inception scores on CIFAR-10. Our unsupervised model achieves state-of-the-art performance, and our conditional model outperforms all others except SGAN.

Unsupervised		Supervised	
Method	Score	Method	Score
ALI [8] (in [27])	$5.34 \pm .05$	SteinGAN [26]	6.35
BEGAN [4]	5.62	DCGAN (with labels, in [26])	6.58
DCGAN [22] (in [11])	$6.16 \pm .07$	Improved GAN [23]	$8.09 \pm .07$
Improved GAN (-L+HA) [23]	$6.86 \pm .06$	AC-GAN [20]	$8.25 \pm .07$
EGAN-Ent-VI [7]	$7.07 \pm .10$	SGAN-no-joint [11]	$8.37 \pm .08$
DFM [27]	$7.72 \pm .13$	WGAN-GP ResNet (ours)	$8.42 \pm .10$
<b>WGAN-GP ResNet (ours)</b>	$7.86 \pm .07$	<b>SGAN</b> [11]	$8.59 \pm .12$

# WGAN-GP: Summary

- Robustness to architectural choices
- Became a very popular GAN model - 2000+ citations, has been used in NVIDIA's Progressive GANs, StyleGAN, etc - biggest GAN successes
- Residual architecture widely adopted.
- Possible negative- slow wall clock time due to gradient penalty.
- Gradient penalty applied on a heuristic distribution of samples from current generator. Could be unstable when learning rates are high.

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# Progressive growing of GANs

## PROGRESSIVE GROWING OF GANs FOR IMPROVED QUALITY, STABILITY, AND VARIATION

**Tero Karras**

NVIDIA

**Timo Aila**

NVIDIA

**Samuli Laine**

NVIDIA

**Jaakko Lehtinen**

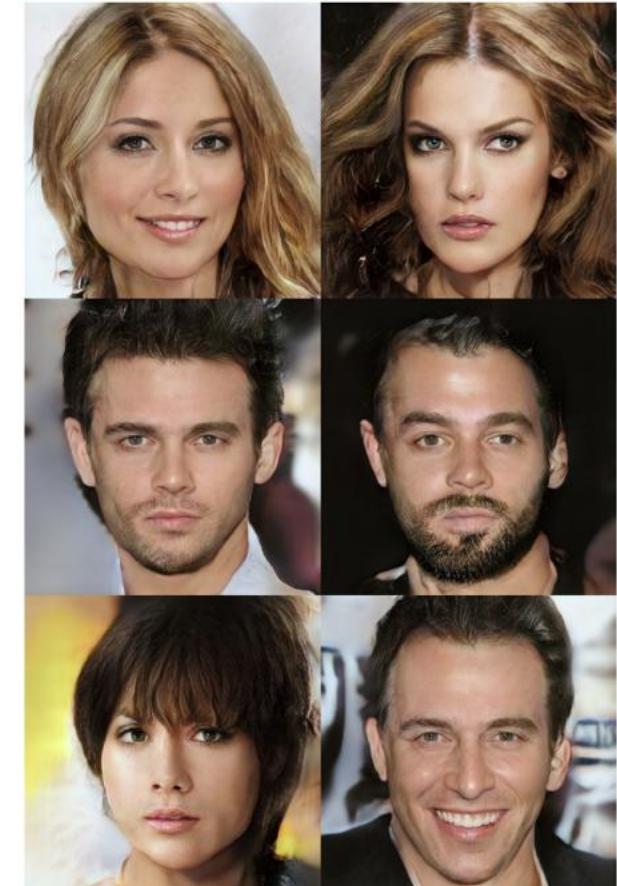
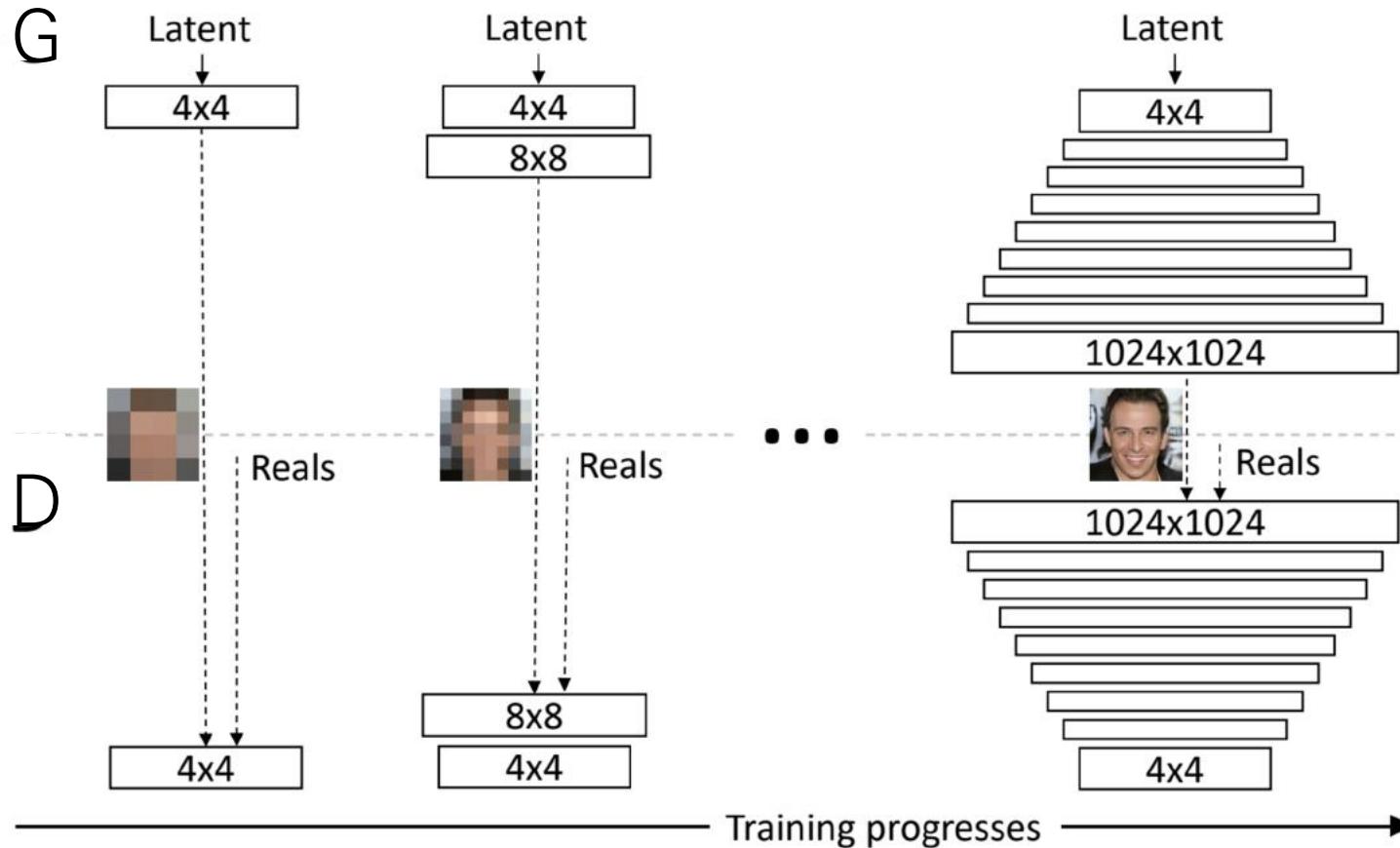
NVIDIA and Aalto University

{tkarras, taila, slaine, jlehtinen}@nvidia.com

### ABSTRACT

We describe a new training methodology for generative adversarial networks. The key idea is to grow both the generator and discriminator progressively: starting from a low resolution, we add new layers that model increasingly fine details as training progresses. This both speeds the training up and greatly stabilizes it, allowing us to produce images of unprecedented quality, e.g., CELEBA images at  $1024^2$ . We also propose a simple way to increase the variation in generated images, and achieve a record inception score of 8.80 in unsupervised CIFAR10. Additionally, we describe several implementation details that are important for discouraging unhealthy competition between the generator and discriminator. Finally, we suggest a new metric for evaluating GAN results, both in terms of image quality and variation. As an additional contribution, we construct a higher-quality version of the CELEBA dataset.

# Progressive growing of GANs



# Progressive growing of GANs



# Progressive growing of GANs



Mao et al. (2016b) ( $128 \times 128$ )

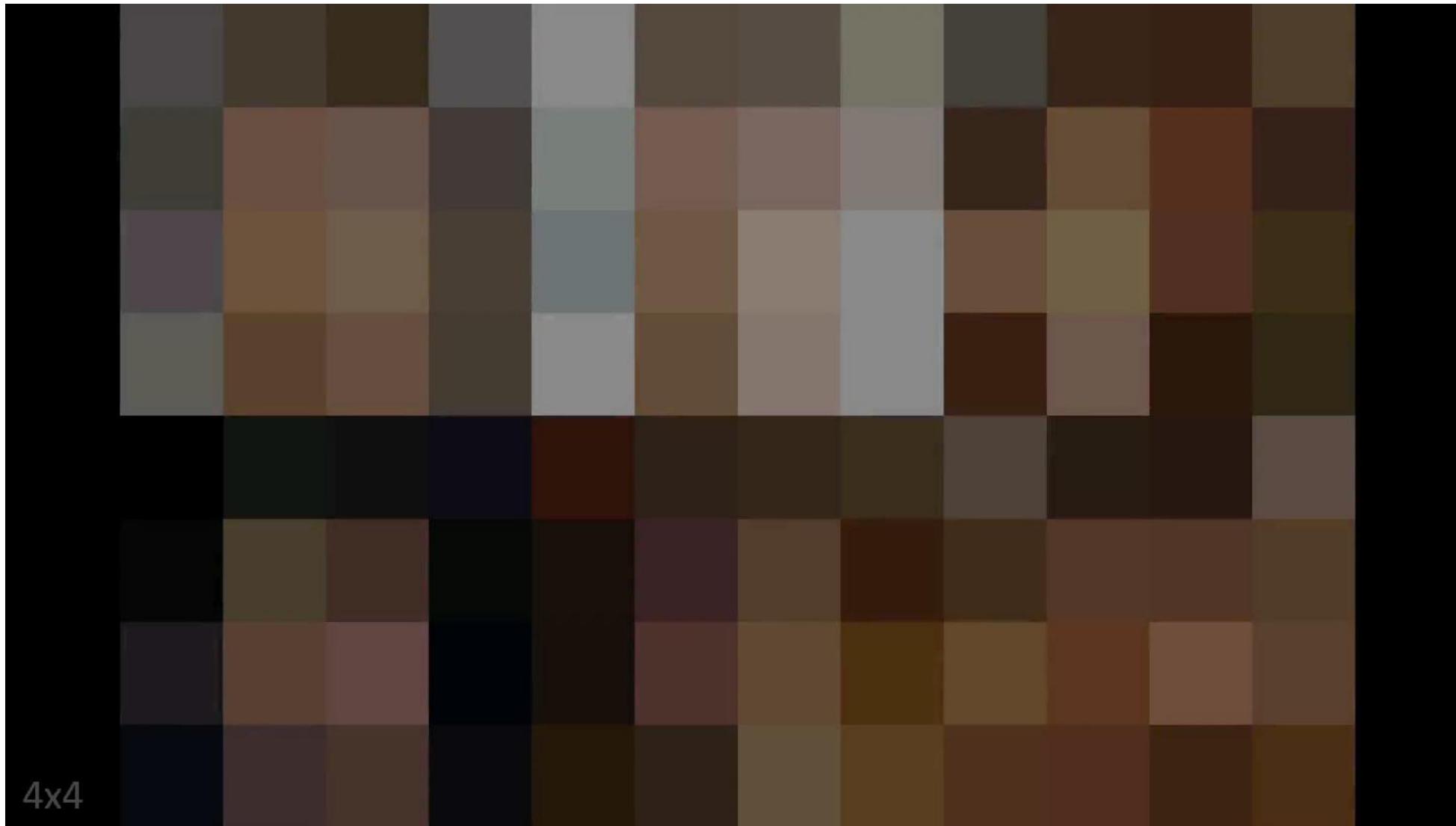
Gulrajani et al. (2017) ( $128 \times 128$ )

Our ( $256 \times 256$ )

# Progressive growing of GANs



# Progressive growing of GANs



4x4

# Progressive growing of GANs



CelebA-HQ  
random interpolations

[Karras et al. 2017]

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# Spectral Normalization GAN (SNGAN)

## SPECTRAL NORMALIZATION FOR GENERATIVE ADVERSARIAL NETWORKS

**Takeru Miyato<sup>1</sup>, Toshiki Kataoka<sup>1</sup>, Masanori Koyama<sup>2</sup>, Yuichi Yoshida<sup>3</sup>**

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### ABSTRACT

One of the challenges in the study of generative adversarial networks is the instability of its training. In this paper, we propose a novel weight normalization technique called spectral normalization to stabilize the training of the discriminator. Our new normalization technique is computationally light and easy to incorporate into existing implementations. We tested the efficacy of spectral normalization on CIFAR10, STL-10, and ILSVRC2012 dataset, and we experimentally confirmed that spectrally normalized GANs (SN-GANs) is capable of generating images of better or equal quality relative to the previous training stabilization techniques. The code with Chainer (Tokui et al., 2015), generated images and pretrained models are available at [https://github.com/pfnet-research/sngan\\_projection](https://github.com/pfnet-research/sngan_projection).

[Miyato et al. 2017]

# Spectral Normalization GAN (SNGAN)

(original) GAN formulation:  $\min_G \max_D V(G, D)$

where  $V(G, D) = \mathbb{E}_{\mathbf{x} \sim q_{\text{data}}} [\log D(\mathbf{x})] + \mathbb{E}_{\mathbf{x}' \sim p_G} [\log(1 - D(\mathbf{x}'))]$

---

WGAN formulation:  $\min_G \left[ \arg \max_{\|f\|_{\text{Lip}} \leq K} V(G, D) \right]$

where  $\|f\|_{\text{Lip}} \leq K \Rightarrow \|f(\mathbf{x}) - f(\mathbf{x}')\| / \|\mathbf{x} - \mathbf{x}'\| \leq K$

- Idea: Use spectral normalization to enforce the Lipschitz constraint

# Spectral Normalization GAN (SNGAN)

- **Spectral Normalization strategy:** enforce the Lipschitz constraint by constraining the spectral norm of each layer of the neural network.

spectral norm of the matrix  $A$ :  $\sigma(A) := \max_{\mathbf{h}: \mathbf{h} \neq \mathbf{0}} \frac{\|A\mathbf{h}\|_2}{\|\mathbf{h}\|_2} = \max_{\|\mathbf{h}\|_2 \leq 1} \|A\mathbf{h}\|_2$

- Let  $g$  be a layer of a network:  $g : \mathbf{h}_{in} \mapsto \mathbf{h}_{out}$   
for a linear layer  $g(\mathbf{h}) = W\mathbf{h}$ :  $\|g\|_{\text{Lip}} = \sup_{\mathbf{h}} \sigma(\nabla g(\mathbf{h})) = \sup_{\mathbf{h}} \sigma(W) = \sigma(W)$
- For the network  $f$ , we assume the Lipschitz norm of the activation function ( $a$ ) equals 1 (typically ok) and use the inequality:

$$\|g_1 \circ g_2\|_{\text{Lip}} \leq \|g_1\|_{\text{Lip}} \cdot \|g_2\|_{\text{Lip}}$$

# Spectral Normalization GAN (SNGAN)

- The Lipschitz norm for the network is:

$$\|f\|_{\text{Lip}} \leq \|(\mathbf{h}_L \mapsto W^{L+1}\mathbf{h}_L)\|_{\text{Lip}} \cdot \|a_L\|_{\text{Lip}} \cdot \|(\mathbf{h}_{L-1} \mapsto W^L\mathbf{h}_{L-1})\|_{\text{Lip}}$$

activation function for layer  $L$

$$\cdots \|a_1\|_{\text{Lip}} \cdot \|(\mathbf{h}_0 \mapsto W^1\mathbf{h}_0)\|_{\text{Lip}} = \prod_{l=1}^{L+1} \|(\mathbf{h}_{l-1} \mapsto W^l\mathbf{h}_{l-1})\|_{\text{Lip}} = \prod_{l=1}^{L+1} \sigma(W^l)$$

- Spectral Normalize the weights at each layer:  $\bar{W}_{\text{SN}}(W) := W/\sigma(W)$

where  $\sigma(W)$  is efficiently approximated using the power method.

(as described on the next slide)

# Spectral Normalization GAN (SNGAN)

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**Algorithm 1** SGD with spectral normalization

---

- Initialize  $\tilde{\mathbf{u}}_l \in \mathcal{R}^{d_l}$  for  $l = 1, \dots, L$  with a random vector (sampled from isotropic distribution).
- For each update and each layer  $l$ : ..... (warm start  $\tilde{\mathbf{u}}_l$  and  $\tilde{\mathbf{v}}_l$  from previous iteration)
  1. Apply power iteration method to a unnormalized weight  $W^l$ : (single iteration seems to work)

$$\tilde{\mathbf{v}}_l \leftarrow (W^l)^T \tilde{\mathbf{u}}_l / \| (W^l)^T \tilde{\mathbf{u}}_l \|_2 \quad (20)$$

$$\tilde{\mathbf{u}}_l \leftarrow W^l \tilde{\mathbf{v}}_l / \| W^l \tilde{\mathbf{v}}_l \|_2 \quad (21)$$

2. Calculate  $\bar{W}_{\text{SN}}$  with the spectral norm:

$$\bar{W}_{\text{SN}}^l(W^l) = W^l / \sigma(W^l), \text{ where } \sigma(W^l) = \tilde{\mathbf{u}}_l^T W^l \tilde{\mathbf{v}}_l \quad (22)$$

3. Update  $W^l$  with SGD on mini-batch dataset  $\mathcal{D}_M$  with a learning rate  $\alpha$ :

$$W^l \leftarrow W^l - \alpha \nabla_{W^l} \ell(\bar{W}_{\text{SN}}^l(W^l), \mathcal{D}_M) \quad (23)$$

# Spectral Normalization GAN (SNGAN)

$$V_D(\hat{G}, D) = \mathbb{E}_{\mathbf{x} \sim q_{\text{data}}(\mathbf{x})} [\min(0, -1 + D(\mathbf{x}))] + \mathbb{E}_{\mathbf{z} \sim p(\mathbf{z})} [\min(0, -1 - D(\hat{G}(\mathbf{z})))]$$

$$V_G(G, \hat{D}) = - \mathbb{E}_{\mathbf{z} \sim p(\mathbf{z})} [\hat{D}(G(\mathbf{z}))],$$

---

## Geometric GAN

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# Spectral Normalization GAN (SNGAN)

$z \in \mathbb{R}^{128} \sim \mathcal{N}(0, I)$	RGB image $x \in \mathbb{R}^{128 \times 128 \times 3}$	RGB image $x \in \mathbb{R}^{128 \times 128 \times 3}$
dense, $4 \times 4 \times 1024$	ResBlock down 64	ResBlock down 64
ResBlock up 1024	ResBlock down 128	ResBlock down 128
ResBlock up 512	ResBlock down 256	ResBlock down 256
ResBlock up 256	ResBlock down 512	Concat(Embed( $y$ ), $\mathbf{h}$ )
ResBlock up 128	ResBlock down 512	ResBlock down 512
ResBlock up 64	ResBlock down 1024	ResBlock down 1024
BN, ReLU, $3 \times 3$ conv 3	ResBlock 1024	ResBlock 1024
Tanh	ReLU	ReLU
(a) Generator	Global sum pooling	Global sum pooling
	dense $\rightarrow 1$	dense $\rightarrow 1$
	(b) Discriminator for unconditional GANs.	(c) Discriminator for conditional GANs. For computational ease, we embedded the integer label $y \in \{0, \dots, 1000\}$ into 128 dimension before concatenating the vector to the output of the intermediate layer.

# Spectral Normalization GAN (SNGAN)

Welsh springer spaniel



Pizza

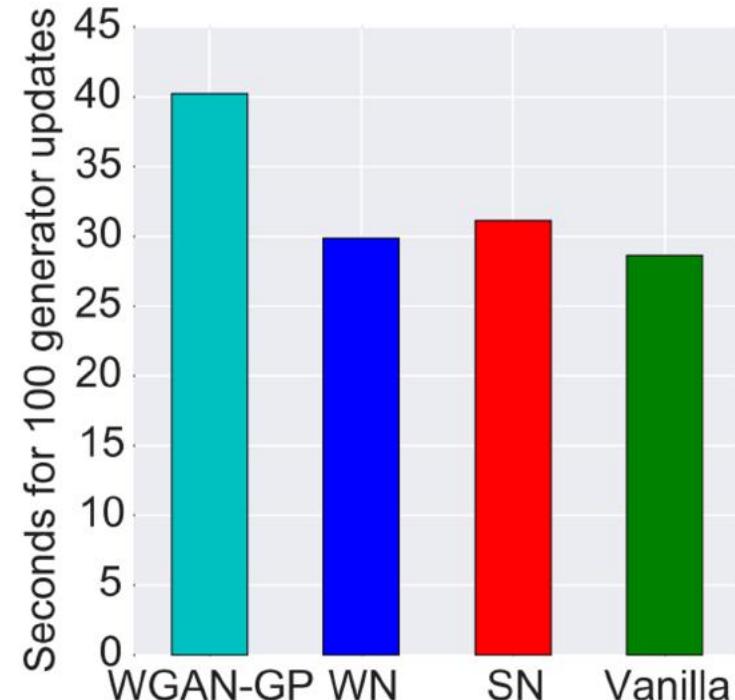


[Miyato et al. 2017]

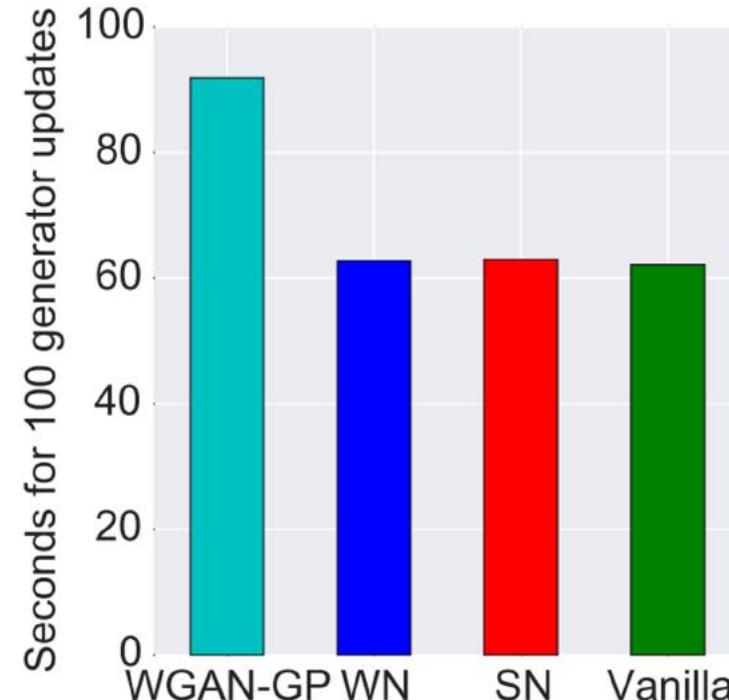
# SNGAN: Summary

- High quality class conditional samples at Imagenet scale
- First GAN to work on full Imagenet (million image dataset)
- Computational benefits over WGAN-GP (single power iteration and no need of a backward pass)

# SNGAN: Computational Benefits



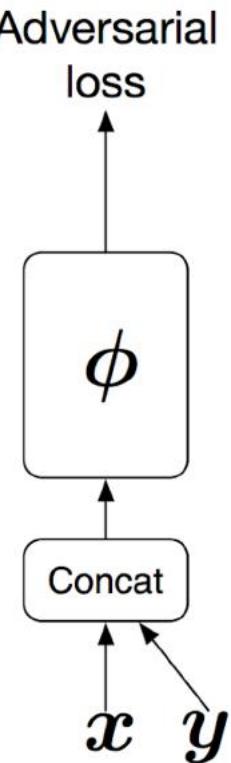
(a) CIFAR-10 (image size: $32 \times 32 \times 3$ )



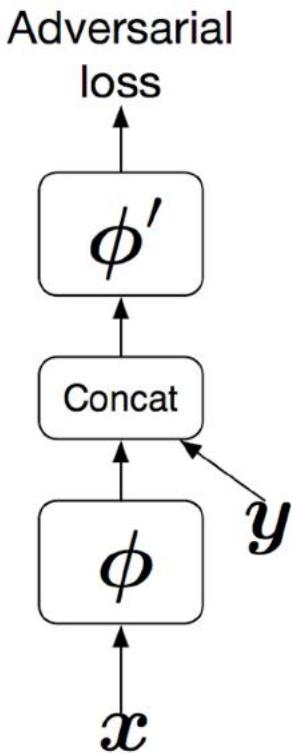
(b) STL-10 (images size: $48 \times 48 \times 3$ )

# Projection Discriminator

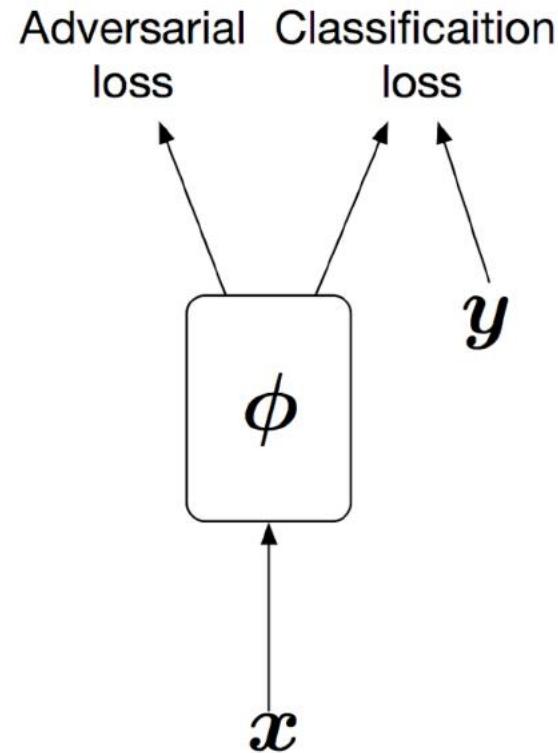
**(a) cGANs,  
input concat**  
(Mirza & Osindero, 2014)



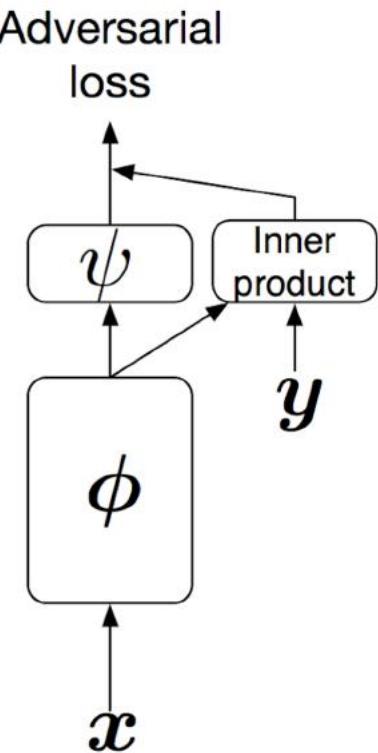
**(b) cGANs,  
hidden concat**  
(Reed et al., 2016)



**(c) AC-GANs**  
(Odena et al., 2017)



**(d) (ours) Projection**



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  - Improved Training of GANs (Salimans et al, 2016)
  - WGAN, WGAN-GP, Progressive GAN, SN-GAN, **SAGAN**
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- Applications

# Self Attention GAN (SAGAN)

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## Self-Attention Generative Adversarial Networks

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**Han Zhang\***

Rutgers University

**Ian Goodfellow**

Google Brain

**Dimitris Metaxas**

Rutgers University

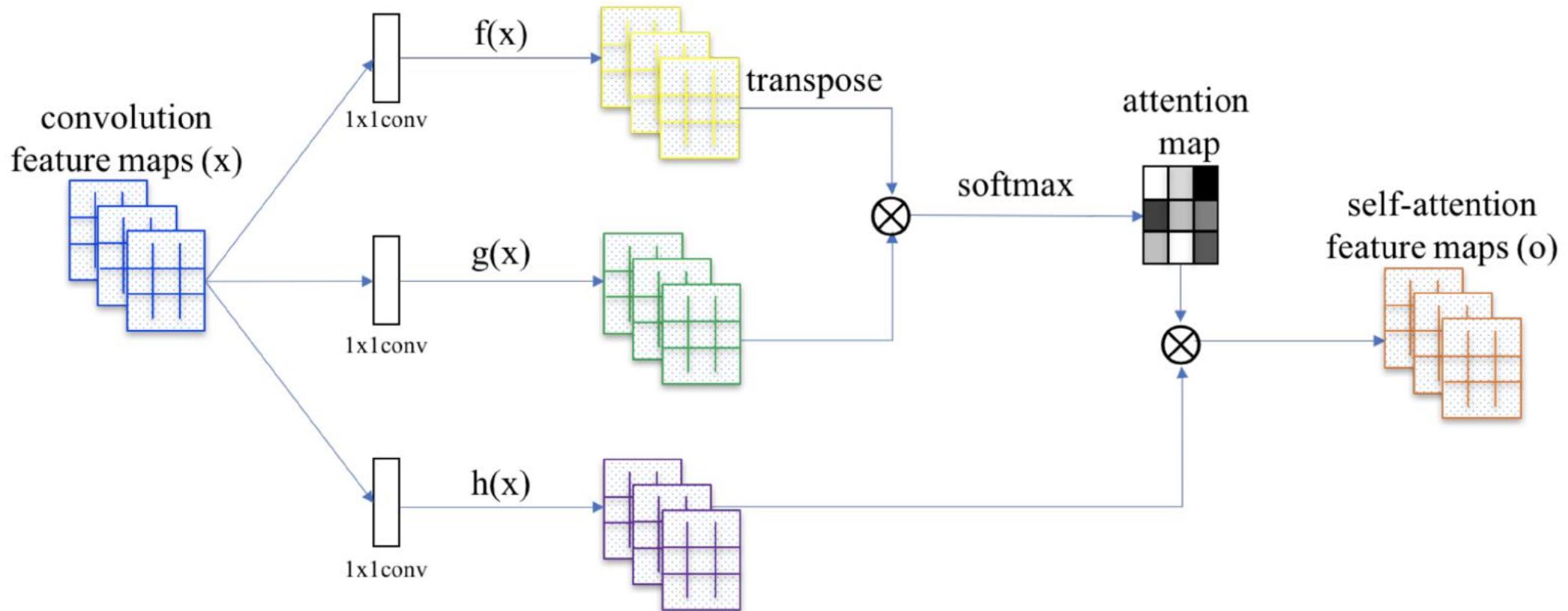
**Augustus Odena**

Google Brain

### Abstract

In this paper, we propose the Self-Attention Generative Adversarial Network (SAGAN) which allows attention-driven, long-range dependency modeling for image generation tasks. Traditional convolutional GANs generate high-resolution details as a function of only spatially local points in lower-resolution feature maps. In SAGAN, details can be generated using cues from all feature locations. Moreover, the discriminator can check that highly detailed features in distant portions of the image are consistent with each other. Furthermore, recent work has shown that generator conditioning affects GAN performance. Leveraging this insight, we apply spectral normalization to the GAN generator and find that this improves training dynamics. The proposed SAGAN achieves the state-of-the-art results, boosting the best published Inception score from 36.8 to 52.52 and reducing Fréchet Inception distance from 27.62 to 18.65 on the challenging ImageNet dataset. Visualization of the attention layers shows that the generator leverages neighborhoods that correspond to object shapes rather than local regions of fixed shape.

# Self Attention GAN (SAGAN)



# Self Attention GAN (SAGAN)

$$f(x) = W_f x, \ g(x) = W_g x$$

$$\beta_{j,i} = \frac{\exp(s_{ij})}{\sum_{i=1}^N \exp(s_{ij})}$$

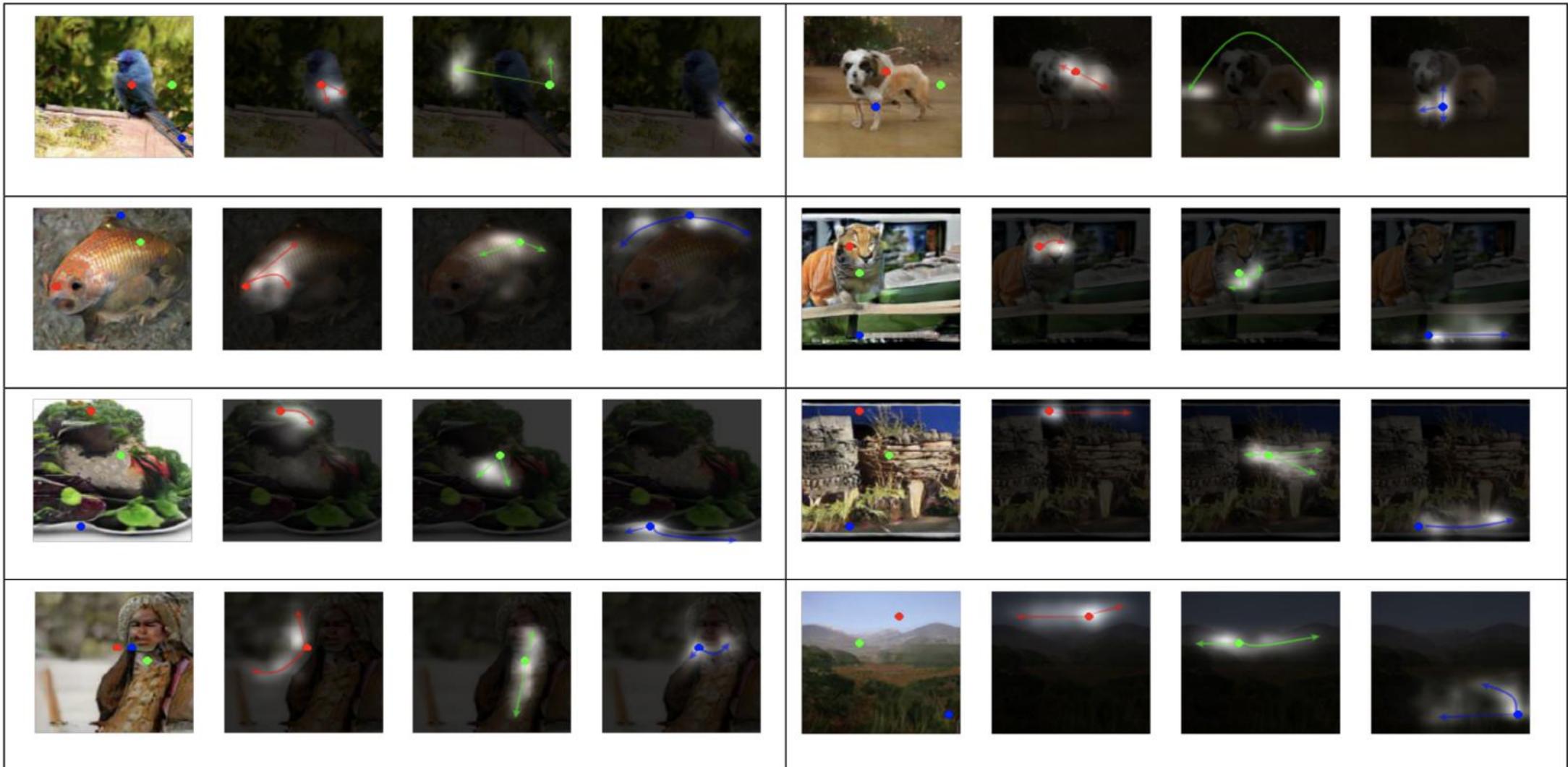
$$s_{ij} = f(\mathbf{x}_i)^T g(\mathbf{x}_j)$$

$$\mathbf{y}_i = \gamma \mathbf{o}_i + \mathbf{x}_i$$

# Self Attention GAN (SAGAN)

- Applies spectral normalization to both the generator and discriminator weight matrices
  - This is counter-intuitive to popular belief that you only have to mathematically condition the discriminator
- Uses self-attention in both the generator and discriminator
- Hinge Loss
- First GAN to produce “good” unconditional full ImageNet samples
- Conditional models
  - Conditional BN for G, Projection Discriminator for D

# Self Attention GAN (SAGAN)



[Zhang et al. 2018]

# Self Attention GAN (SAGAN)



[Zhang et al. 2018]

# Self Attention GAN (SAGAN)

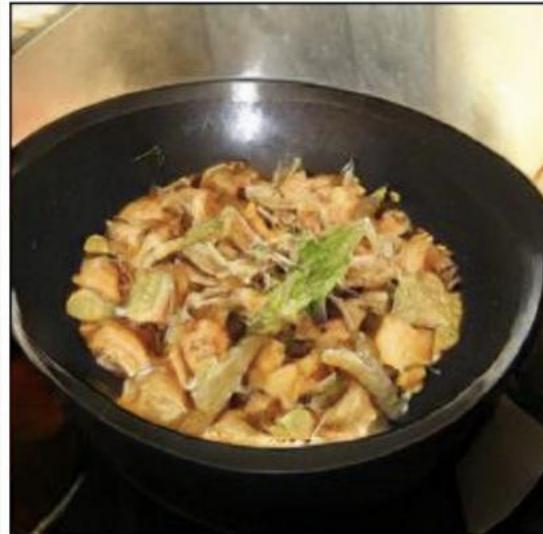
Model	Inception Score	FID
AC-GAN [31]	28.5	/
SNGAN-projection [17]	36.8	27.62*
SAGAN	<b>52.52</b>	<b>18.65</b>

Table 2: Comparison of the proposed SAGAN with state-of-the-art GAN models [19, 17] for class conditional image generation on ImageNet. FID of SNGAN-projection is calculated from officially released weights.

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# BigGAN



# BigGAN



# BigGAN

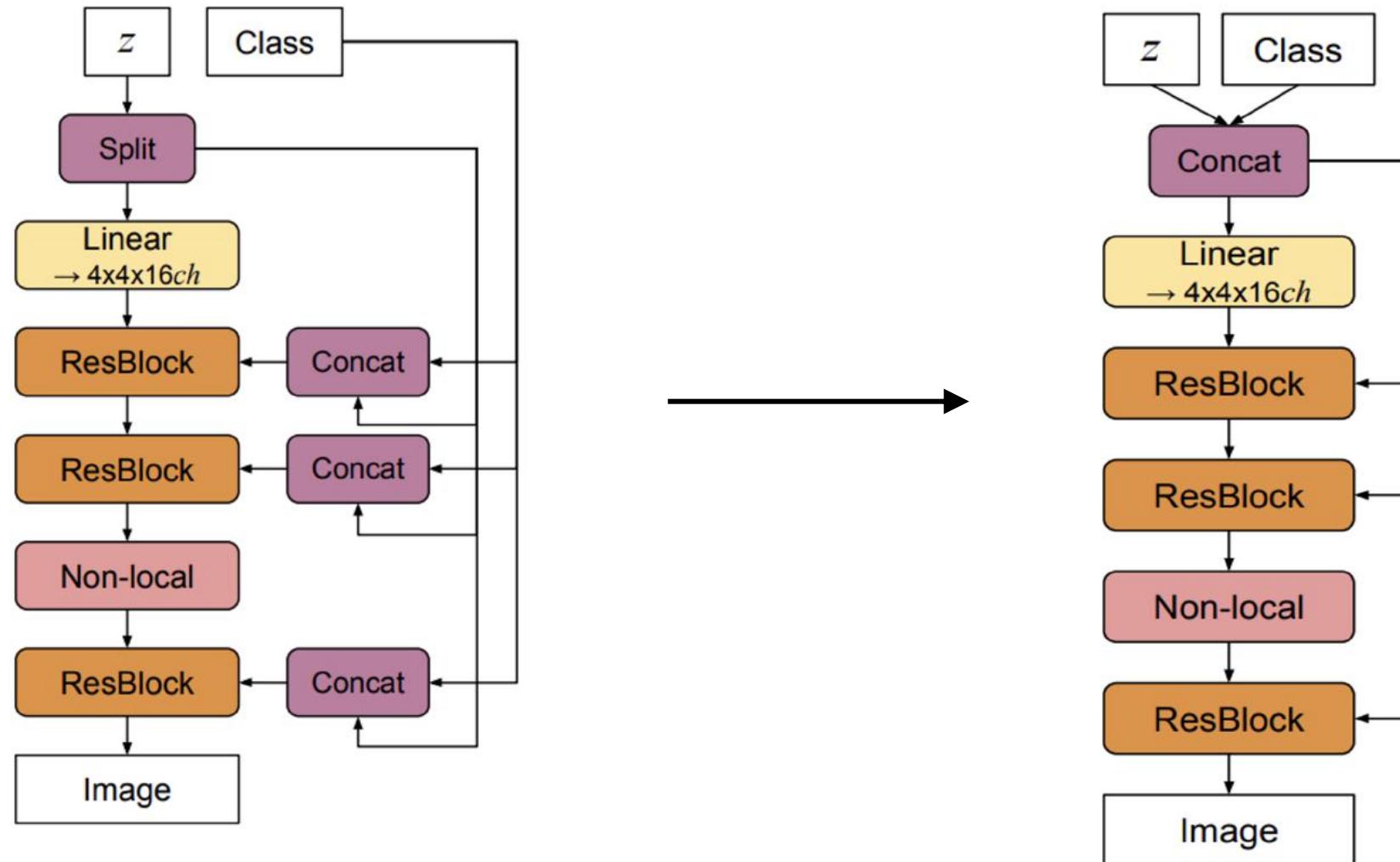
$$R_\beta(W) = \beta \|W^\top W - I\|_F^2$$



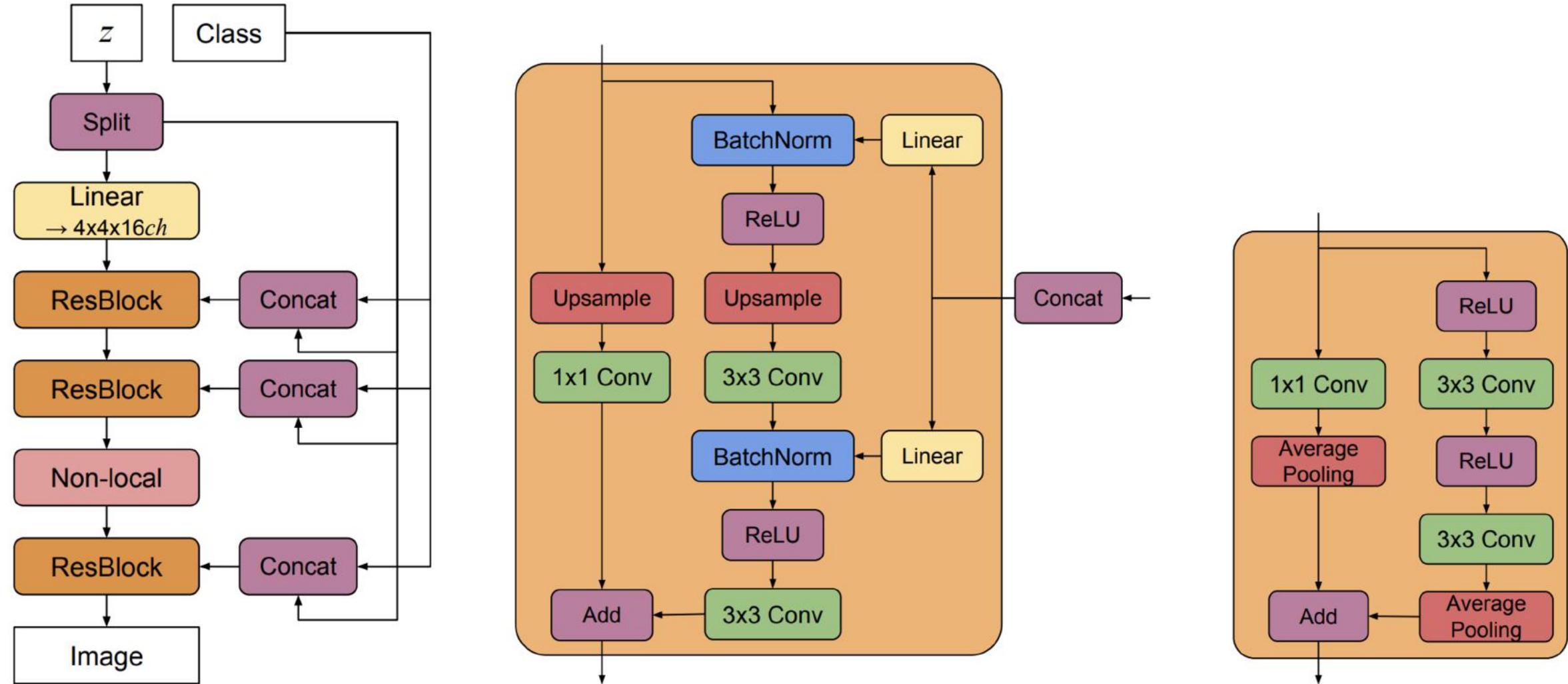
$$R_\beta(W) = \beta \|W^\top W \odot (1 - I)\|_F^2,$$

Orthogonal Regularization

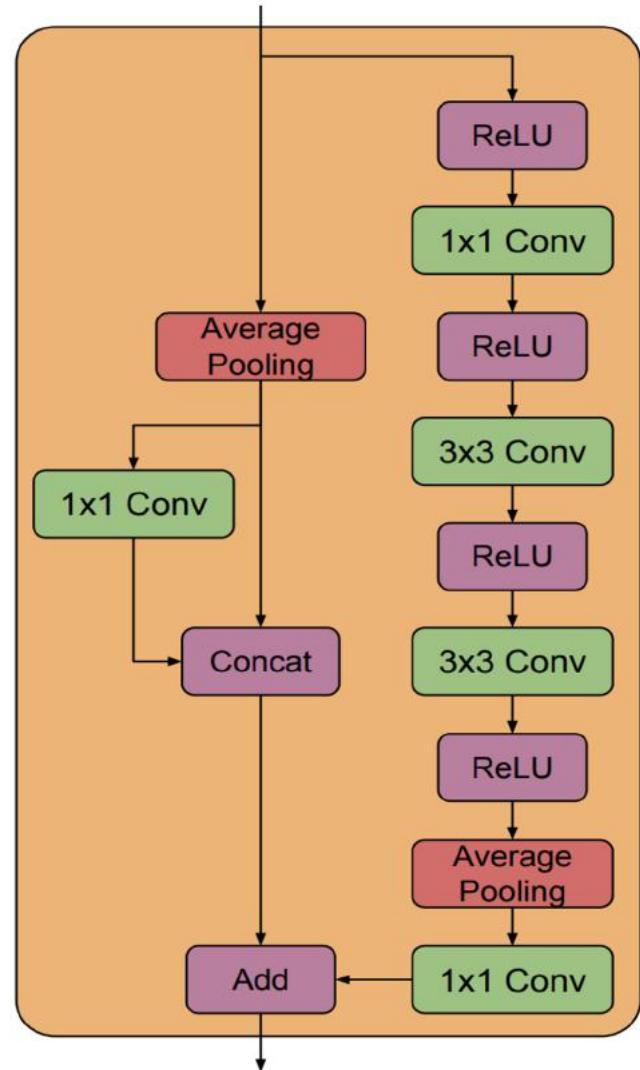
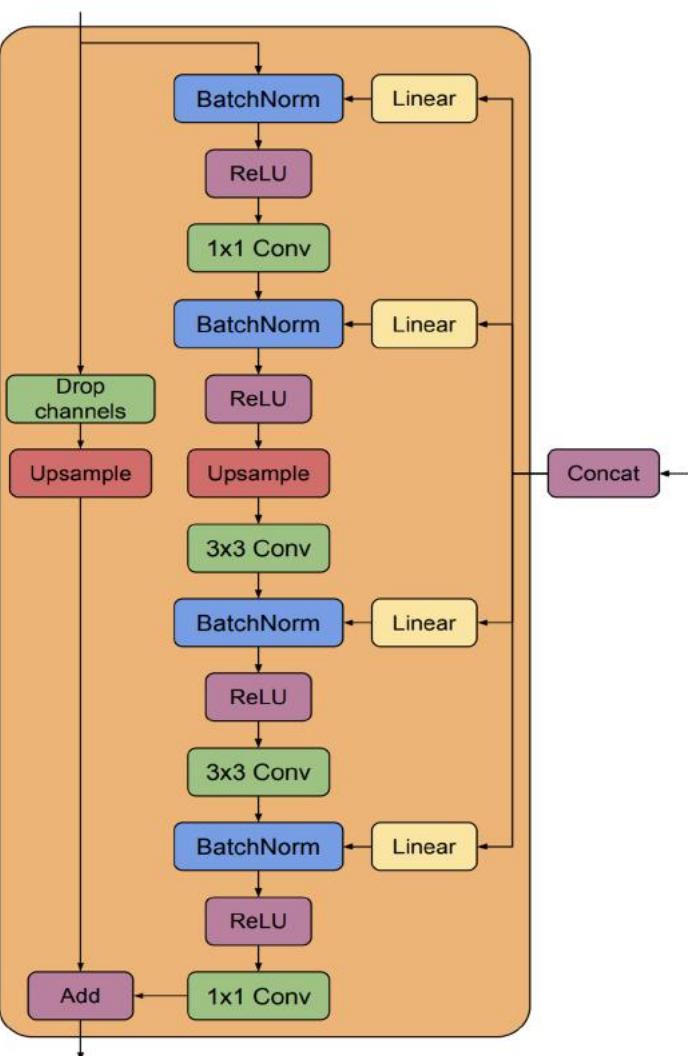
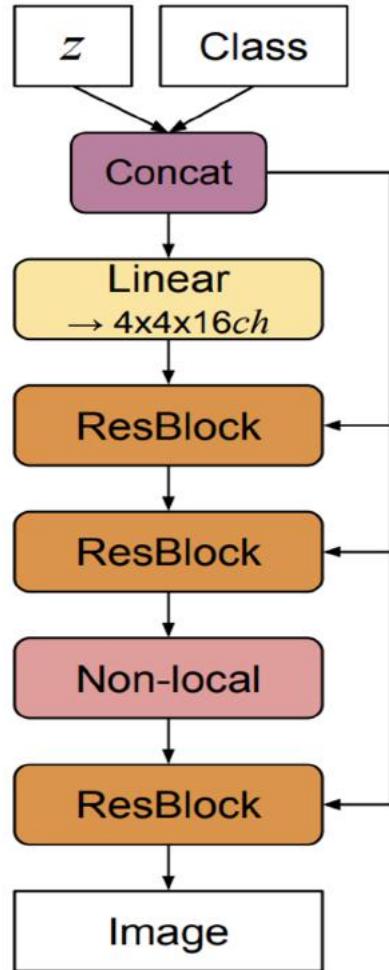
# BigGAN and BigGAN-deep



# BigGAN



# BigGAN-deep



# BigGAN

Table 6: BigGAN architecture for  $512 \times 512$  images. Relative to the  $256 \times 256$  architecture, we add an additional ResBlock at the  $512 \times 512$  resolution. Memory constraints force us to move the non-local block in both networks back to  $64 \times 64$  resolution as in the  $128 \times 128$  pixel setting.

$z \in \mathbb{R}^{160} \sim \mathcal{N}(0, I)$
Embed( $y$ ) $\in \mathbb{R}^{128}$
Linear $(20 + 128) \rightarrow 4 \times 4 \times 16ch$
ResBlock up $16ch \rightarrow 16ch$
ResBlock up $16ch \rightarrow 8ch$
ResBlock up $8ch \rightarrow 8ch$
ResBlock up $8ch \rightarrow 4ch$
Non-Local Block $(64 \times 64)$
ResBlock up $4ch \rightarrow 2ch$
ResBlock up $2ch \rightarrow ch$
ResBlock up $ch \rightarrow ch$
BN, ReLU, $3 \times 3$ Conv $ch \rightarrow 3$
Tanh

(a) Generator

RGB image $x \in \mathbb{R}^{512 \times 512 \times 3}$
ResBlock down $ch \rightarrow ch$
ResBlock down $ch \rightarrow 2ch$
ResBlock down $2ch \rightarrow 4ch$
Non-Local Block $(64 \times 64)$
ResBlock down $4ch \rightarrow 8ch$
ResBlock down $8ch \rightarrow 8ch$
ResBlock down $8ch \rightarrow 16ch$
ResBlock down $16ch \rightarrow 16ch$
ResBlock $16ch \rightarrow 16ch$
ReLU, Global sum pooling
Embed( $y$ ) $\cdot h$ + (linear $\rightarrow 1$ )

(b) Discriminator

# BigGAN

- Increase your batch size (as much as you can)
- Use Cross-Replica (Sync) Batch Norm
- Increase your model size
- Wider helps as much as deeper
- Fuse class information at all levels
- Hinge Loss
- Orthonormal regularization & Truncation Trick

# BigGAN

Batch	Ch.	Param (M)	Shared	Skip- $z$	Ortho.	Itr $\times 10^3$	FID	IS
256	64	81.5	SA-GAN Baseline			1000	18.65	52.52
512	64	81.5	✗	✗	✗	1000	15.30	58.77( $\pm 1.18$ )
1024	64	81.5	✗	✗	✗	1000	14.88	63.03( $\pm 1.42$ )
2048	64	81.5	✗	✗	✗	732	12.39	76.85( $\pm 3.83$ )
2048	96	173.5	✗	✗	✗	295( $\pm 18$ )	9.54( $\pm 0.62$ )	92.98( $\pm 4.27$ )
2048	96	160.6	✓	✗	✗	185( $\pm 11$ )	9.18( $\pm 0.13$ )	94.94( $\pm 1.32$ )
2048	96	158.3	✓	✓	✗	152( $\pm 7$ )	8.73( $\pm 0.45$ )	98.76( $\pm 2.84$ )
2048	96	158.3	✓	✓	✓	165( $\pm 13$ )	8.51( $\pm 0.32$ )	99.31( $\pm 2.10$ )
2048	64	71.3	✓	✓	✓	371( $\pm 7$ )	10.48( $\pm 0.10$ )	86.90( $\pm 0.61$ )

# BigGAN

Model	Res.	FID/IS	(min FID) / IS	FID / (valid IS)	FID / (max IS)
SN-GAN	128	27.62/36.80	N/A	N/A	N/A
SA-GAN	128	18.65/52.52	N/A	N/A	N/A
BigGAN	128	$8.7 \pm .6$ / $98.8 \pm 3$	$7.7 \pm .2$ / $126.5 \pm 0$	$9.6 \pm .4$ / $166.3 \pm 1$	$25 \pm 2$ / $206 \pm 2$
BigGAN	256	$8.7 \pm .1$ / $142.3 \pm 2$	$7.7 \pm .1$ / $178.0 \pm 5$	$9.3 \pm .3$ / $233.1 \pm 1$	$25 \pm 5$ / $291 \pm 4$
BigGAN	512	8.1/144.2	7.6/170.3	11.8/241.4	27.0/275
BigGAN-deep	128	$5.7 \pm .3$ / $124.5 \pm 2$	$6.3 \pm .3$ / $148.1 \pm 4$	$7.4 \pm .6$ / $166.5 \pm 1$	$25 \pm 2$ / $253 \pm 11$
BigGAN-deep	256	$6.9 \pm .2$ / $171.4 \pm 2$	$7.0 \pm .1$ / $202.6 \pm 2$	$8.1 \pm .1$ / $232.5 \pm 2$	$27 \pm 8$ / $317 \pm 6$
BigGAN-deep	512	7.5/152.8	7.7/181.4	11.5/241.5	39.7/298

# BigGAN - Truncation Trick



(a)

(b)

Remarkably, our best results come from using a different latent distribution for sampling than was used in training. Taking a model trained with  $z \sim \mathcal{N}(0, I)$  and sampling  $z$  from a *truncated normal* (where values which fall outside a range are resampled to fall inside that range) immediately provides a boost to IS and FID. We call this the *Truncation Trick*: truncating a  $z$  vector by resampling the values with magnitude above a chosen threshold leads to improvement in individual sample quality at the cost of reduction in overall sample variety. Figure 2(a) demonstrates this: as the threshold is reduced, and elements of  $z$  are truncated towards zero (the mode of the latent distribution), individual samples approach the mode of  $\mathbf{G}$ 's output distribution. Related observations about this trade-off were made in (Marchesi, 2016; Pieters & Wiering, 2014).

# BigGAN - Sampling

The default behavior with batch normalized classifier networks is to use a running average of the activation moments at test time. Previous works (Radford et al., 2016) have instead used batch statistics when sampling images. While this is not technically an invalid way to sample, it means that results are dependent on the test batch size (and how many devices it is split across), and further complicates reproducibility.

We find that this detail is extremely important, with changes in test batch size producing drastic changes in performance. This is further exacerbated when one uses exponential moving averages of  $\mathbf{G}$ 's weights for sampling, as the BatchNorm running averages are computed with non-averaged weights and are poor estimates of the activation statistics for the averaged weights.

To counteract both these issues, we employ “standing statistics,” where we compute activation statistics at sampling time by running the  $\mathbf{G}$  through multiple forward passes (typically 100) each with different batches of random noise, and storing means and variances aggregated across all forward passes. Analogous to using running statistics, this results in  $\mathbf{G}$ 's outputs becoming invariant to batch size and the number of devices, even when producing a single sample.

# BigGAN



(a)  $128 \times 128$



(b)  $256 \times 256$

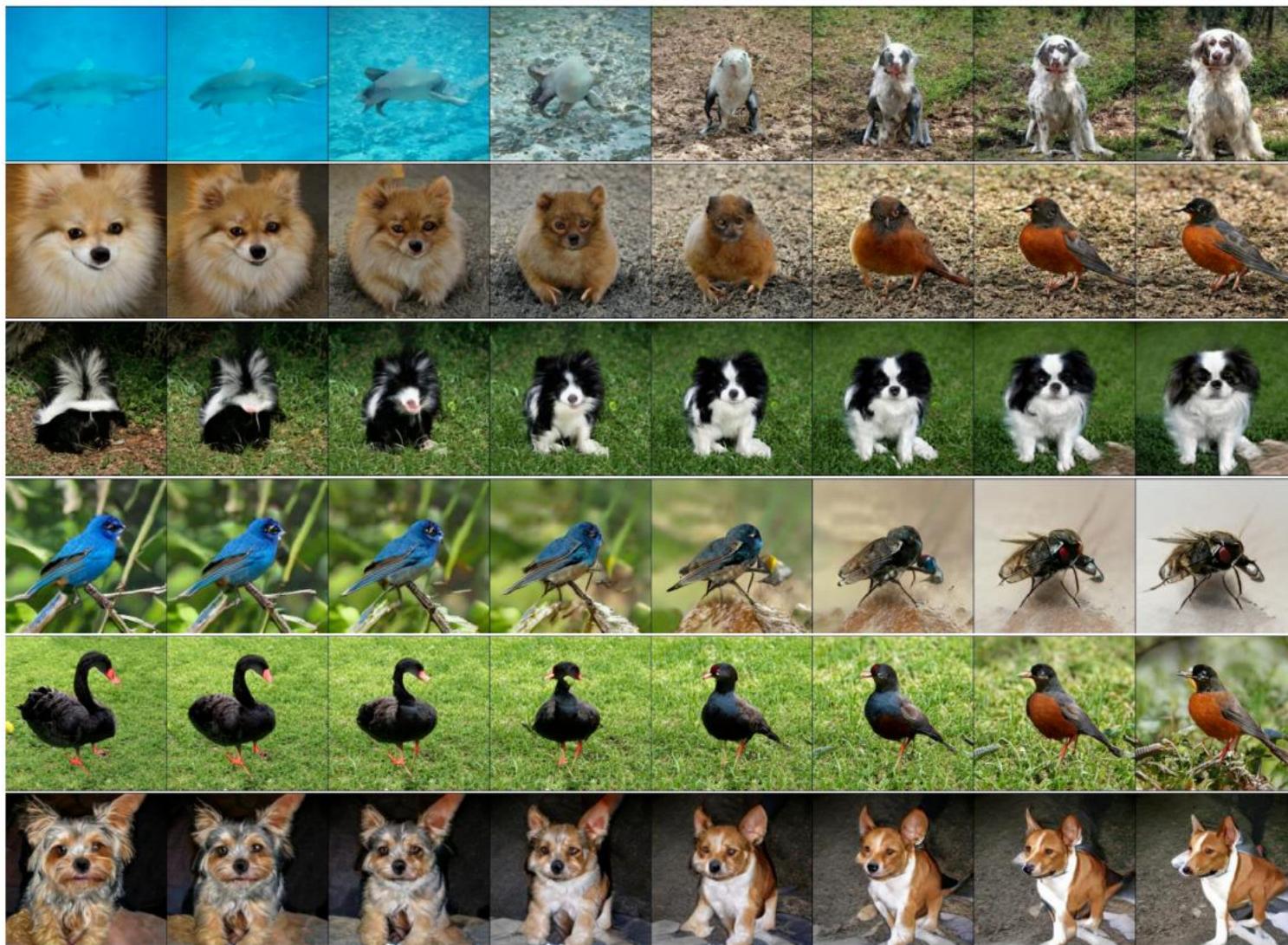


(c)  $512 \times 512$



(d)

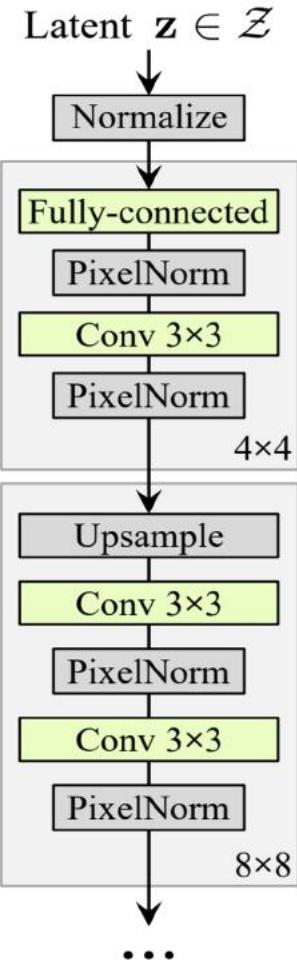
# BigGAN



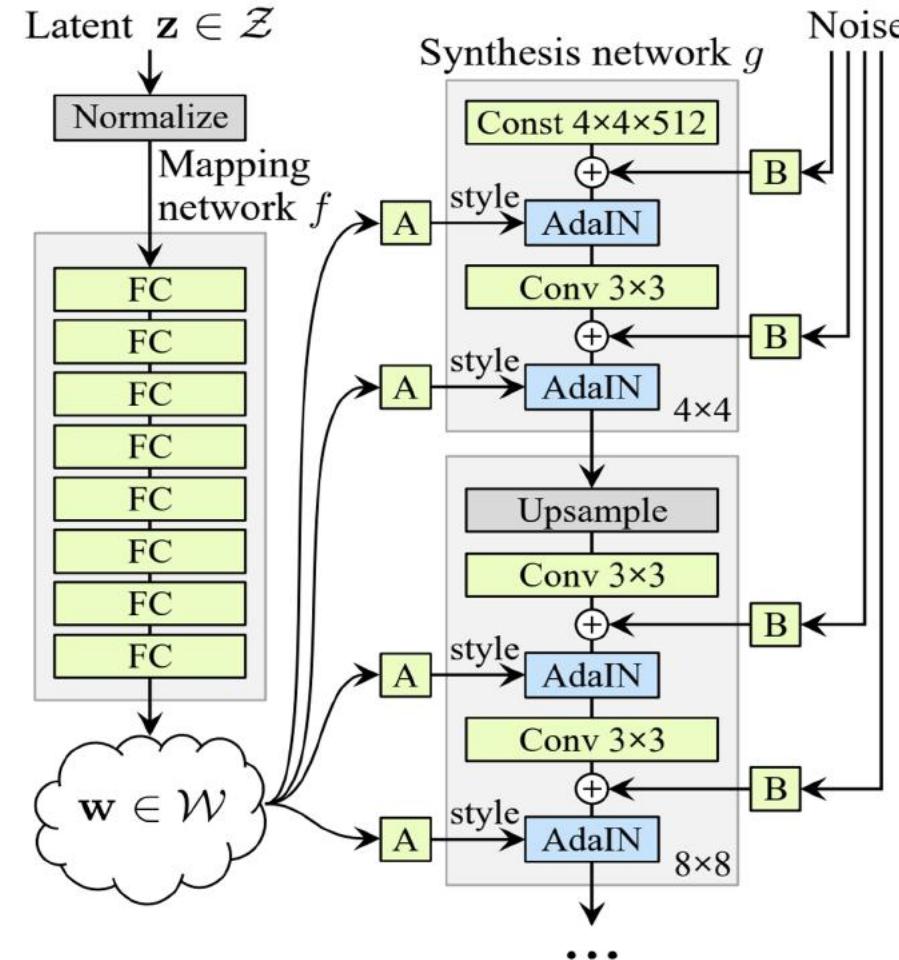
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# StyleGAN



(a) Traditional

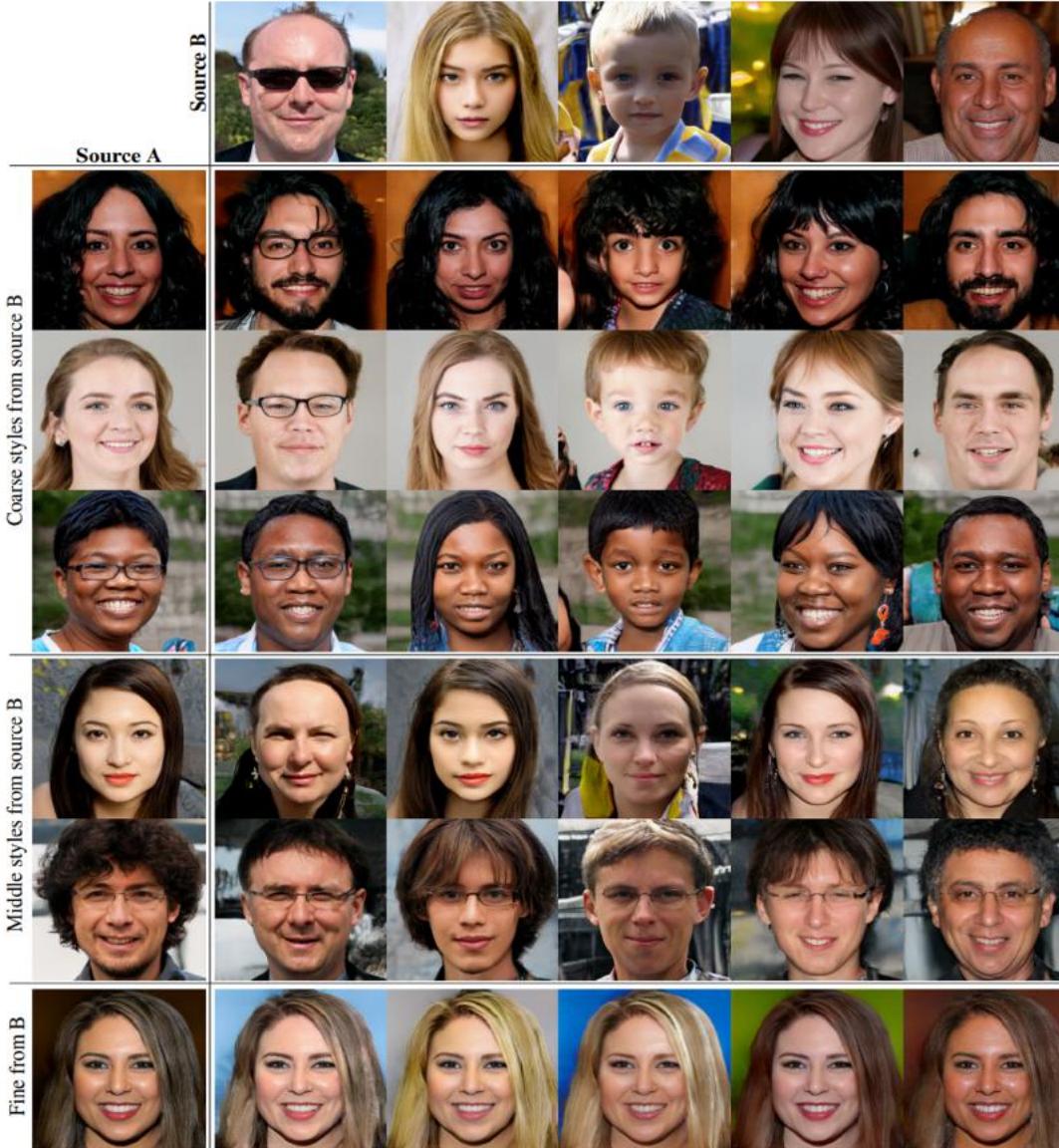


(b) Style-based generator

# StyleGAN - Adaptive Instance Norm

$$\text{AdaIN}(\mathbf{x}_i, \mathbf{y}) = \mathbf{y}_{s,i} \frac{\mathbf{x}_i - \mu(\mathbf{x}_i)}{\sigma(\mathbf{x}_i)} + \mathbf{y}_{b,i}$$

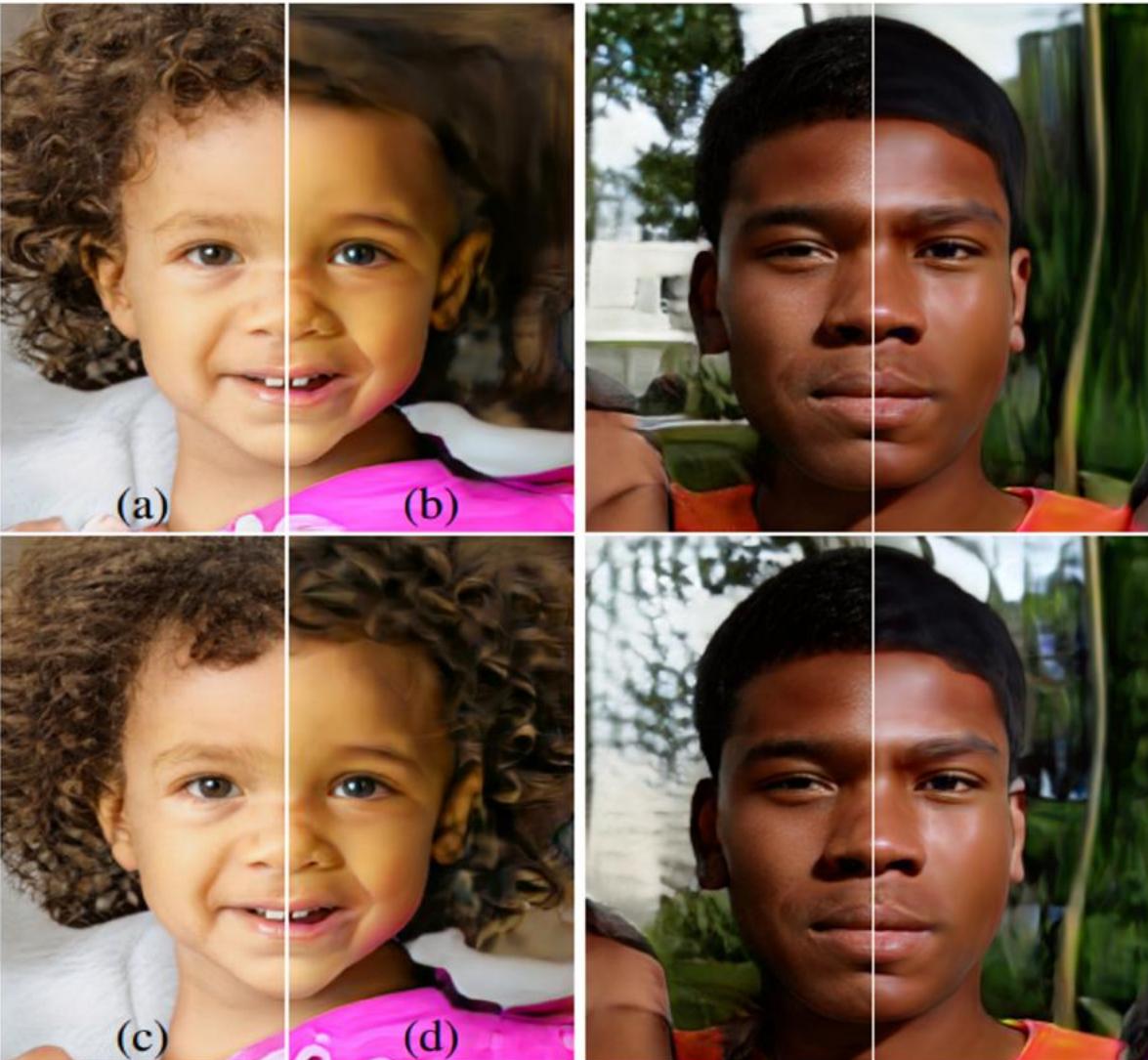
# StyleGAN - Style Transfer



# StyleGAN



# StyleGAN - Effect of adding noise



# StyleGAN - Effect of noise



(a) Generated image

(b) Stochastic variation

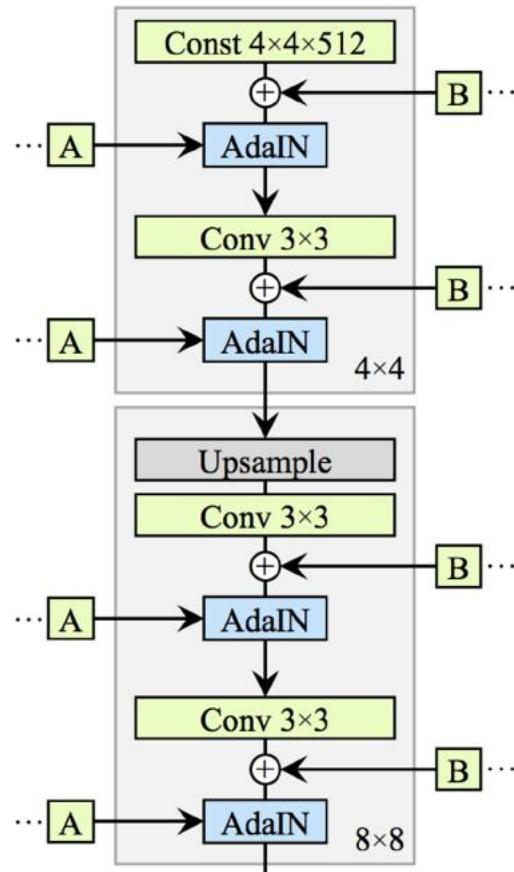
(c) Standard deviation

# StyleGAN-v2

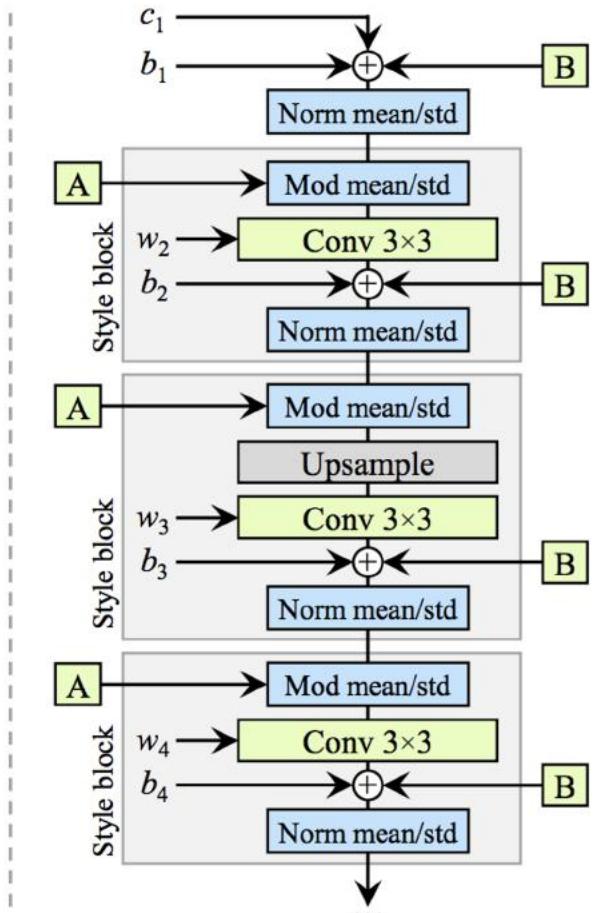


Figure 1. Instance normalization causes water droplet -like artifacts in StyleGAN images. These are not always obvious in the generated images, but if we look at the activations inside the generator network, the problem is always there, in all feature maps starting from the 64x64 resolution. It is a systemic problem that plagues all StyleGAN images.

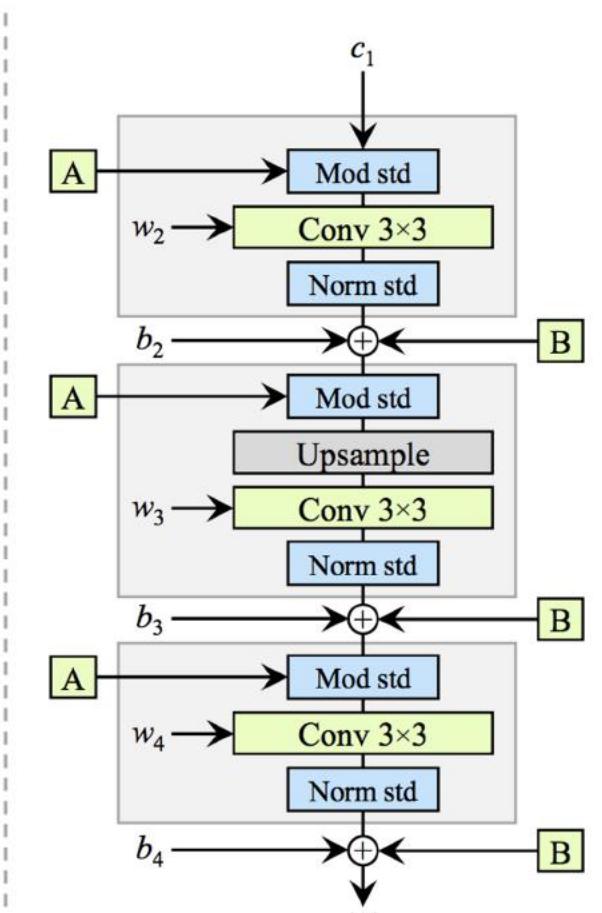
# StyleGAN-v2



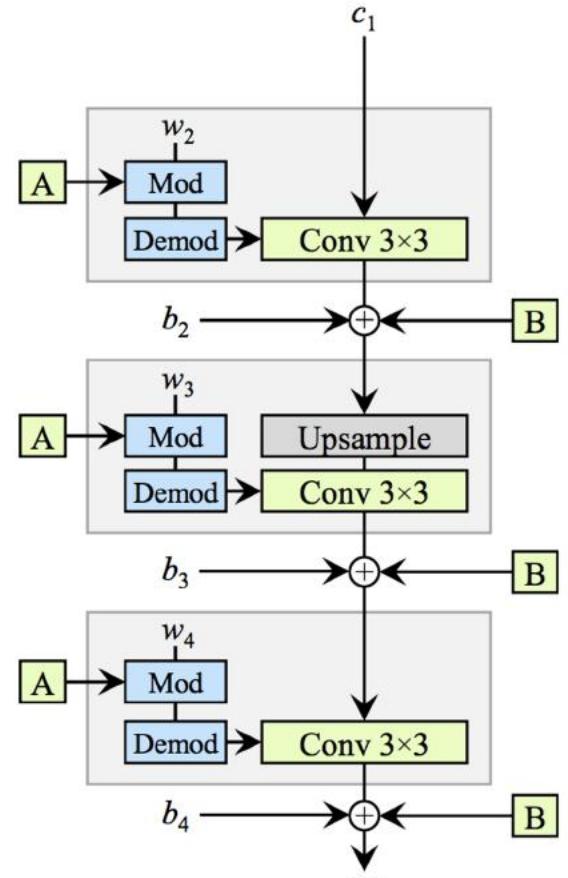
(a) StyleGAN



(b) StyleGAN (detailed)



(c) Revised architecture



(d) Weight demodulation

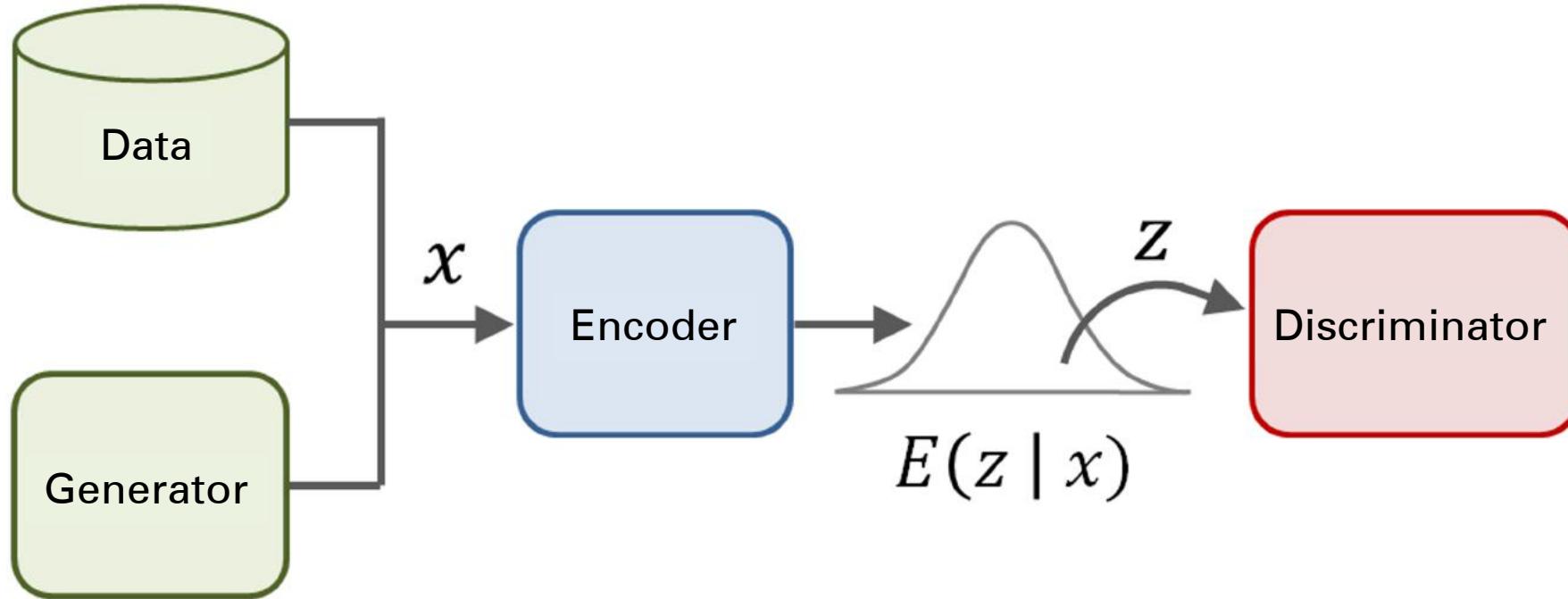


FFHQ,  $\Psi = 0.50$

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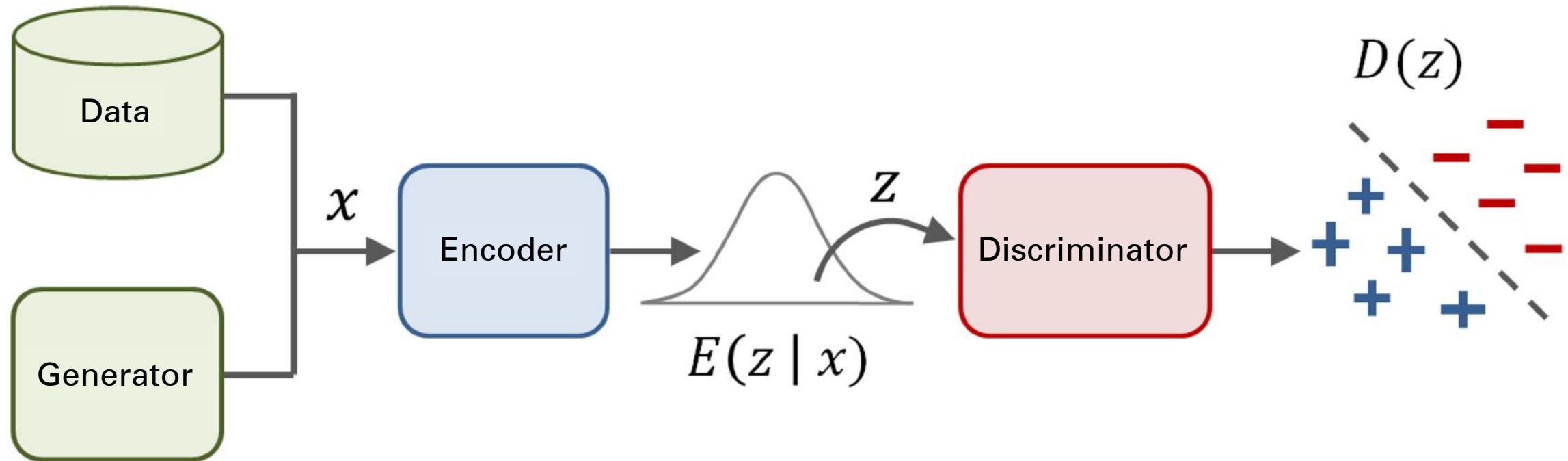
# Information Bottleneck



Variational Information Bottleneck [Alemi et al., 2016]

Variational Information Bottleneck GAN [Peng et al, 2019]

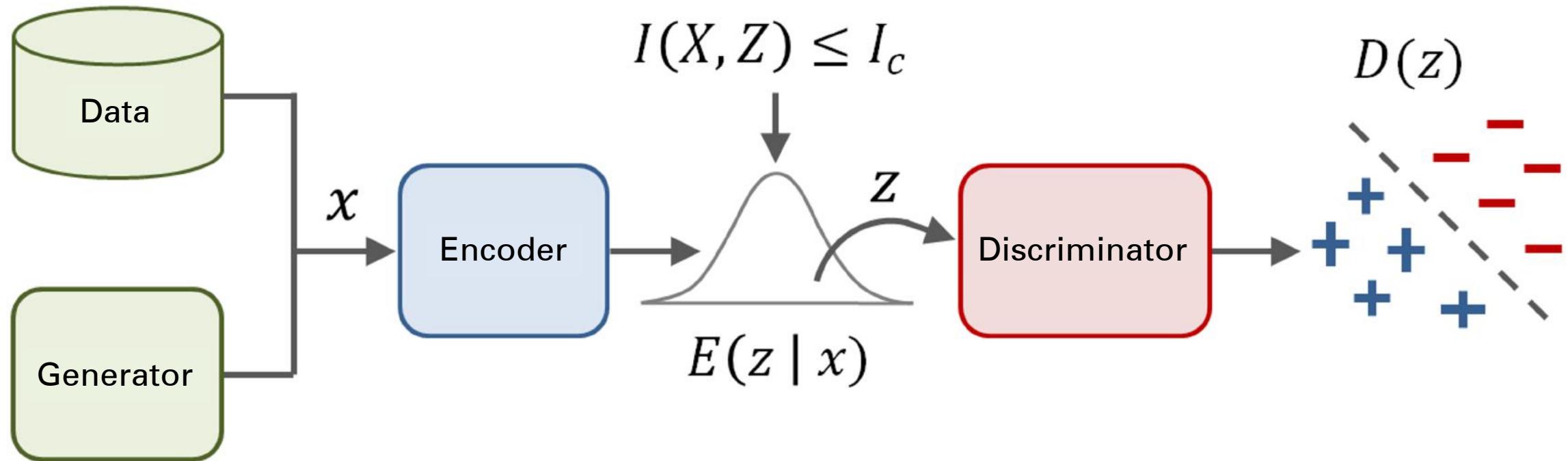
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# Information Bottleneck



Variational Information Bottleneck [Alemi et al., 2016]

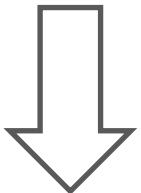
Variational Information Bottleneck GAN [Peng et al, 2019]

# Information Bottleneck

$$I(X, Z) \leq I_c$$

# Information Bottleneck

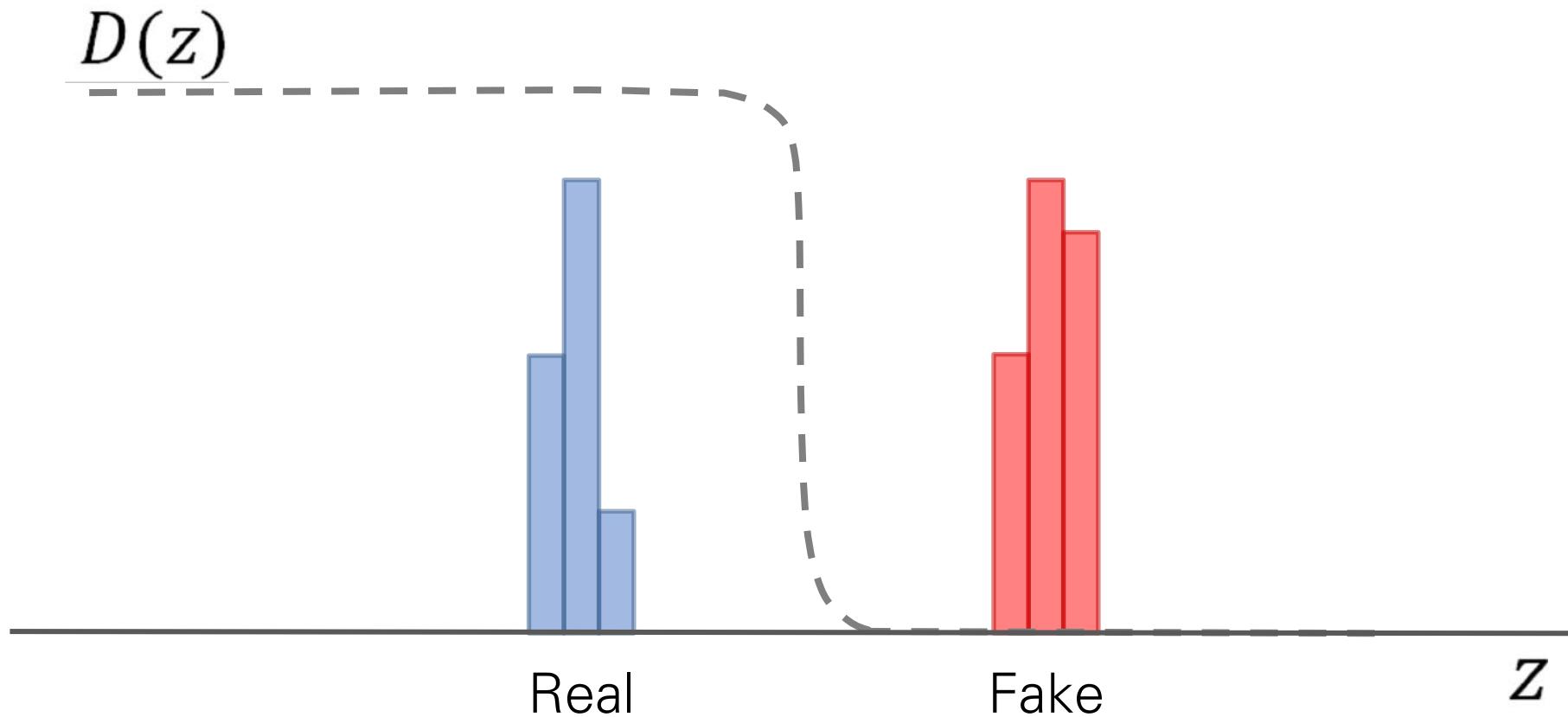
$$I(X, Z) \leq I_c$$



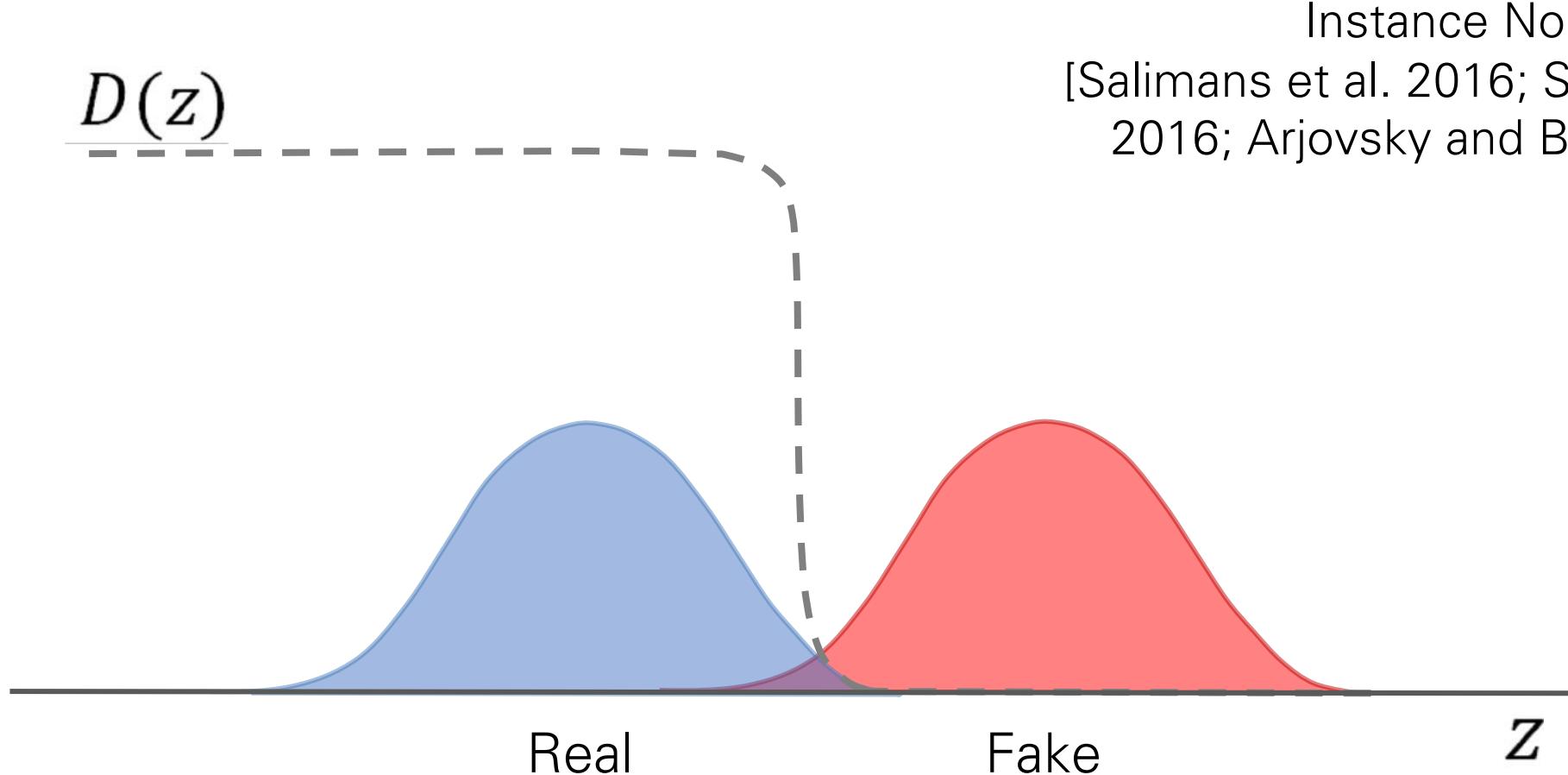
$$\mathbb{E}_{\mathbf{x} \sim \tilde{p}(\mathbf{x})} [\text{KL} [E(\mathbf{z}|\mathbf{x}) || r(\mathbf{z})]] \leq I_c$$

Variational Information Bottleneck (VIB)  
[Alemi et al., 2016]

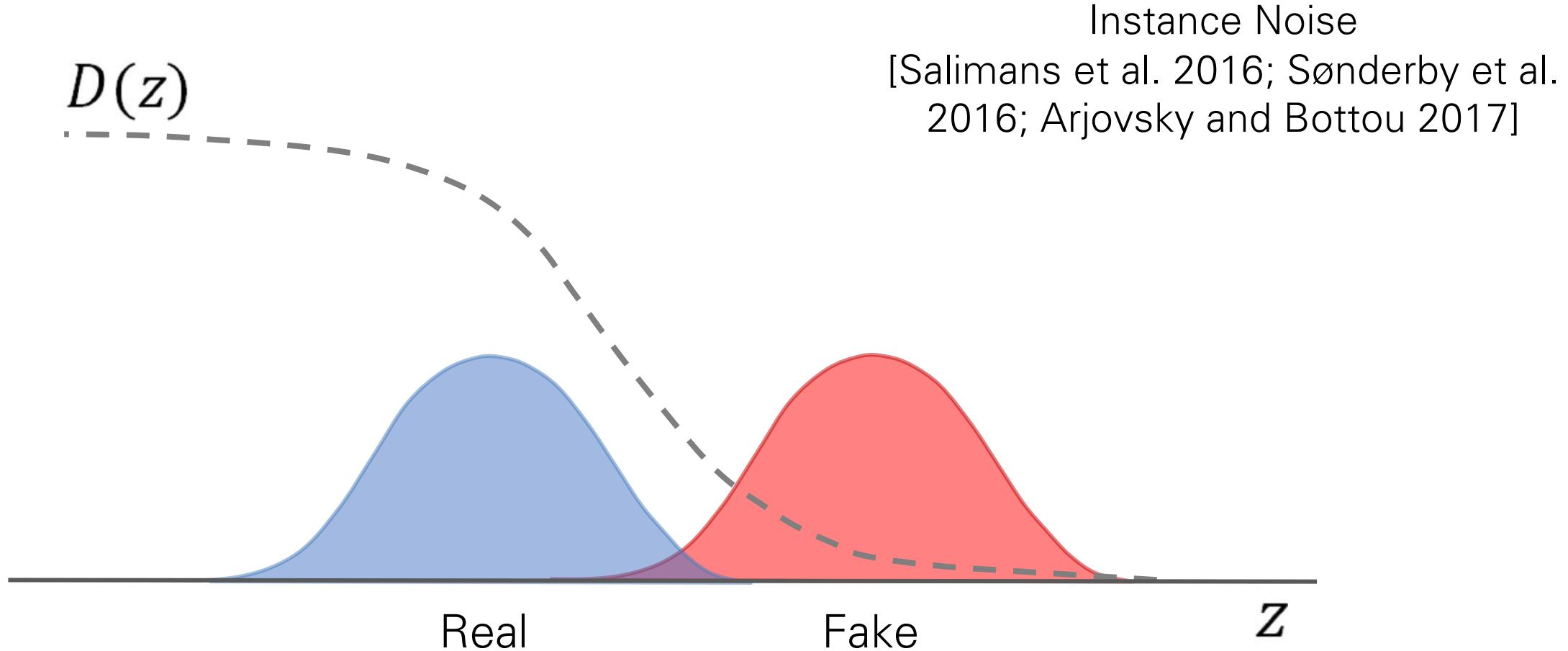
# Variational Information Bottleneck



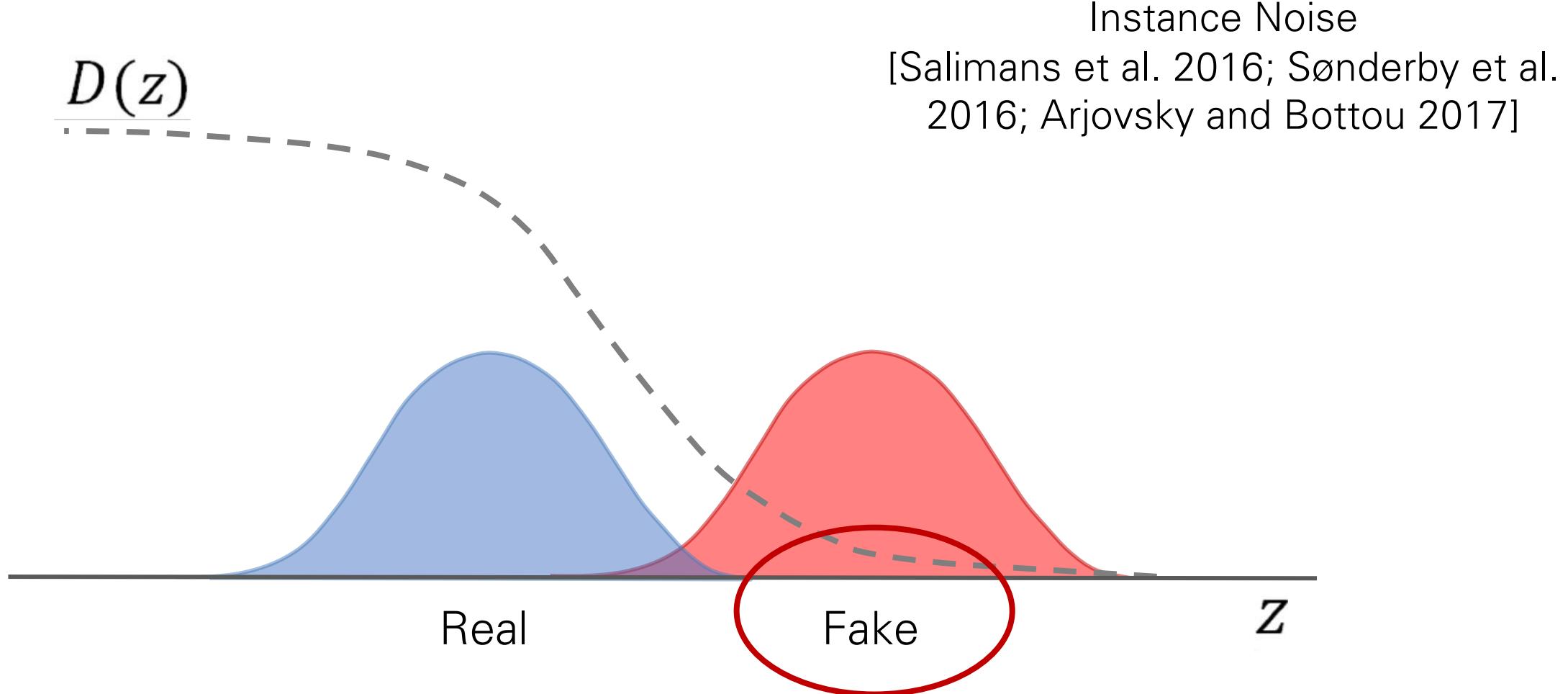
# Variational Information Bottleneck



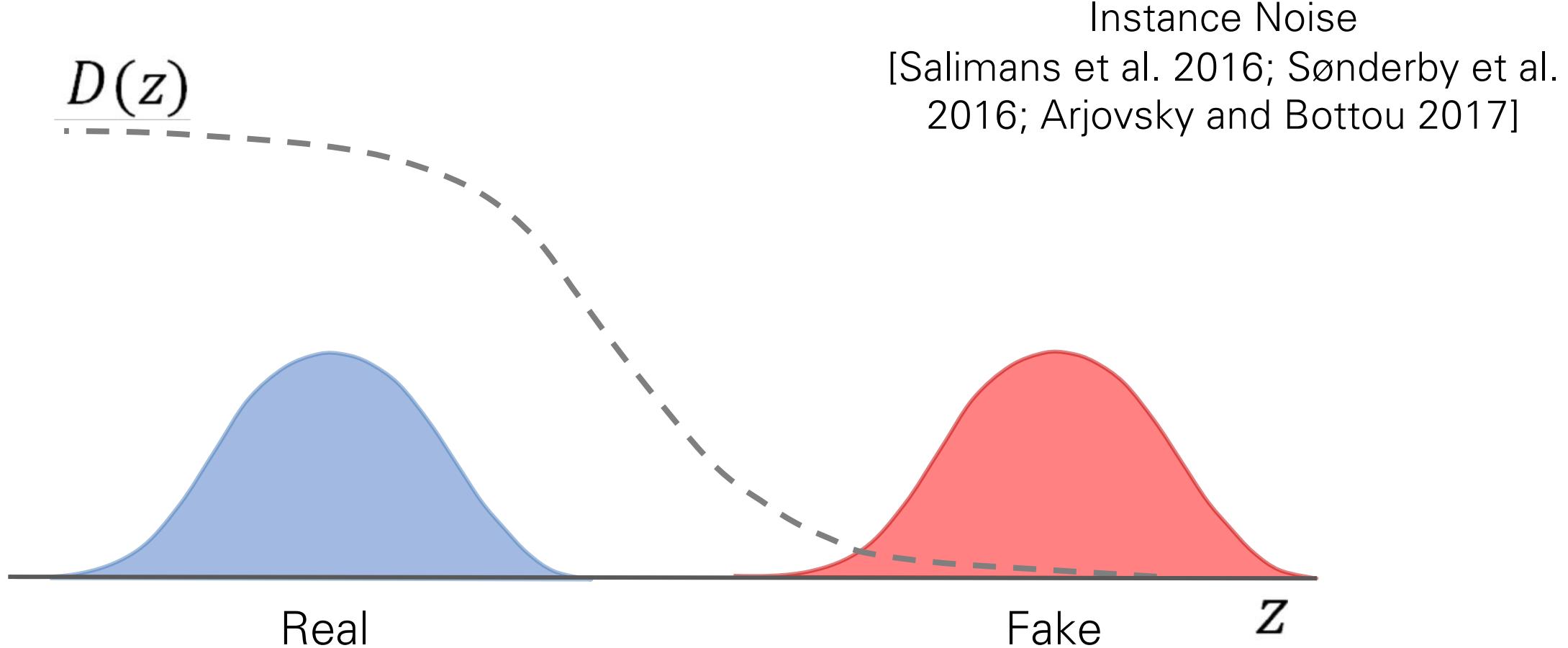
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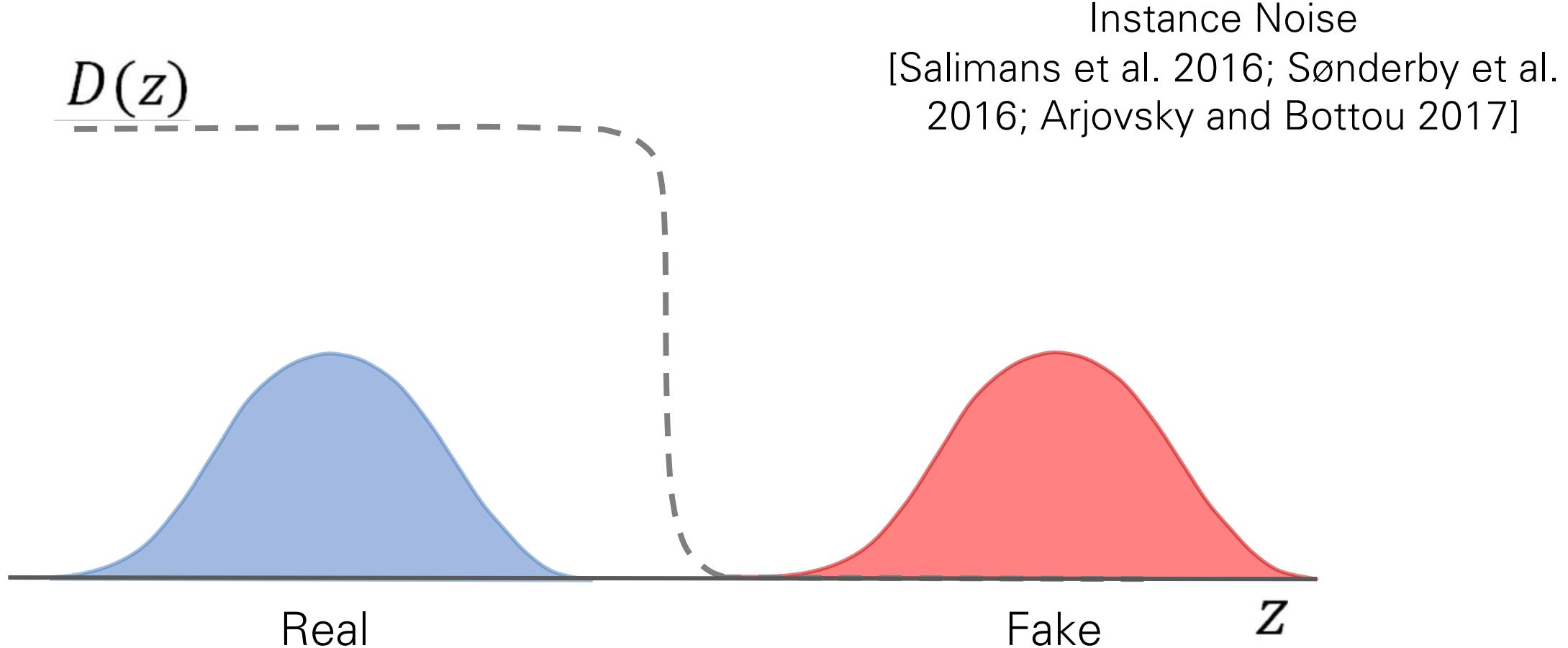
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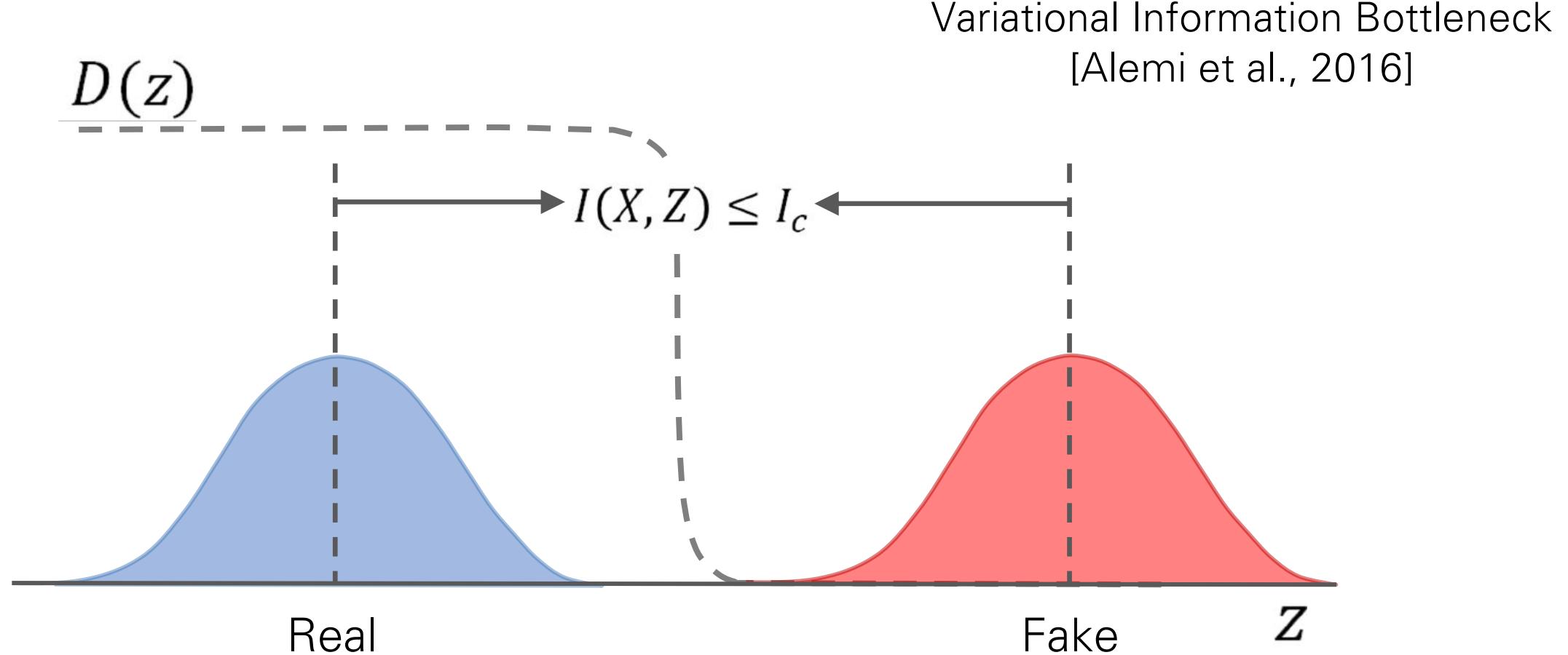
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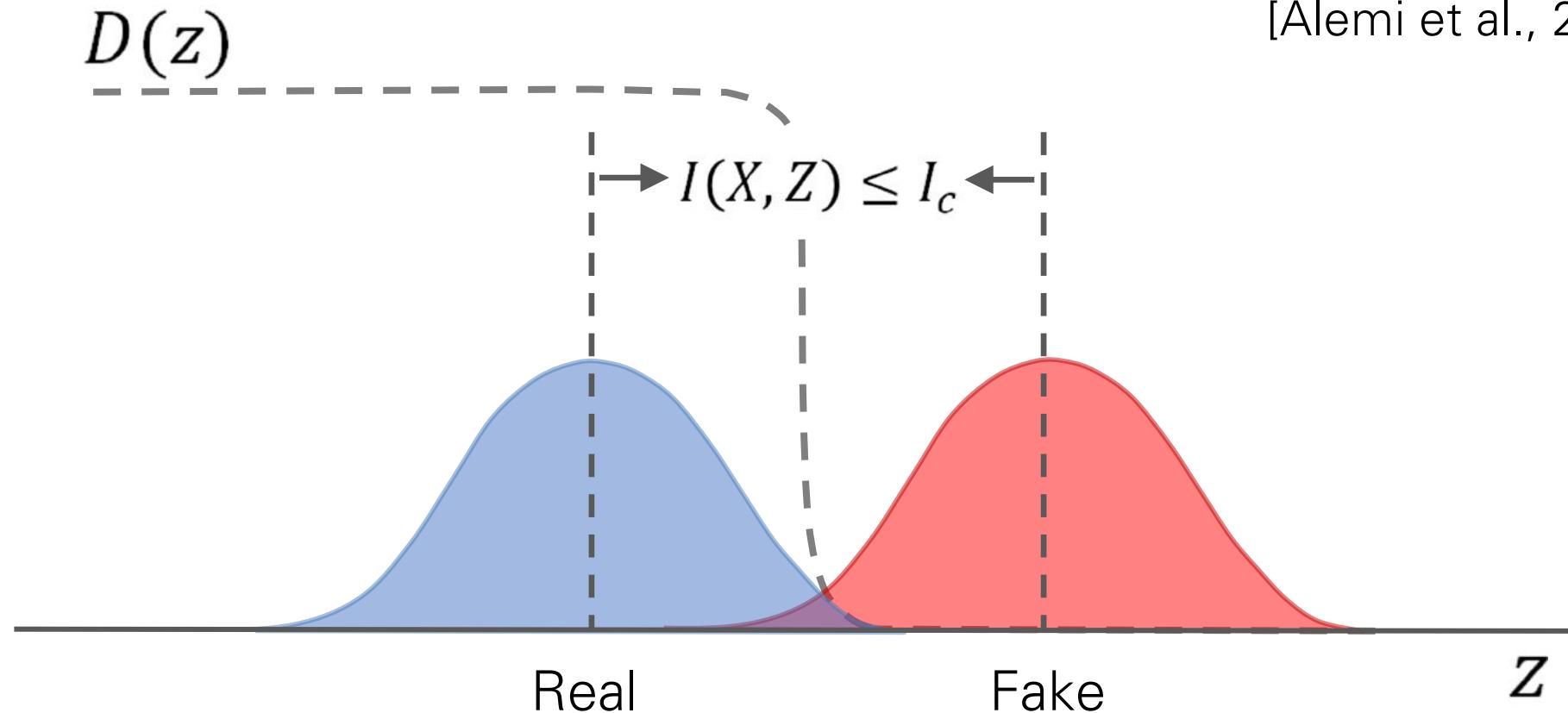
# Variational Information Bottleneck



# Variational Information Bottleneck

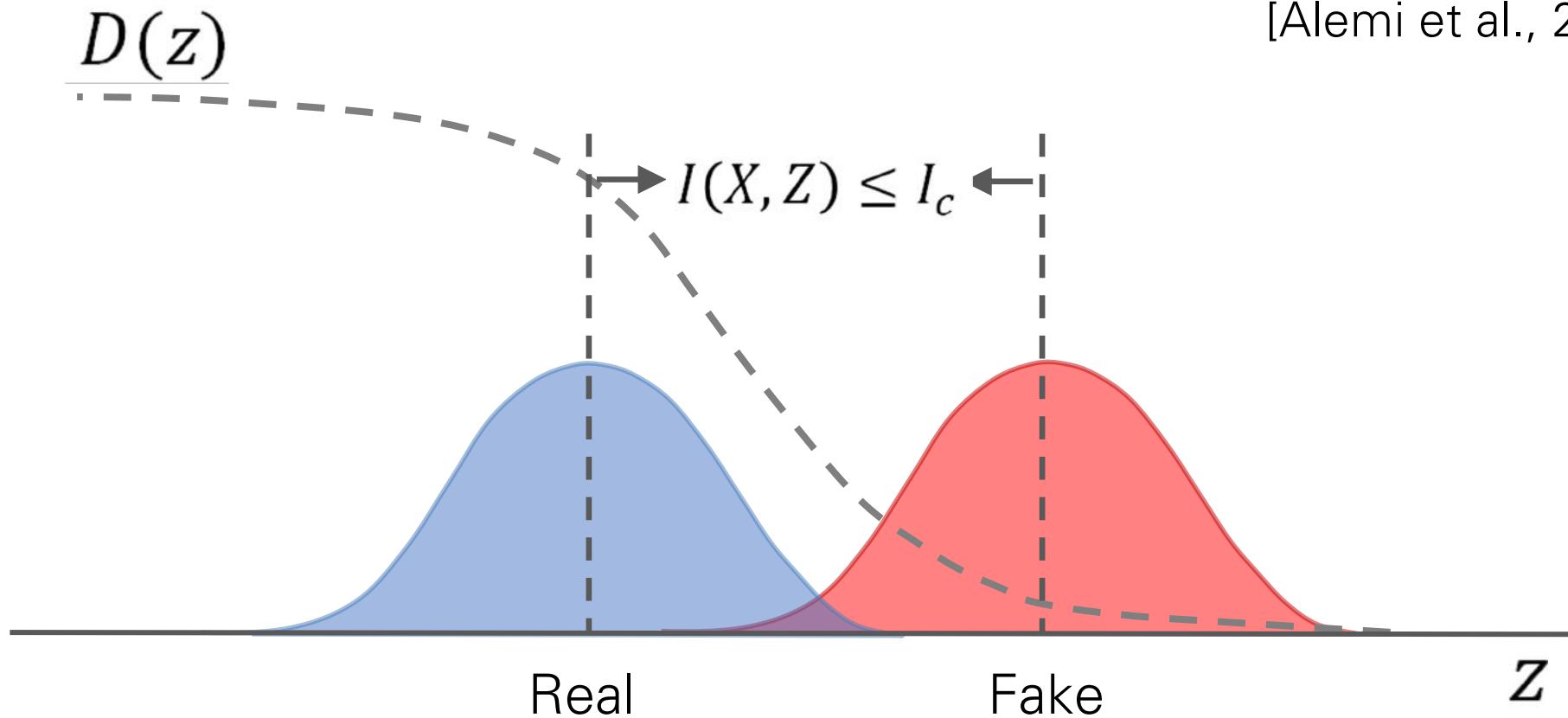


# Variational Information Bottleneck



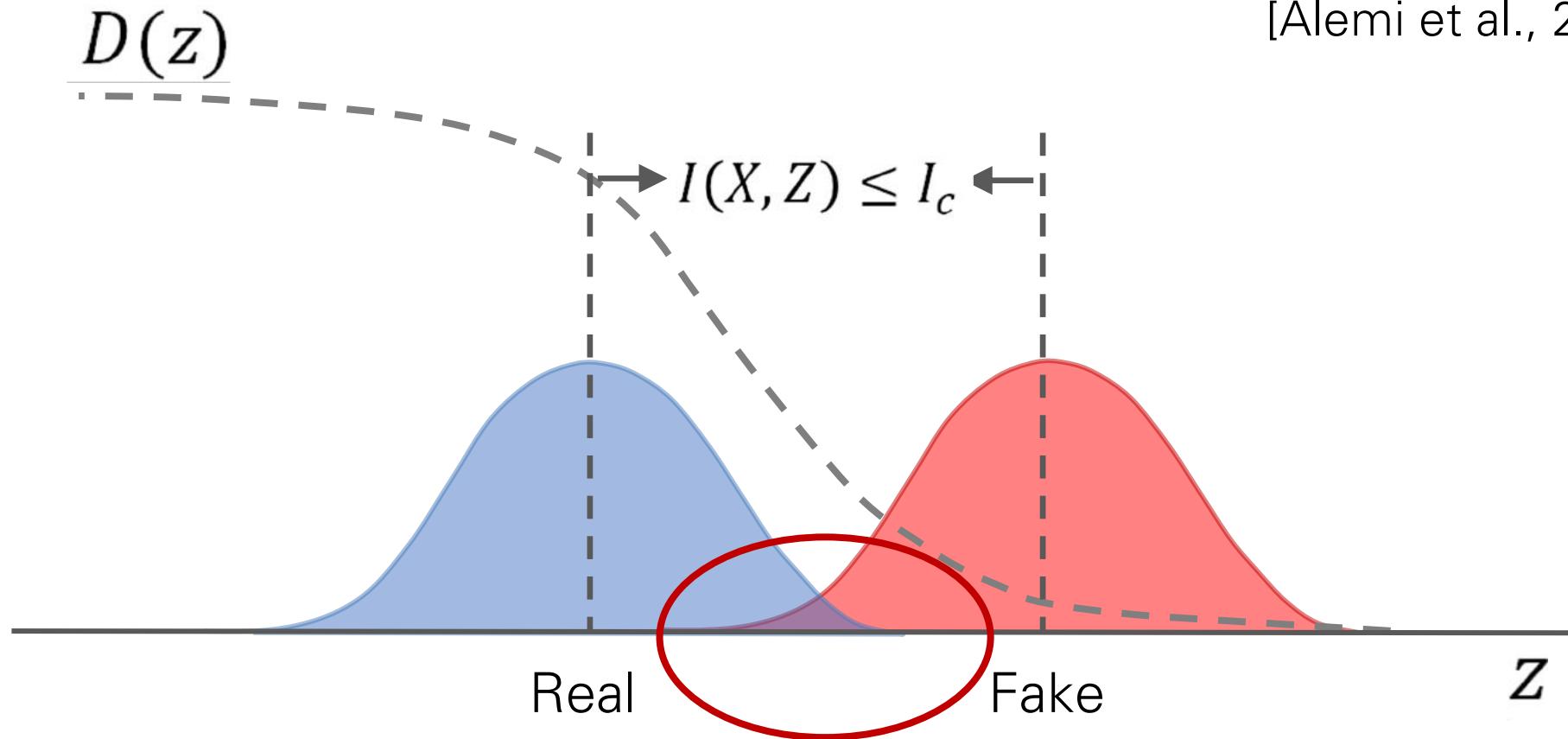
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Variational Information Bottleneck  
[Alemi et al., 2016]



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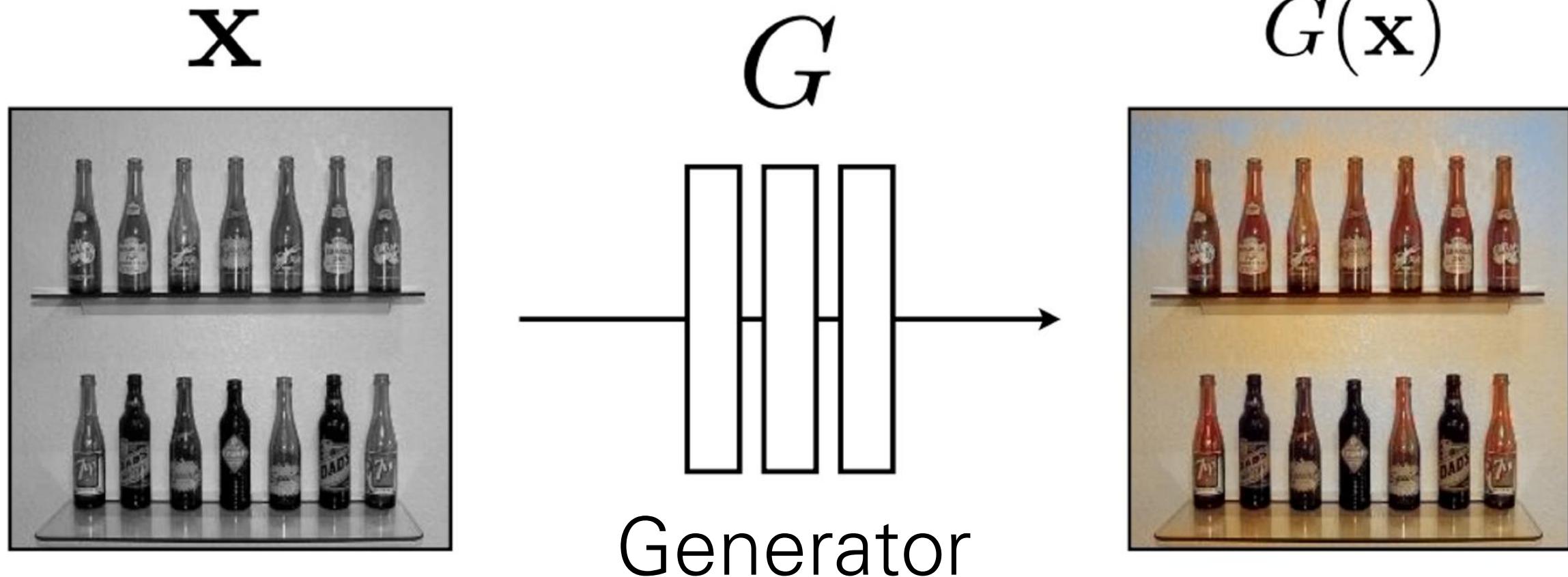
Variational Information Bottleneck  
[Alemi et al., 2016]



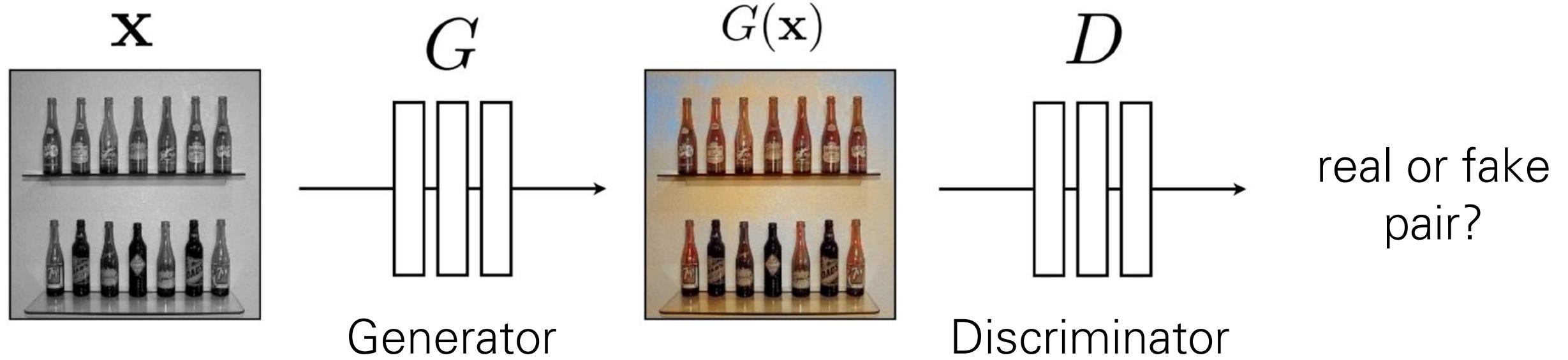
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- **Conditional GANs, Cycle-Consistent Adversarial Networks**
- GANs and Representations
- Applications

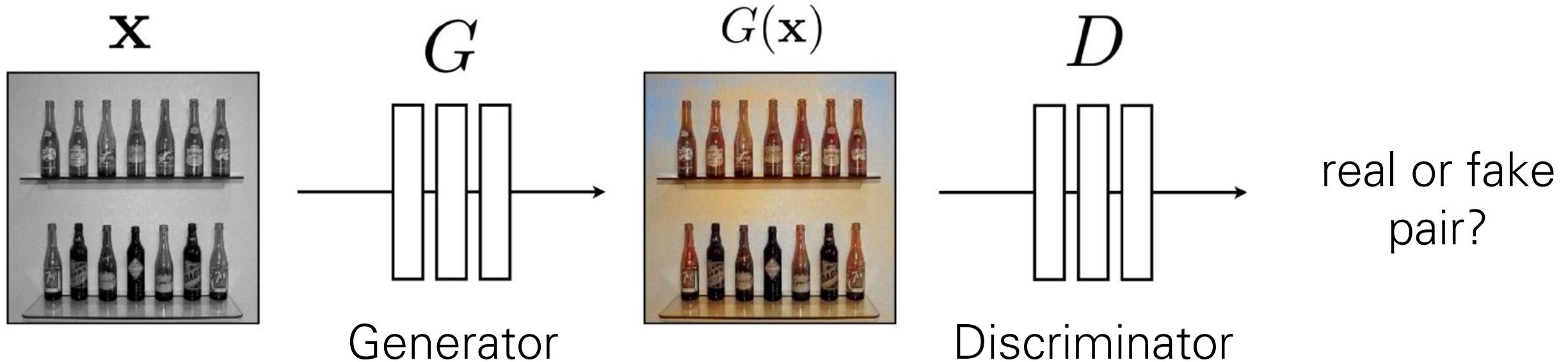
# Conditional GANs / pix2pix



# Conditional GANs / pix2pix



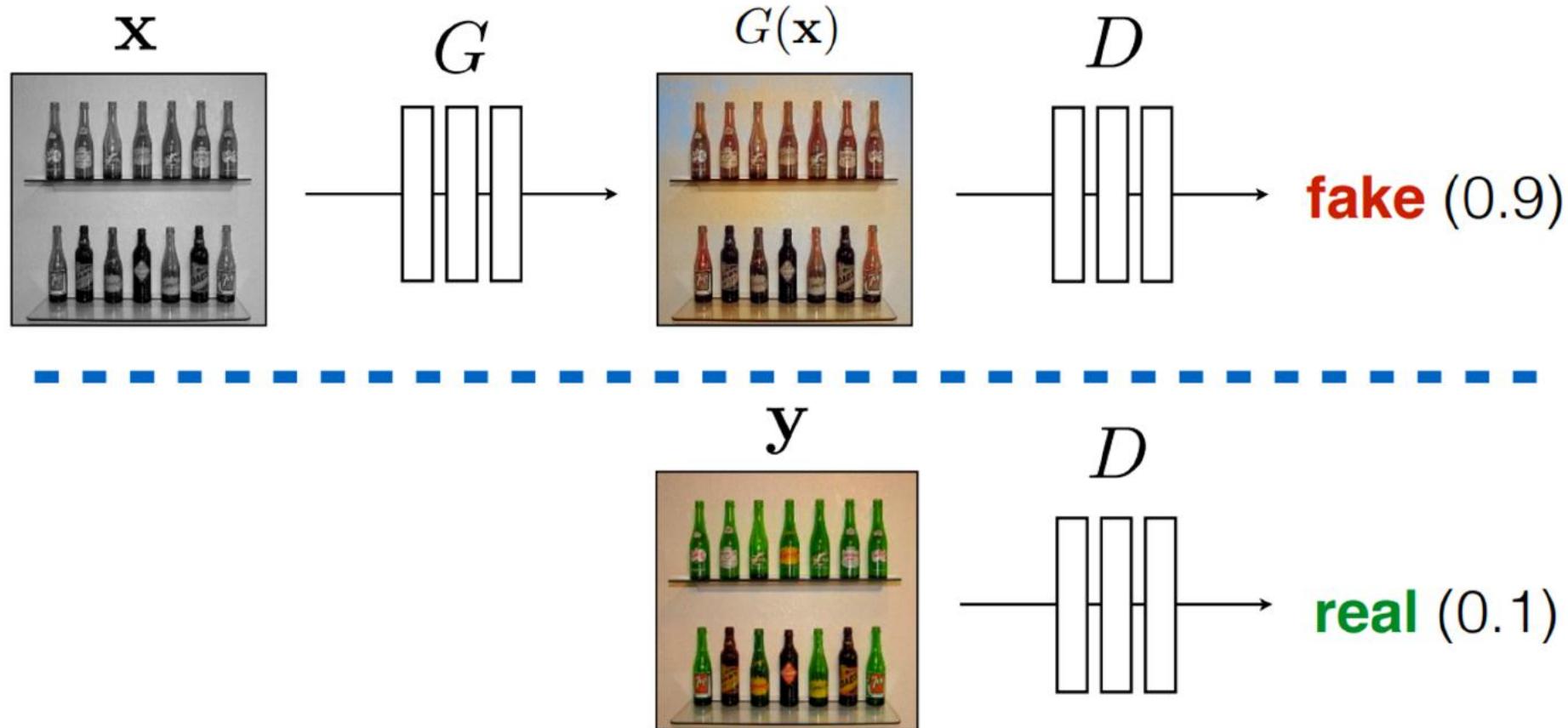
# Conditional GANs / pix2pix



**G** tries to synthesize fake images that fool **D**

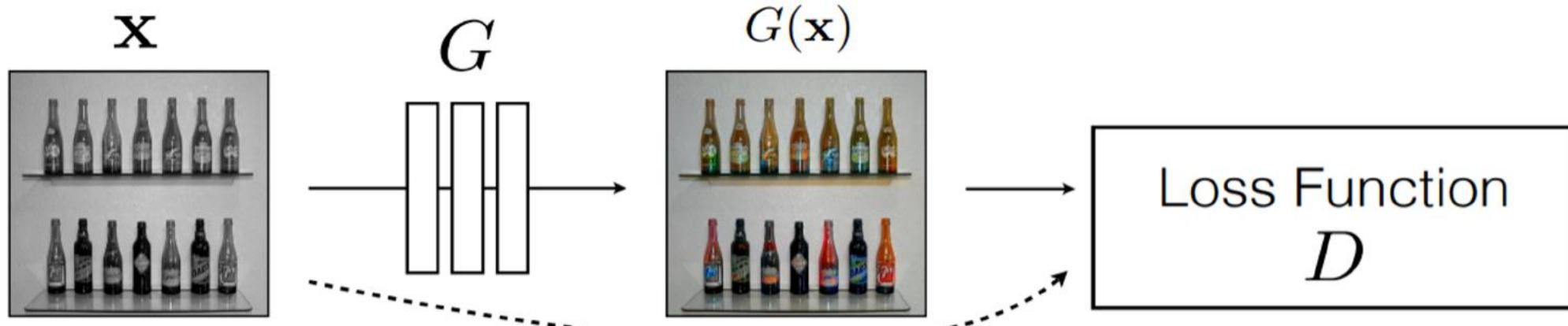
**D** tries to identify the fakes

# Conditional GANs / pix2pix



$$\arg \max_D \mathbb{E}_{\mathbf{x}, \mathbf{y}} [ \boxed{\log D(G(\mathbf{x}))} + \boxed{\log(1 - D(\mathbf{y}))} ]$$

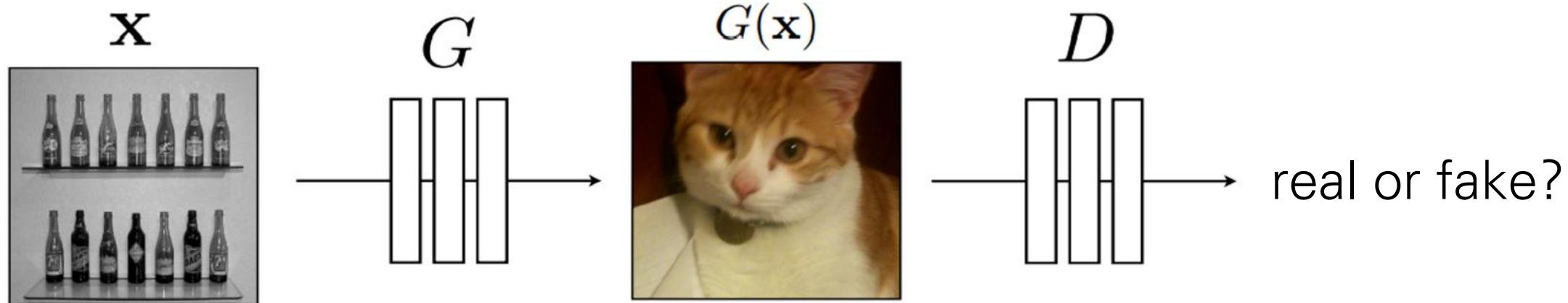
# Conditional GANs / pix2pix



$G$ 's perspective:  $D$  is a loss function.

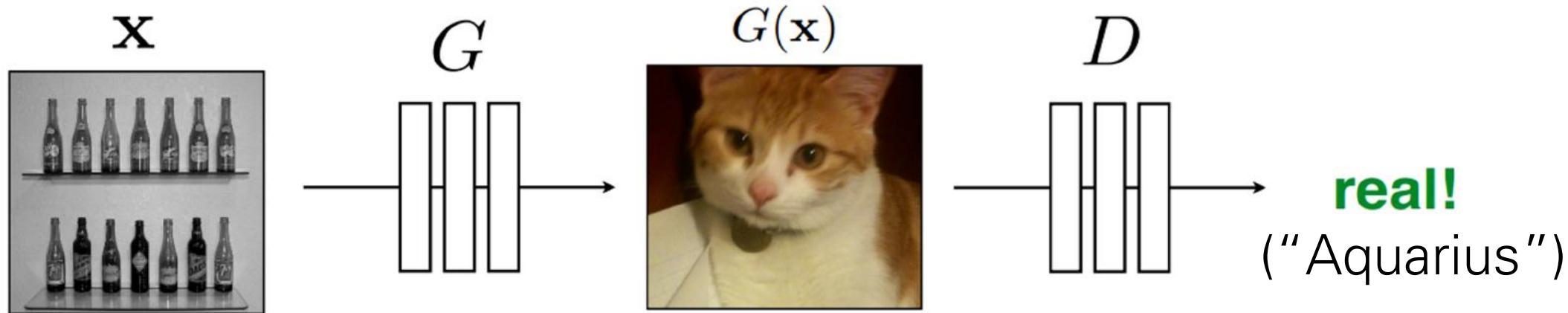
Rather than being hand-designed, it is learned.

# Conditional GANs / pix2pix



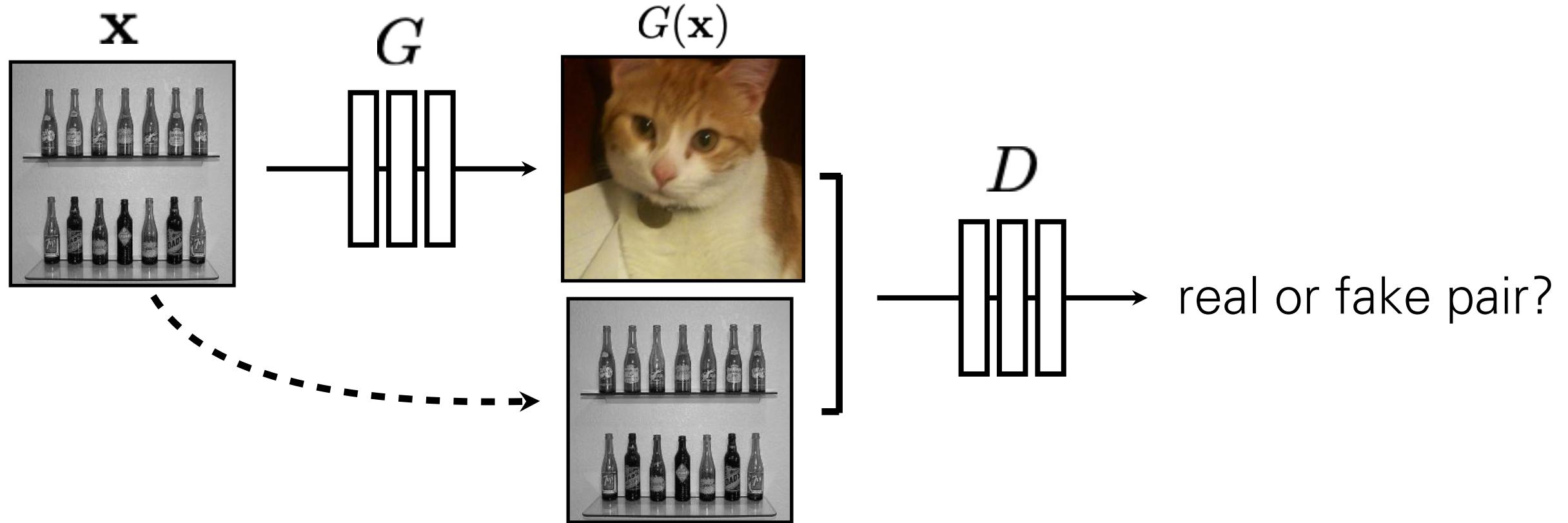
$$\arg \min_G \max_D \mathbb{E}_{\mathbf{x}, \mathbf{y}} [ \log D(G(\mathbf{x})) + \log(1 - D(\mathbf{y})) ]$$

# Conditional GANs / pix2pix



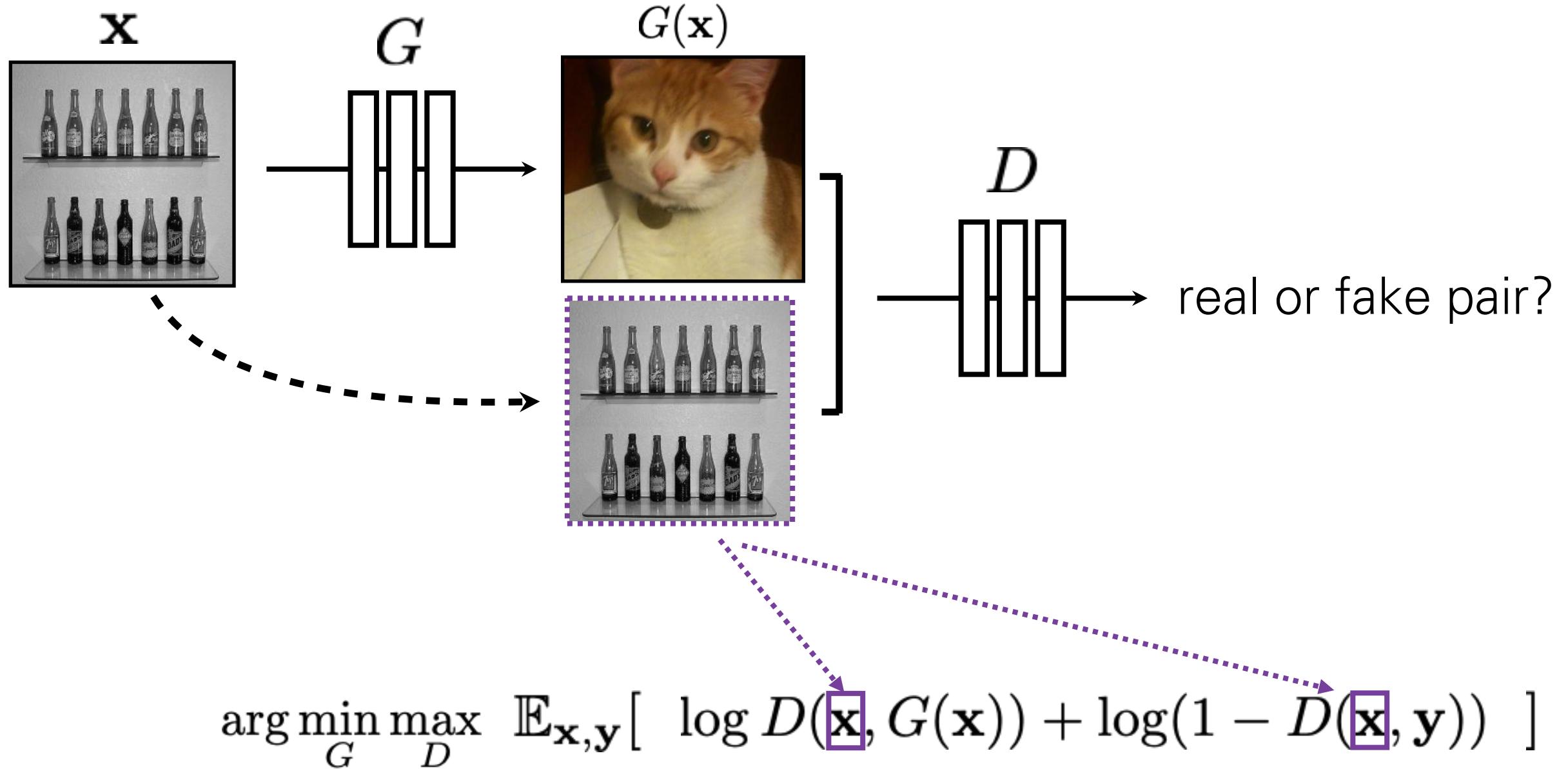
$$\arg \min_G \max_D \mathbb{E}_{\mathbf{x}, \mathbf{y}} [ \log D(G(\mathbf{x})) + \log(1 - D(\mathbf{y})) ]$$

# Conditional GANs / pix2pix

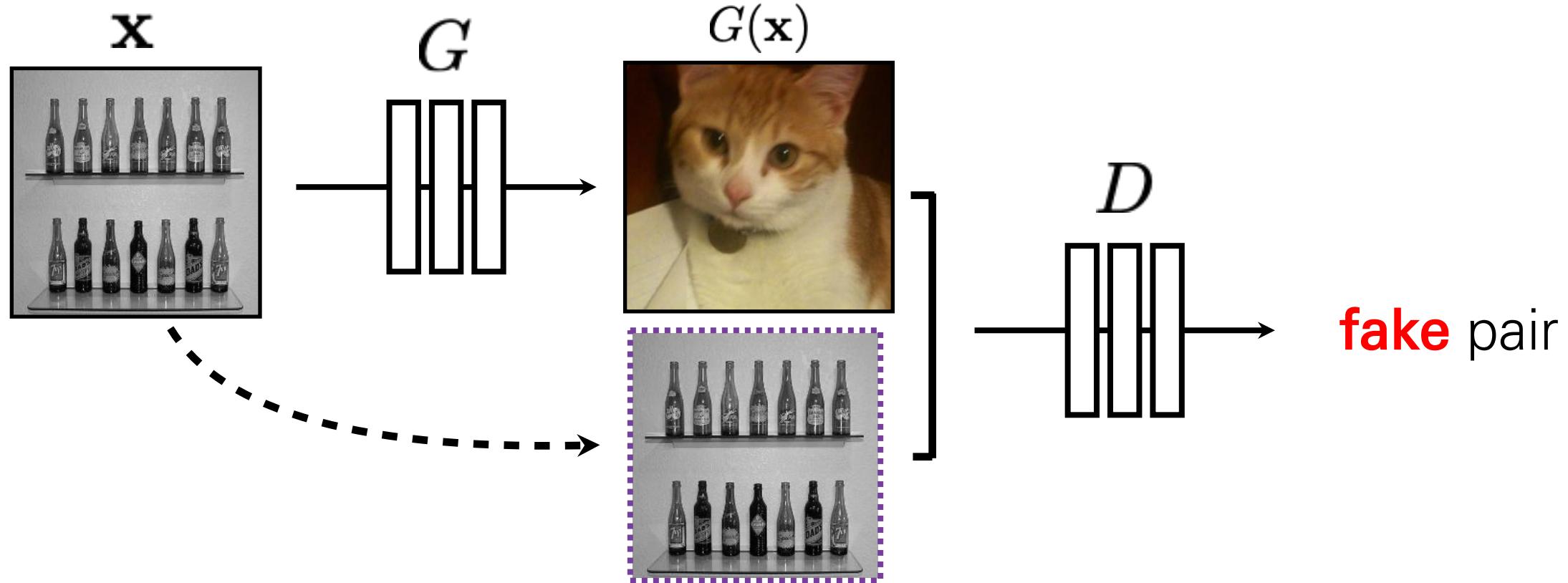


$$\arg \min_G \max_D \mathbb{E}_{\mathbf{x}, \mathbf{y}} [ \log D(G(\mathbf{x})) + \log(1 - D(\mathbf{y})) ]$$

# Conditional GANs / pix2pix

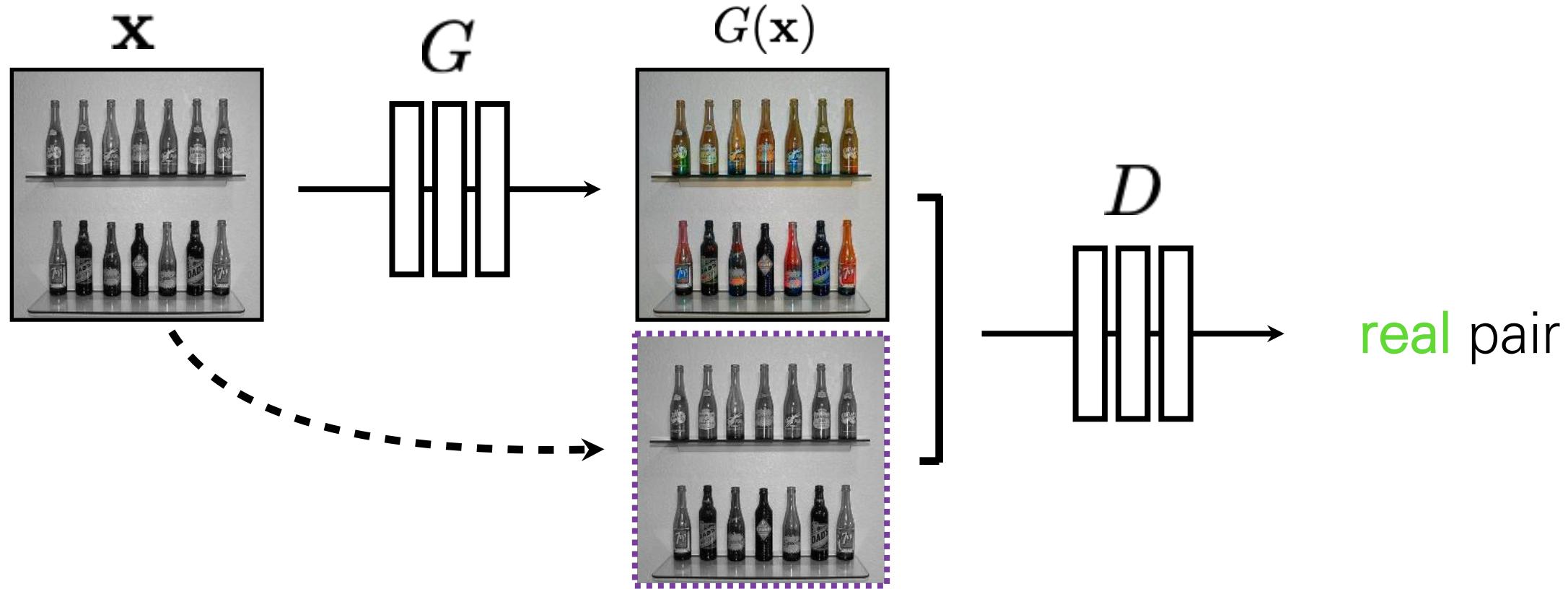


# Conditional GANs / pix2pix



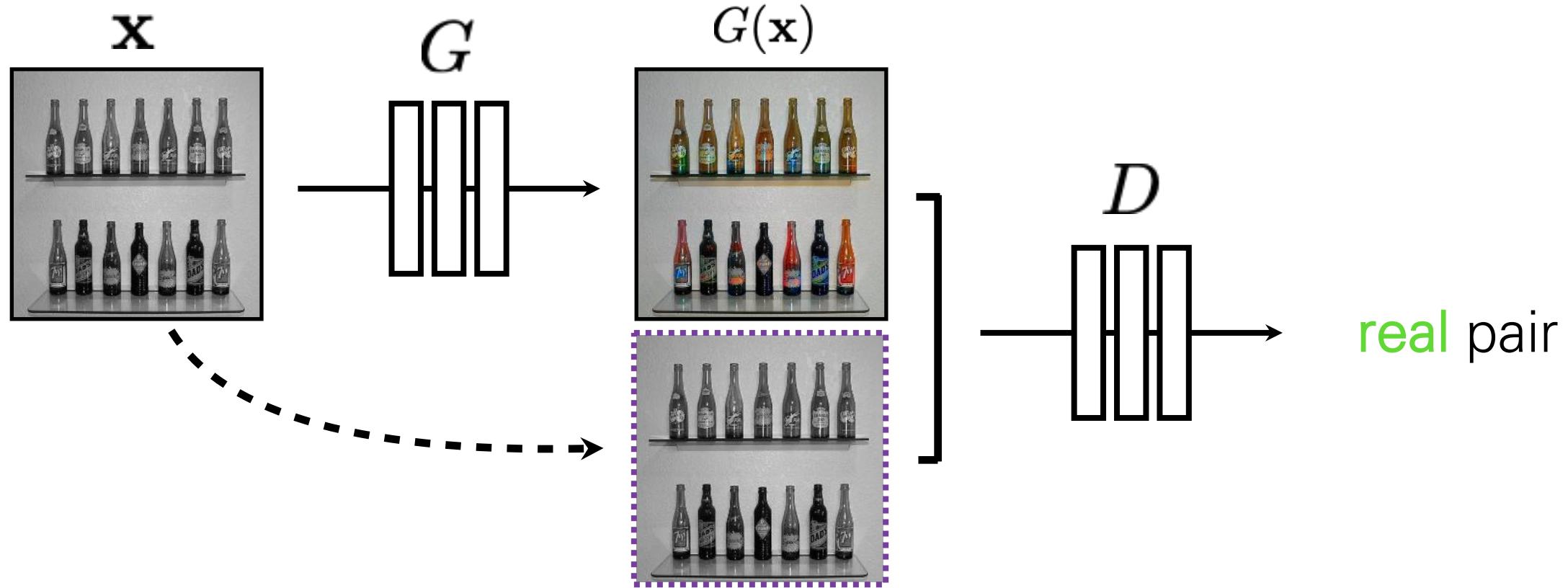
$$\arg \min_G \max_D \mathbb{E}_{\mathbf{x}, \mathbf{y}} [ \log D(\mathbf{x}, G(\mathbf{x})) + \log(1 - D(\mathbf{x}, \mathbf{y})) ]$$

# Conditional GANs / pix2pix



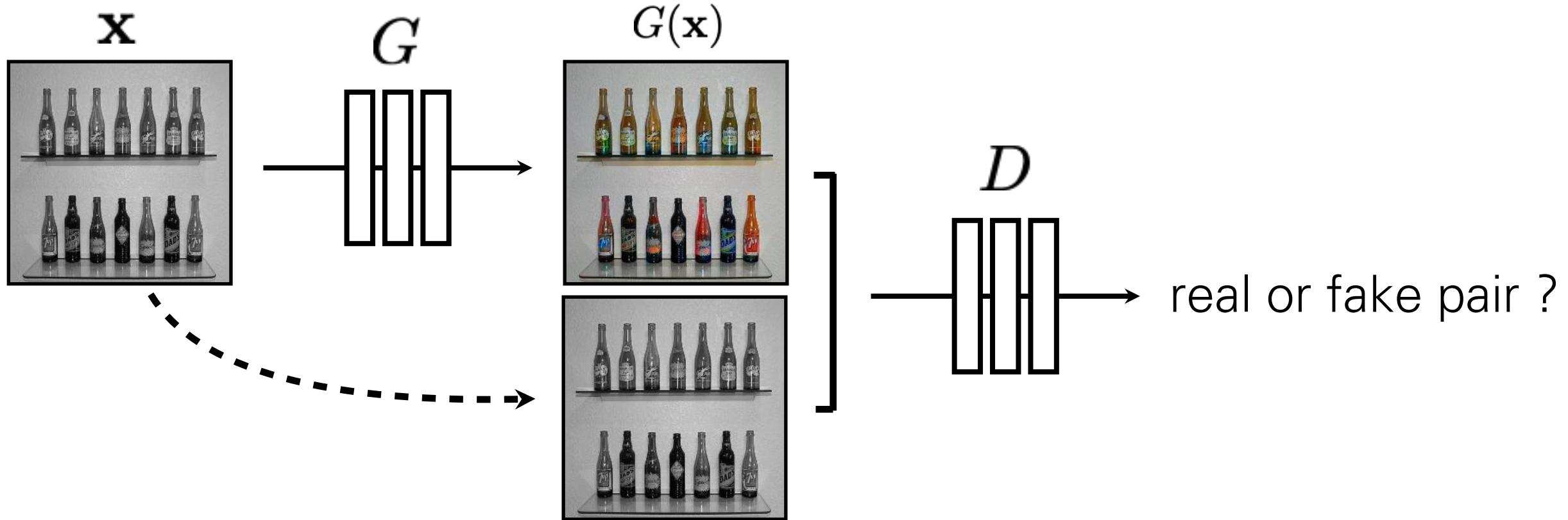
$$\arg \min_G \max_D \mathbb{E}_{\mathbf{x}, \mathbf{y}} [ \log D(\mathbf{x}, G(\mathbf{x})) + \log(1 - D(\mathbf{x}, \mathbf{y})) ]$$

# Conditional GANs / pix2pix



$$\arg \min_G \max_D \mathbb{E}_{\mathbf{x}, \mathbf{y}} [ \log D(\mathbf{x}, G(\mathbf{x})) + \log(1 - D(\mathbf{x}, \mathbf{y})) ]$$

# Conditional GANs / pix2pix



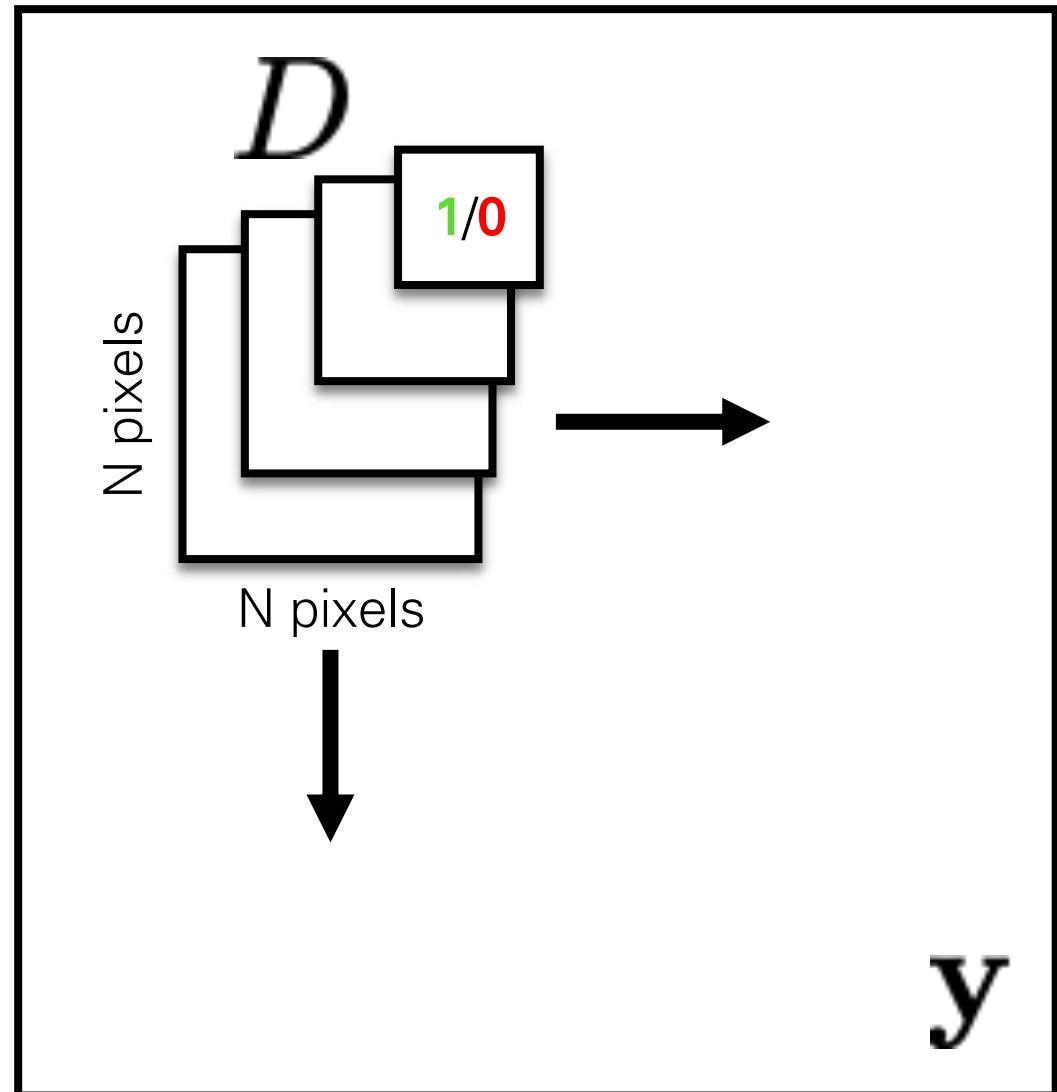
$$\arg \min_G \max_D \mathbb{E}_{\mathbf{x}, \mathbf{y}} [ \log D(\mathbf{x}, G(\mathbf{x})) + \log(1 - D(\mathbf{x}, \mathbf{y})) ]$$

# Conditional GANs / pix2pix

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

# Conditional GANs / pix2pix

Shrinking the capacity:  
Patch Discriminator

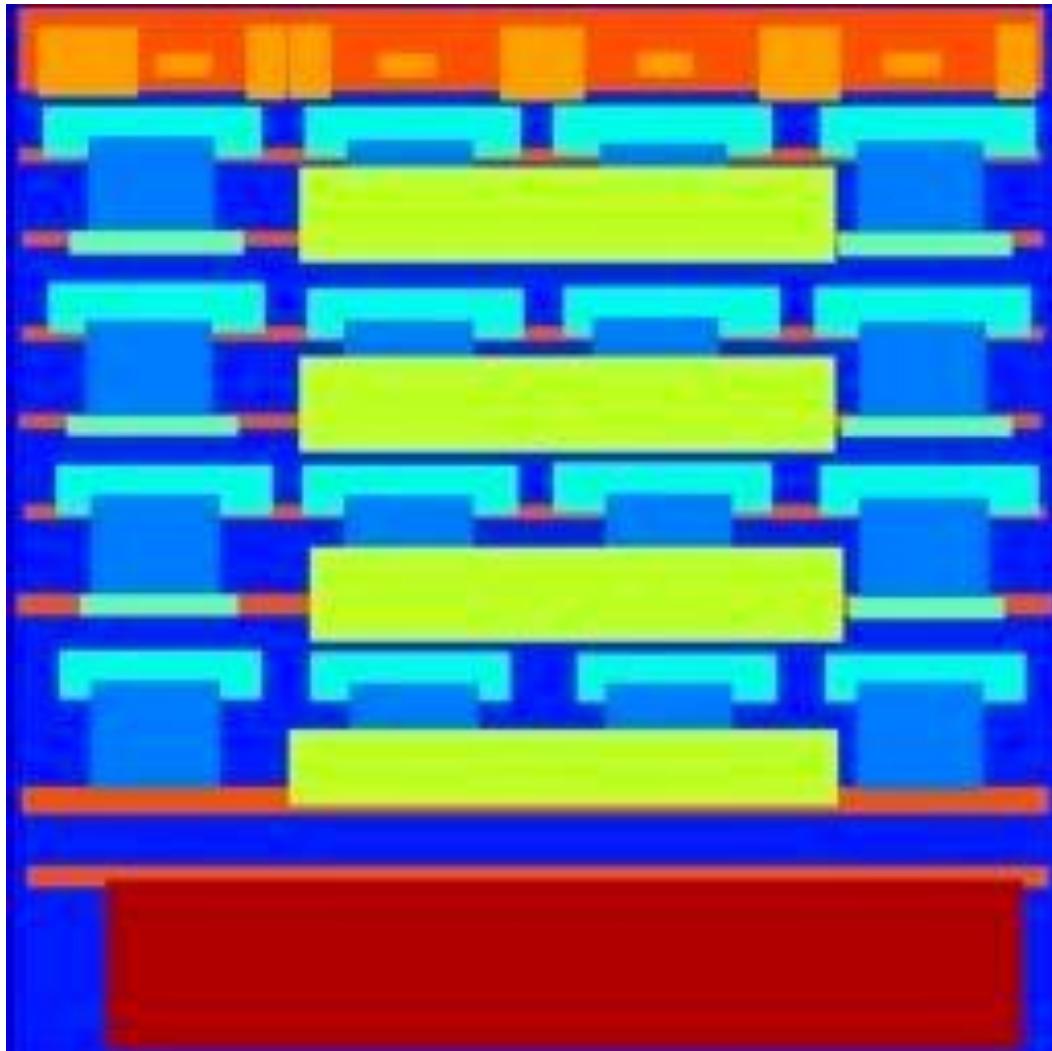


Rather than penalizing if output image looks fake, penalize if each overlapping patch in output looks fake

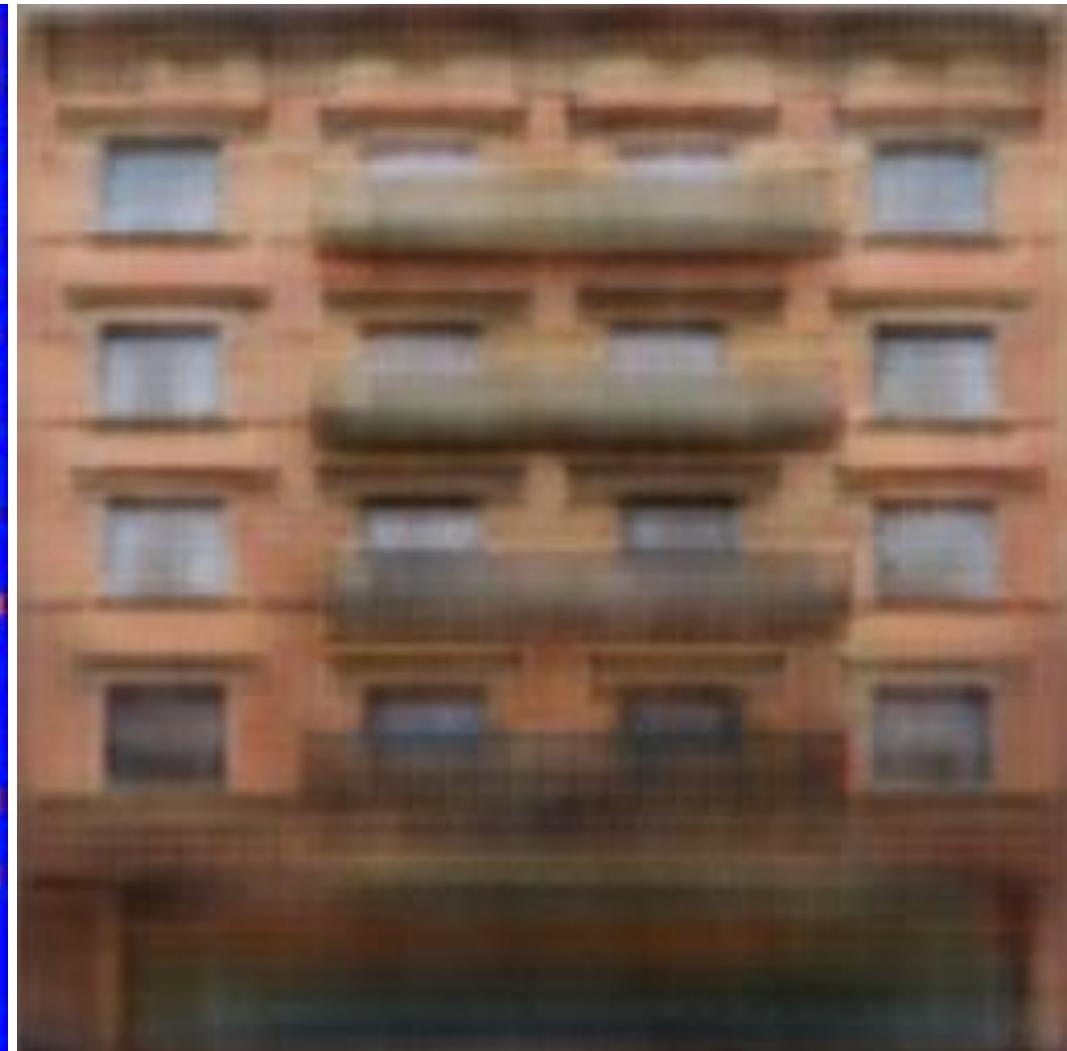
[Li & Wand 2016]  
[Shrivastava et al. 2017]  
[Isola et al. 2017]<sub>200</sub>

# Conditional GANs / pix2pix

Input

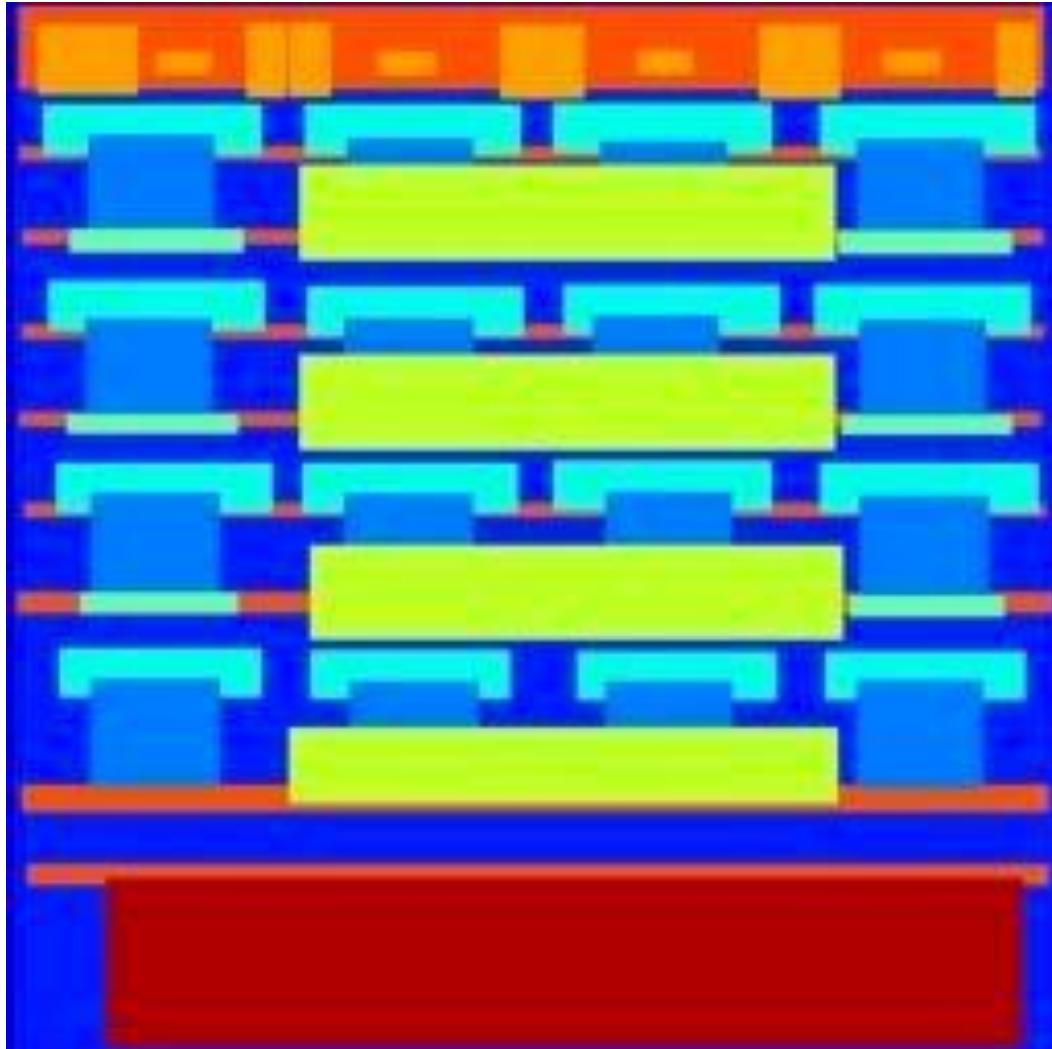


1x1 Discriminator



# Conditional GANs / pix2pix

Input

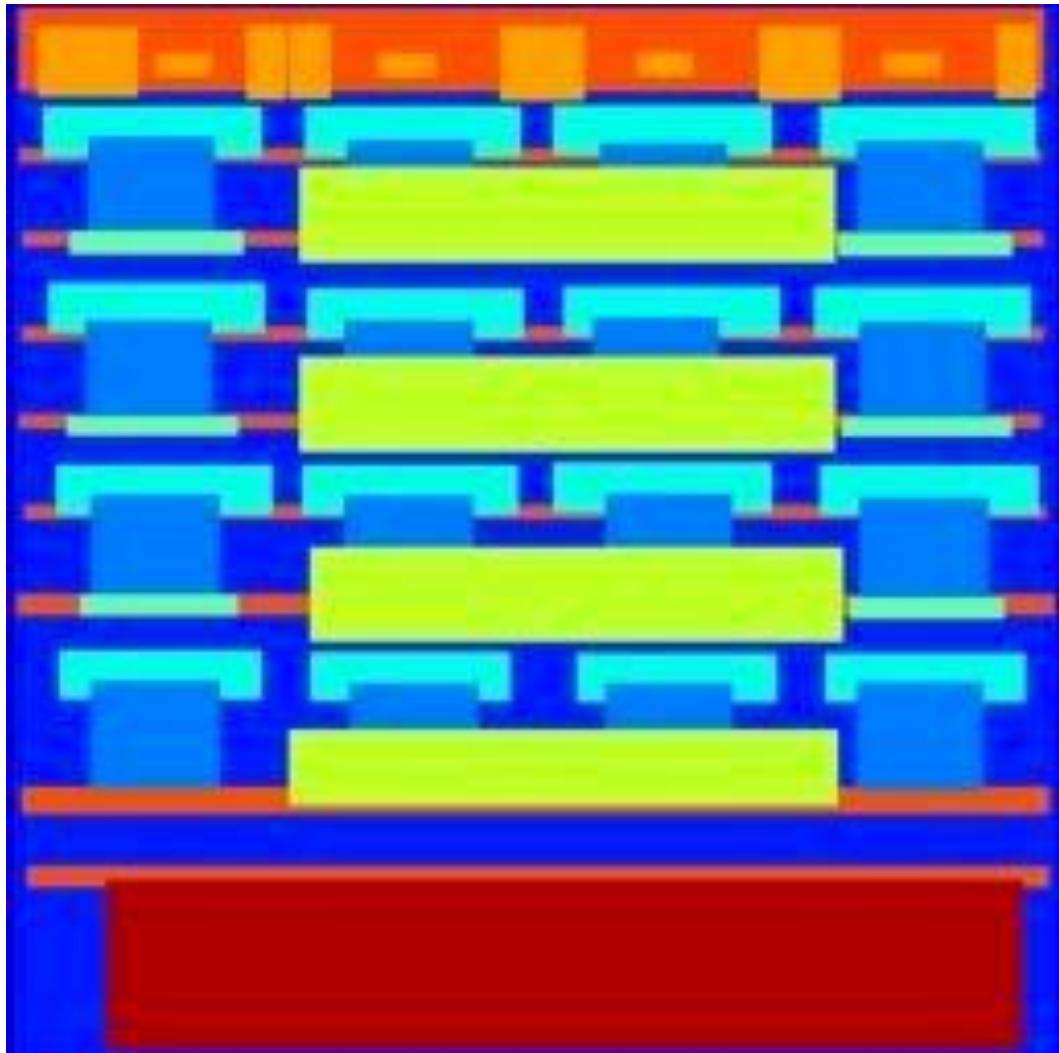


16x16 Discriminator



# Conditional GANs / pix2pix

Input

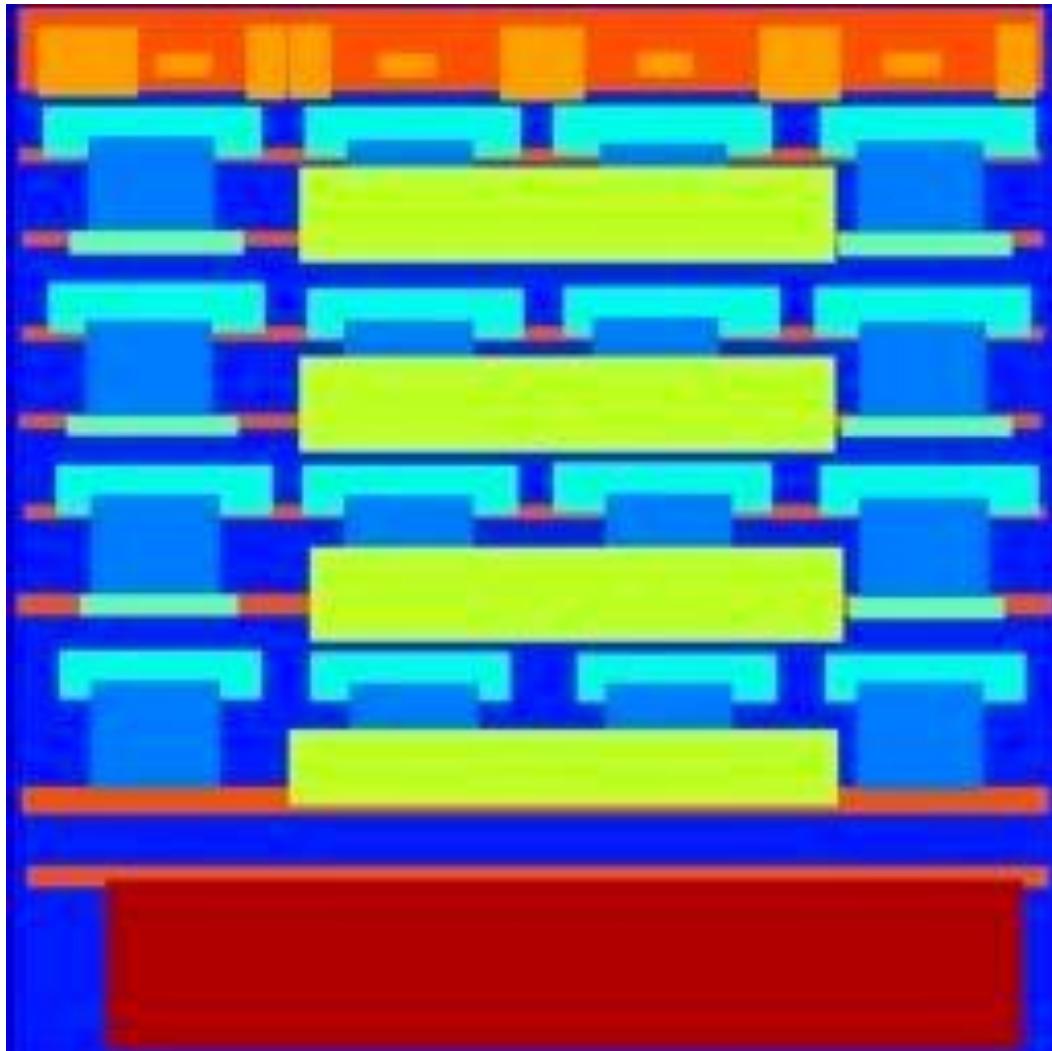


70x70 Discriminator



# Conditional GANs / pix2pix

Input

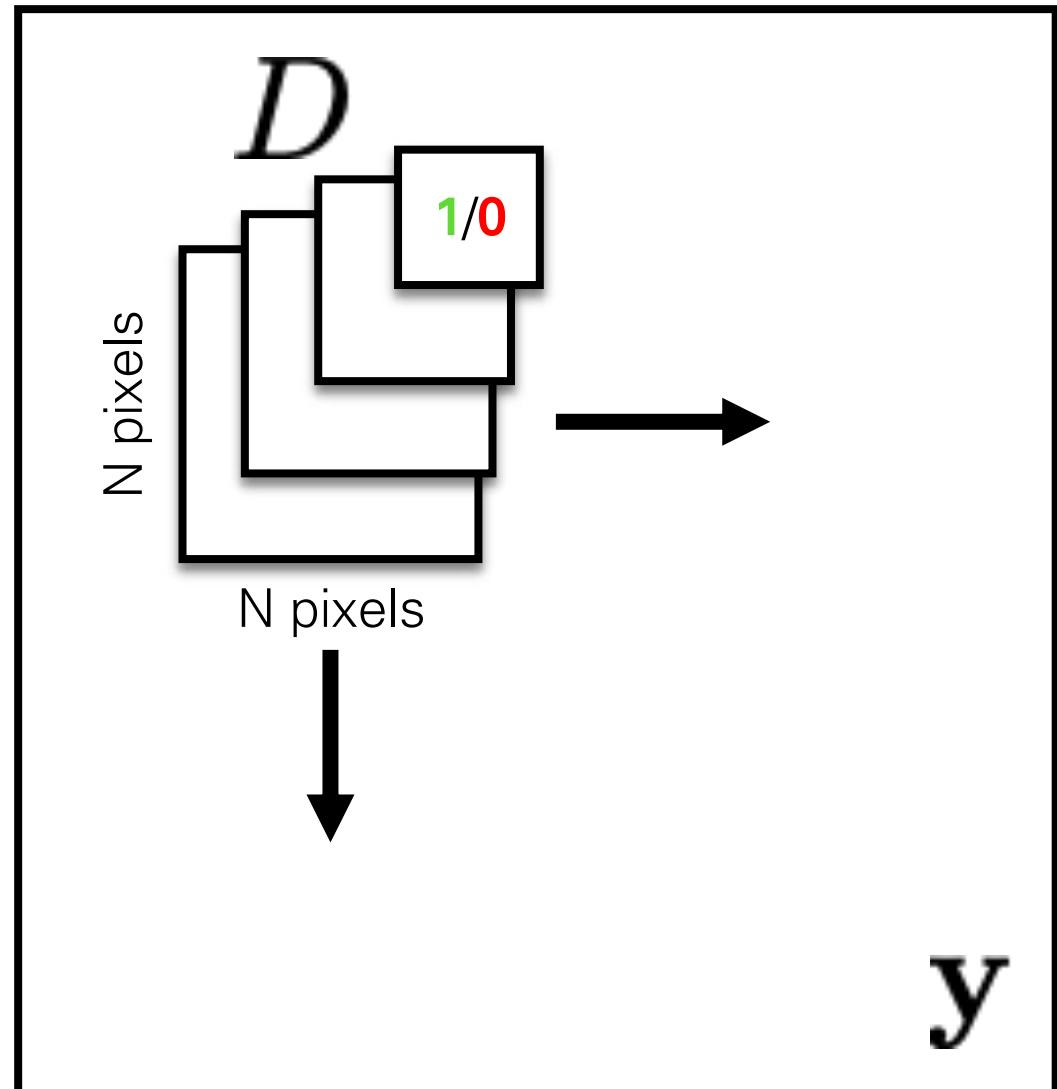


16x16 Discriminator



# Conditional GANs / pix2pix

Shrinking the capacity:  
Patch Discriminator

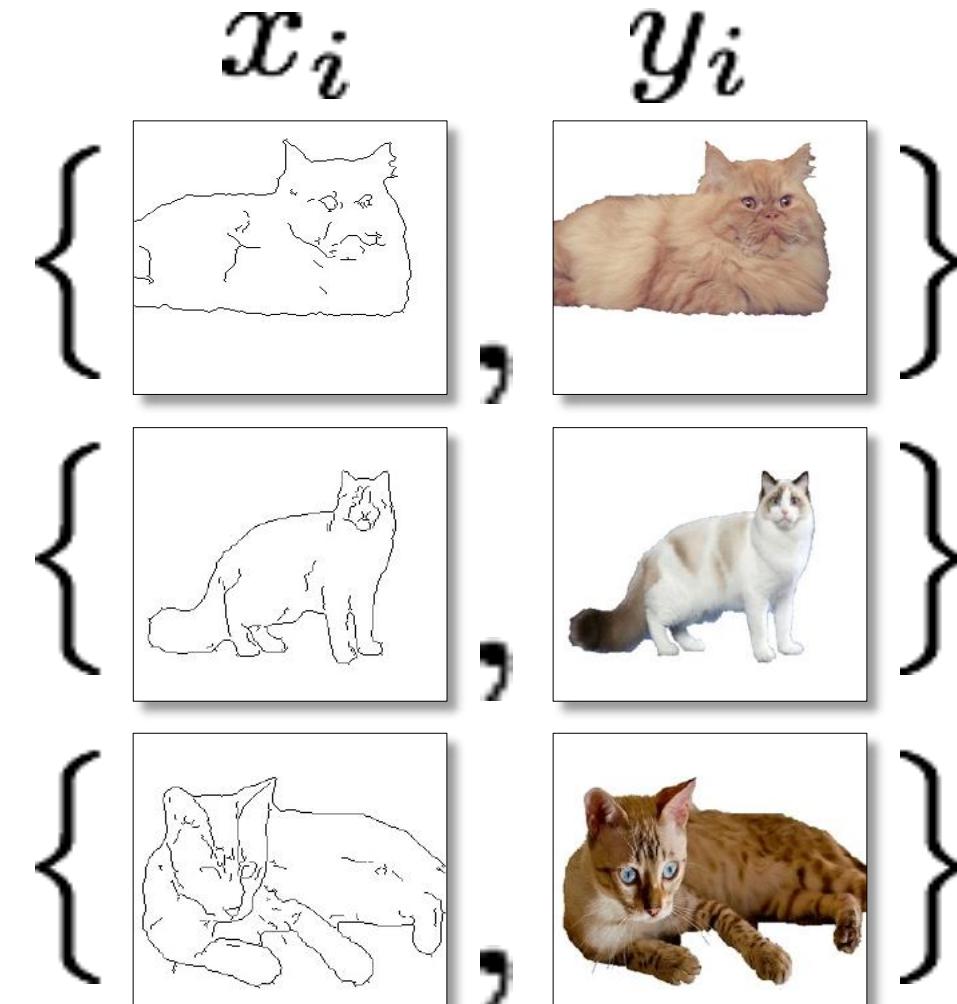


Rather than penalizing if output image looks fake, penalize if each overlapping patch in output looks fake

- Faster, fewer parameters
- More supervised observations
- Applies to arbitrarily large images

[Li & Wand 2016]  
[Shrivastava et al. 2017]  
[Isola et al. 2017] 205

# Conditional GANs / pix2pix



# Conditional GANs / pix2pix

BW → Color

Input



Output



Input



Output



Input

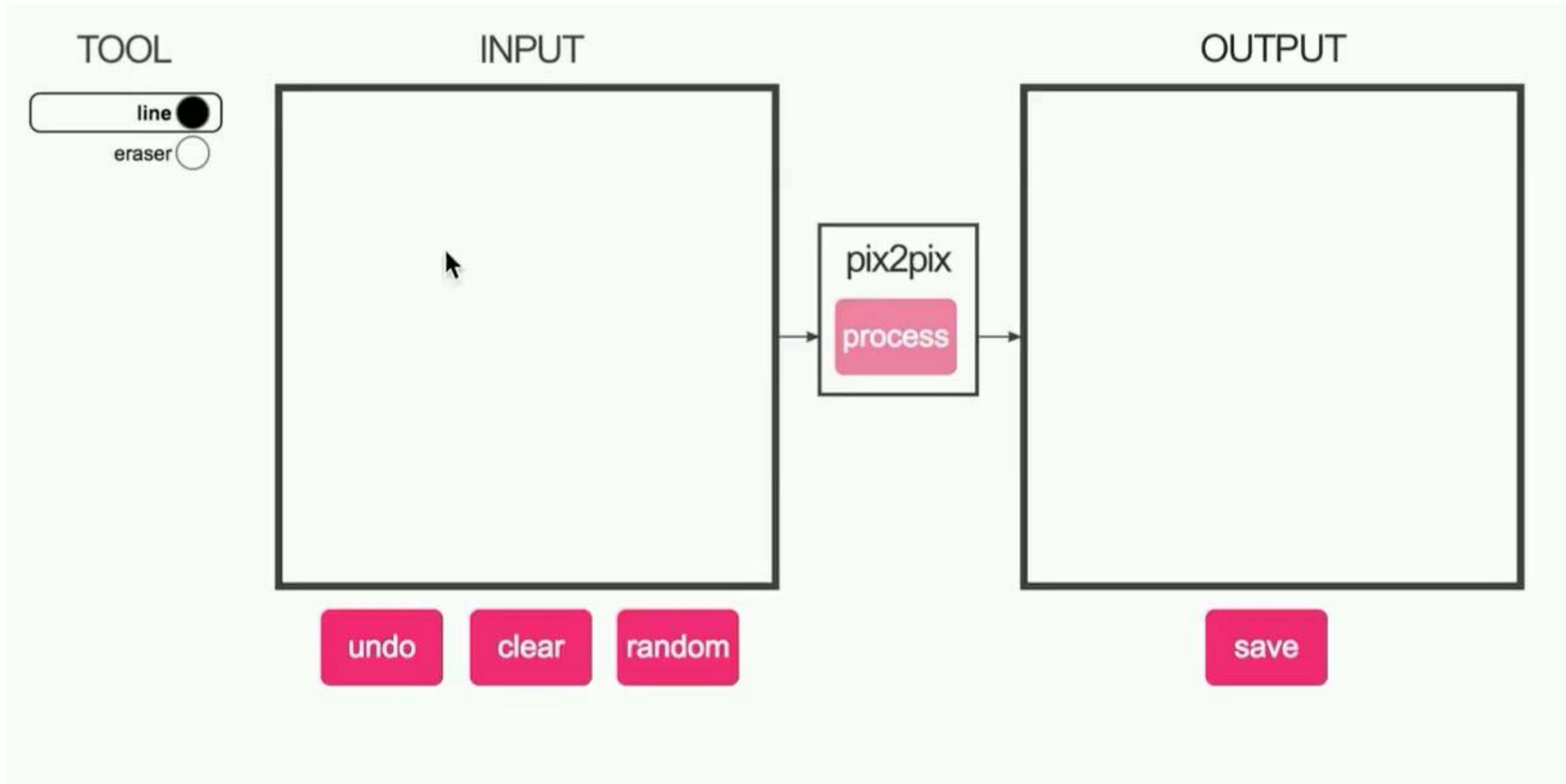


Output

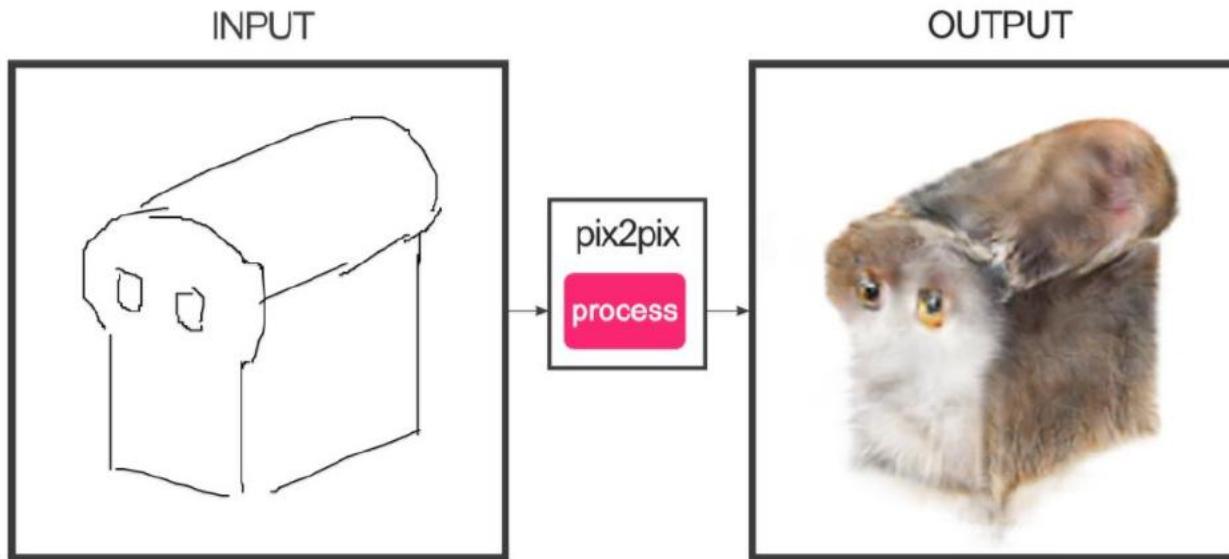


Data from [Russakovsky et al. 2015]

# Conditional GANs / pix2pix #edges2cats [Chris Hesse]



# Conditional GANs / pix2pix



Ivy Tasi @ivymyt



Vitaly Vidmirov @vvid

# Conditional GANs / pix2pix

BW → Color

Input



Output



Input



Output



Input



Output



# Conditional GANs / pix2pix

Structured Prediction

Input  
 $\mathbf{x}$



Output  
 $\hat{\mathbf{y}}$

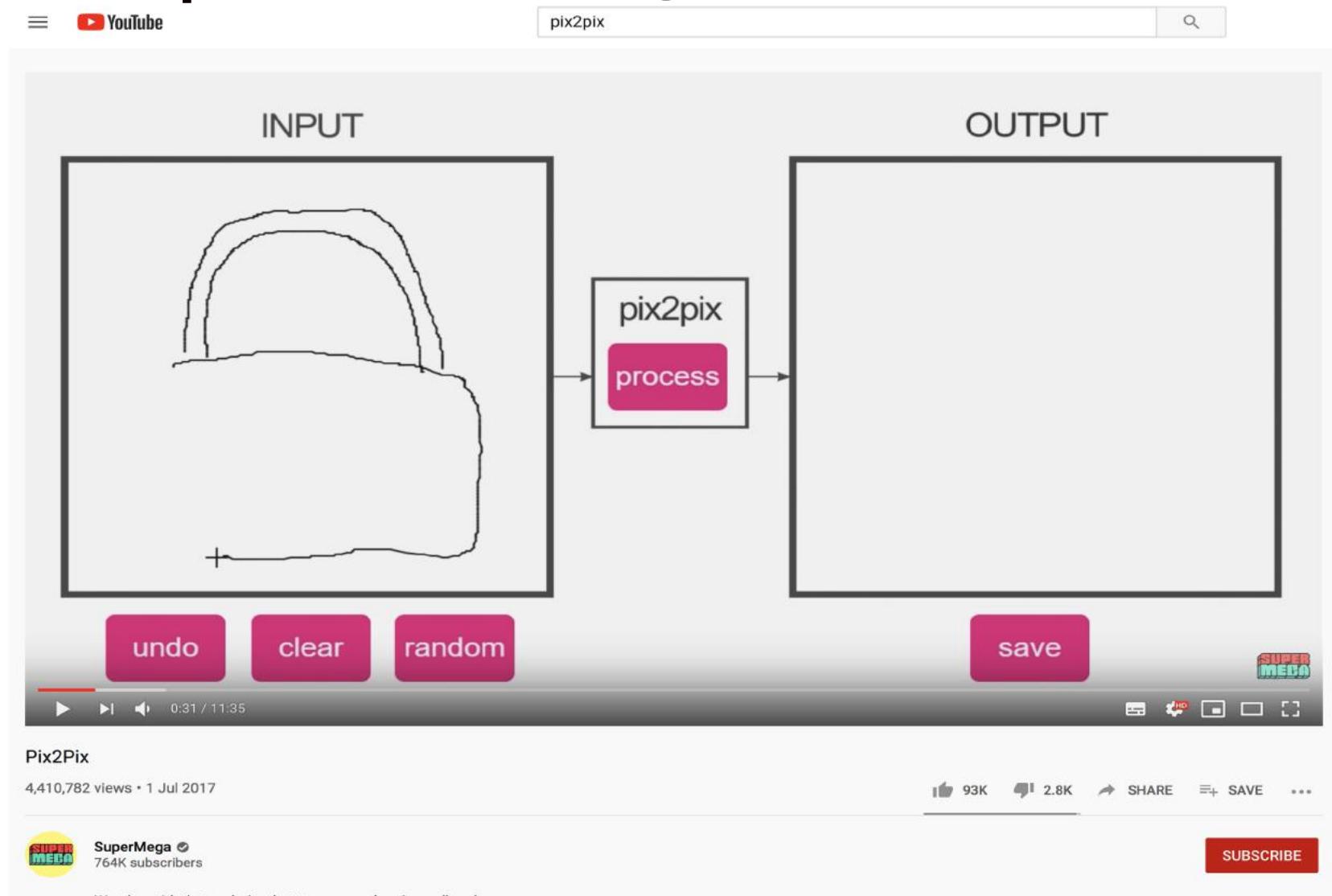


Target  
 $\mathbf{y}$



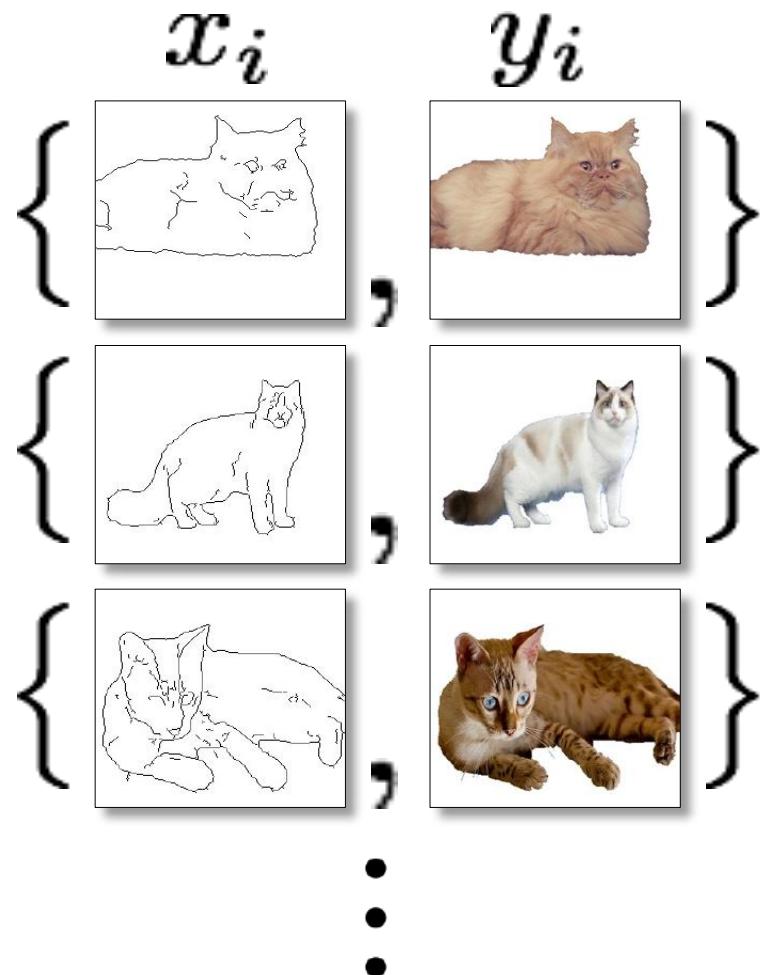
$$L(\hat{\mathbf{y}}, \mathbf{y}) = \|\hat{\mathbf{y}} - \mathbf{y}\|_2$$

# pix2pix impact among artists

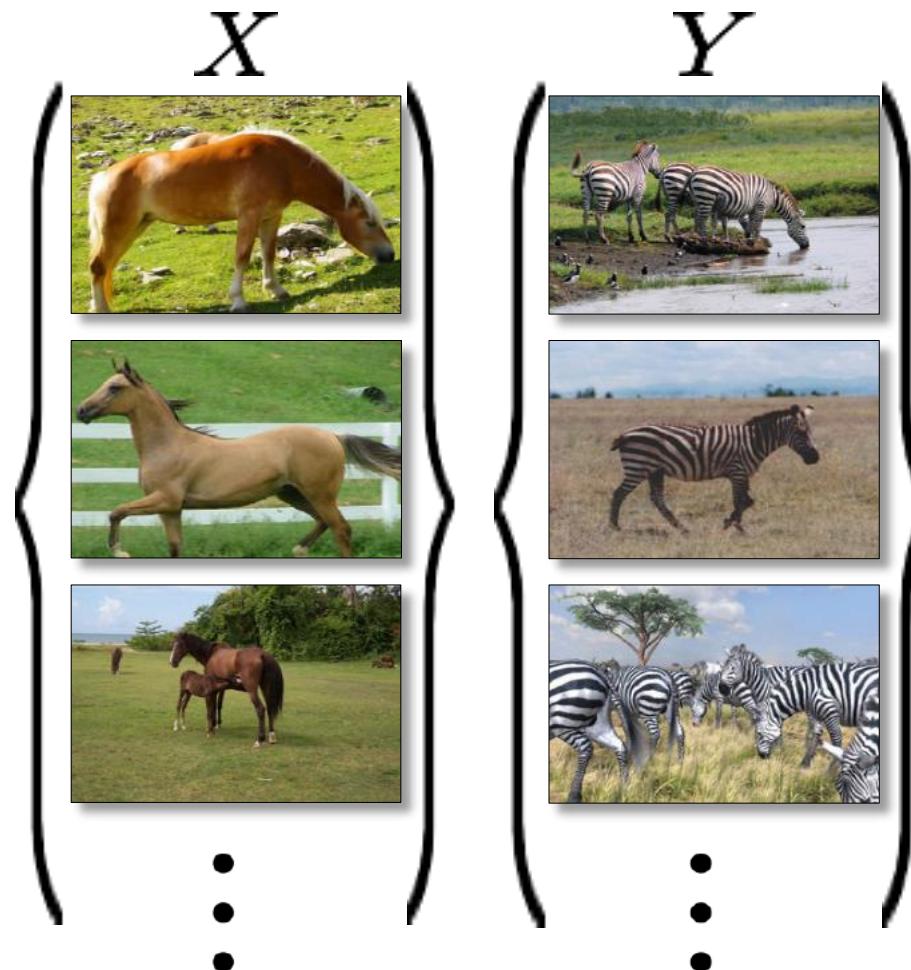


# Cycle-Consistent Adversarial Networks

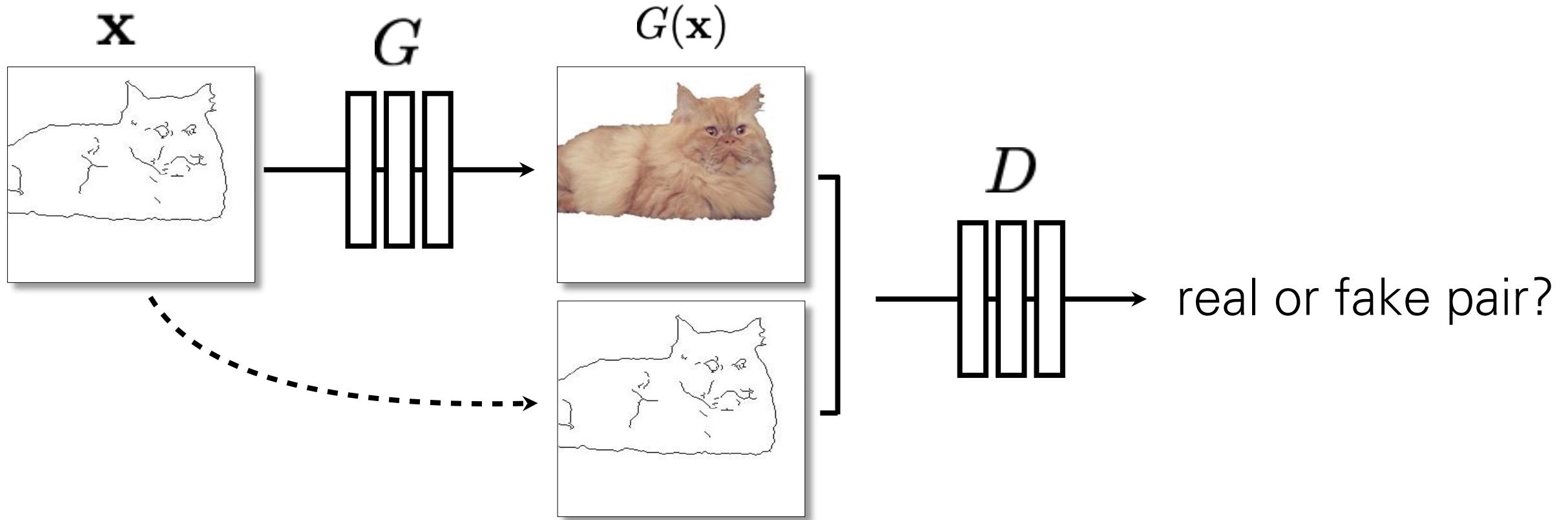
Paired data



Unpaired data

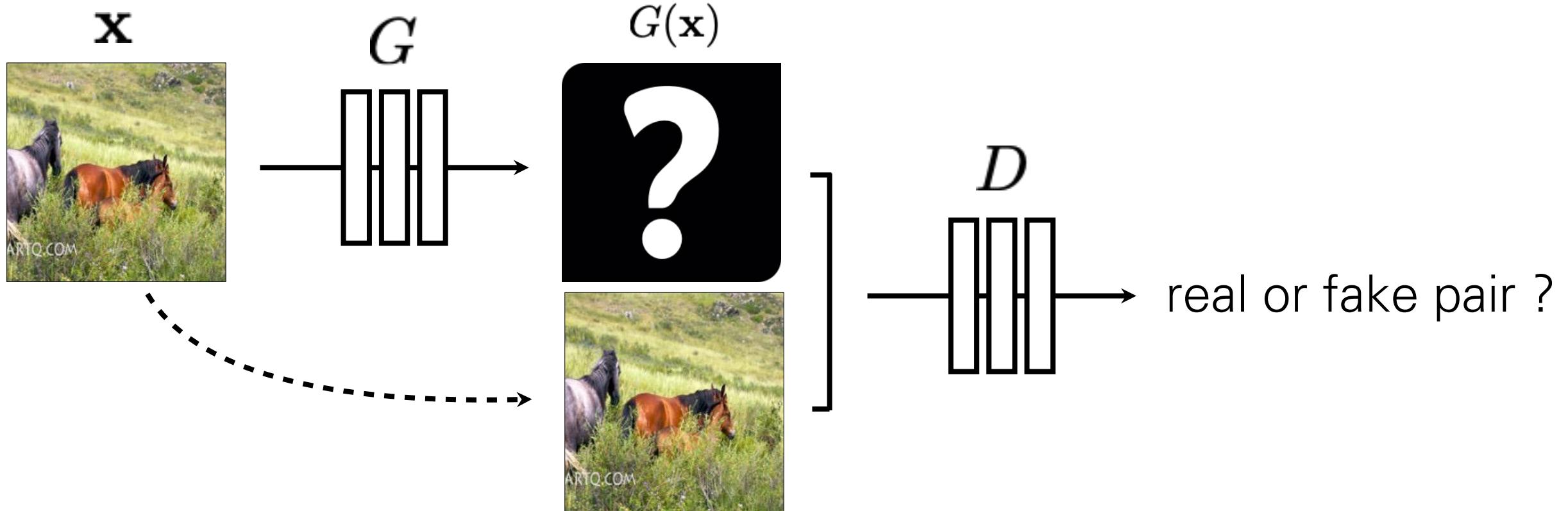


# Cycle-Consistent Adversarial Networks



$$\arg \min_G \max_D \mathbb{E}_{\mathbf{x}, \mathbf{y}} [ \log D(\mathbf{x}, G(\mathbf{x})) + \log(1 - D(\mathbf{x}, \mathbf{y})) ]$$

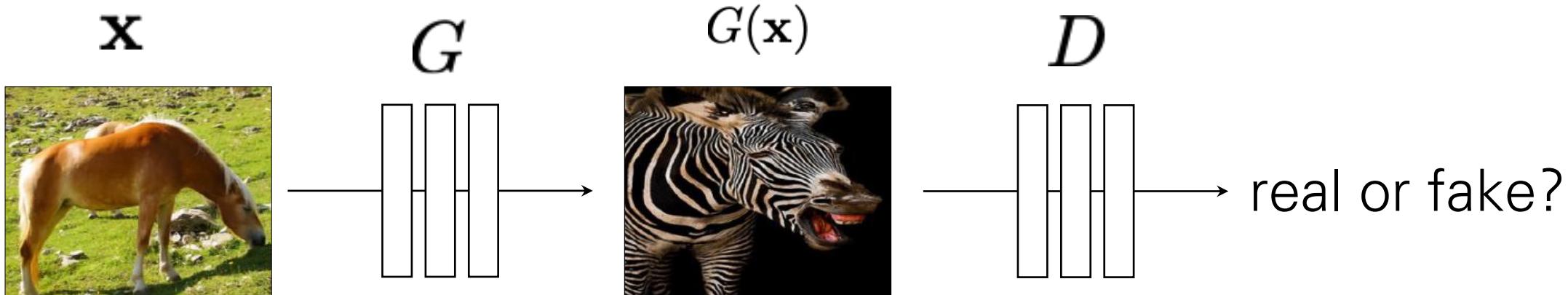
# Cycle-Consistent Adversarial Networks



$$\arg \min_G \max_D \mathbb{E}_{\mathbf{x}, \mathbf{y}} [ \log D(\mathbf{x}, G(\mathbf{x})) + \log(1 - D(\mathbf{x}, \mathbf{y})) ]$$

No input-output pairs!

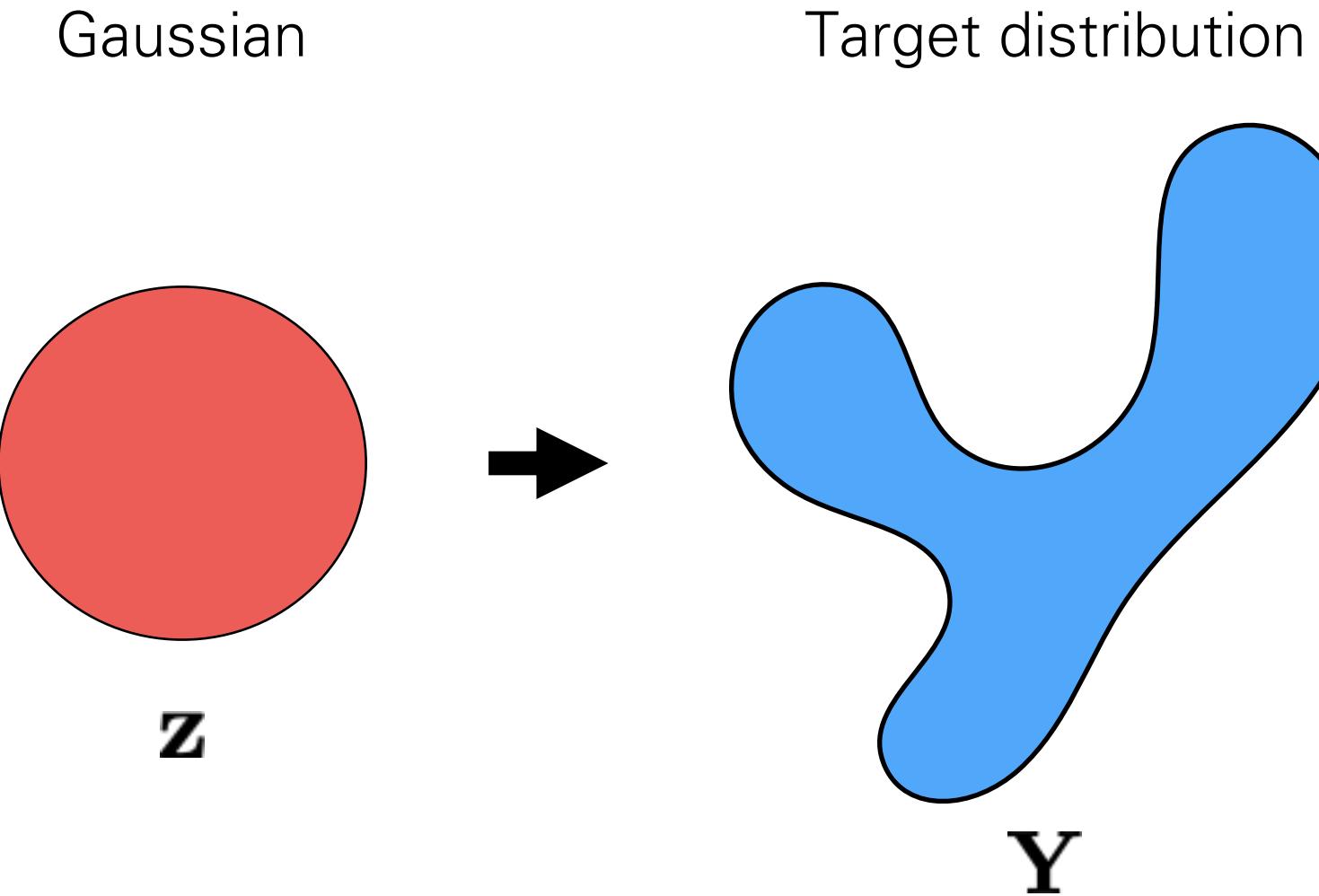
# Cycle-Consistent Adversarial Networks



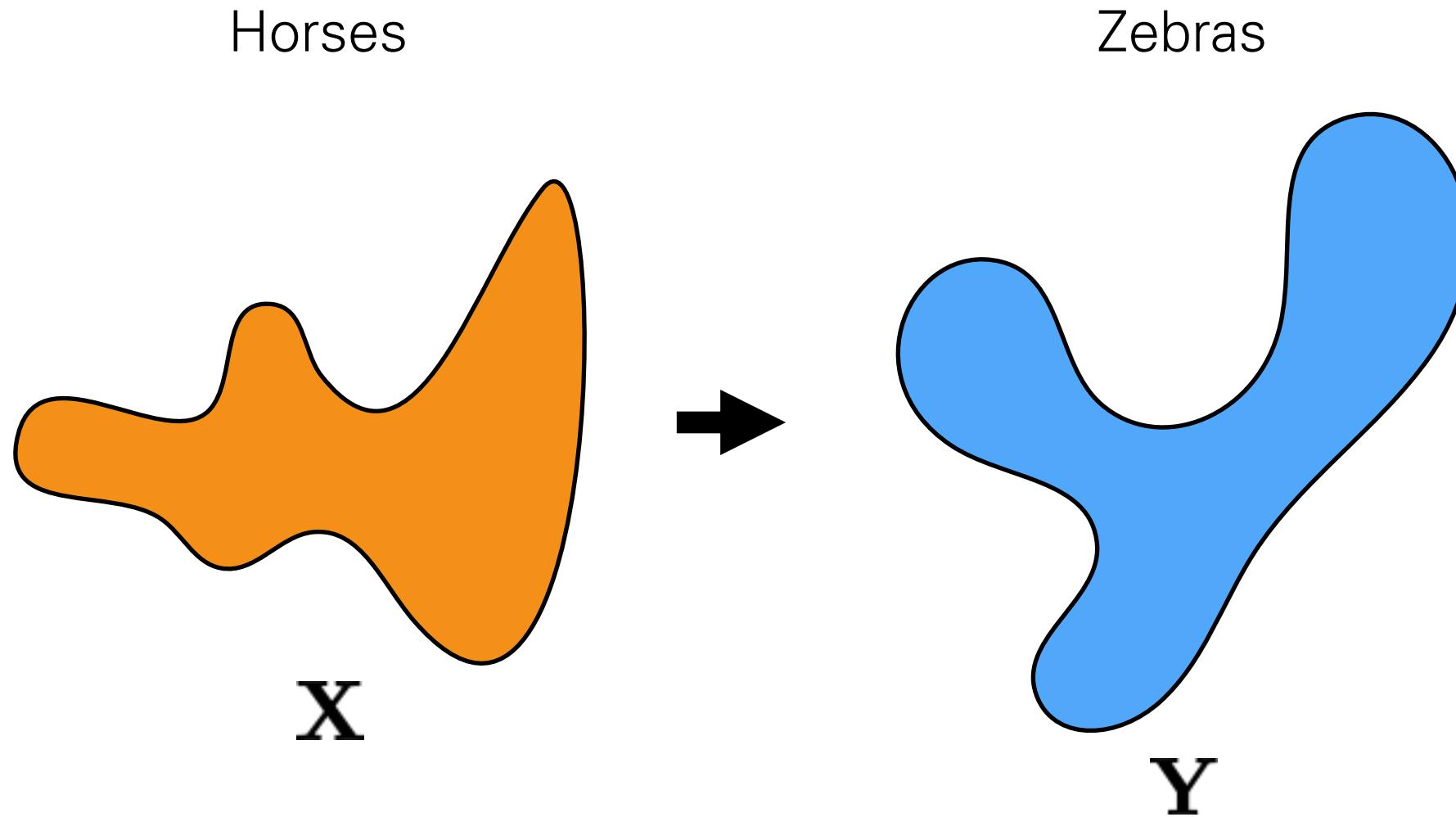
$$\arg \min_G \max_D \mathbb{E}_{\mathbf{x}, \mathbf{y}} [ \log D(G(\mathbf{x})) + \log(1 - D(\mathbf{y})) ]$$

- Usually loss functions check if output matches a target instance
- GAN loss checks if output is part of an admissible set

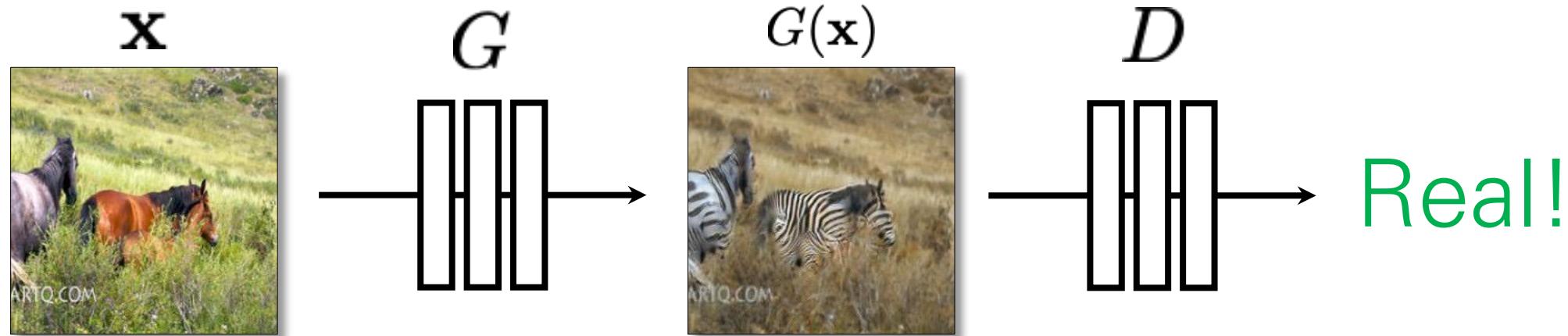
# Cycle-Consistent Adversarial Networks



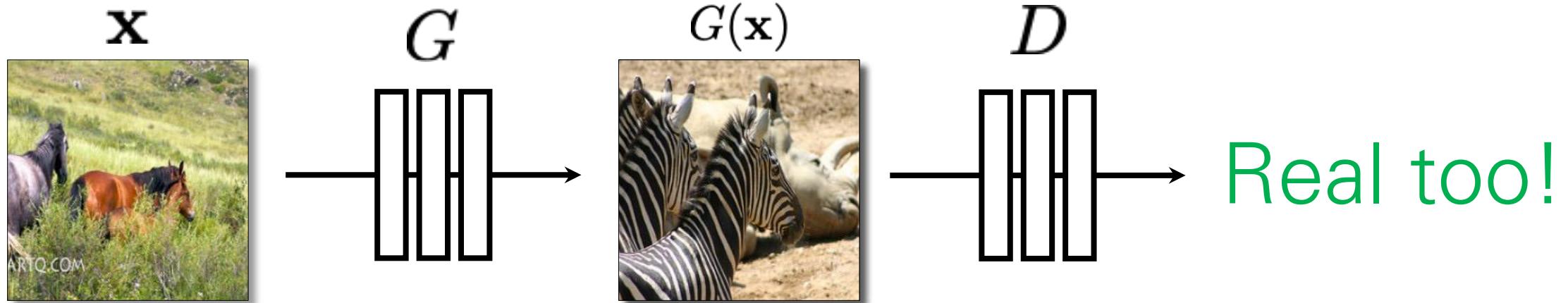
# Cycle-Consistent Adversarial Networks



# Cycle-Consistent Adversarial Networks

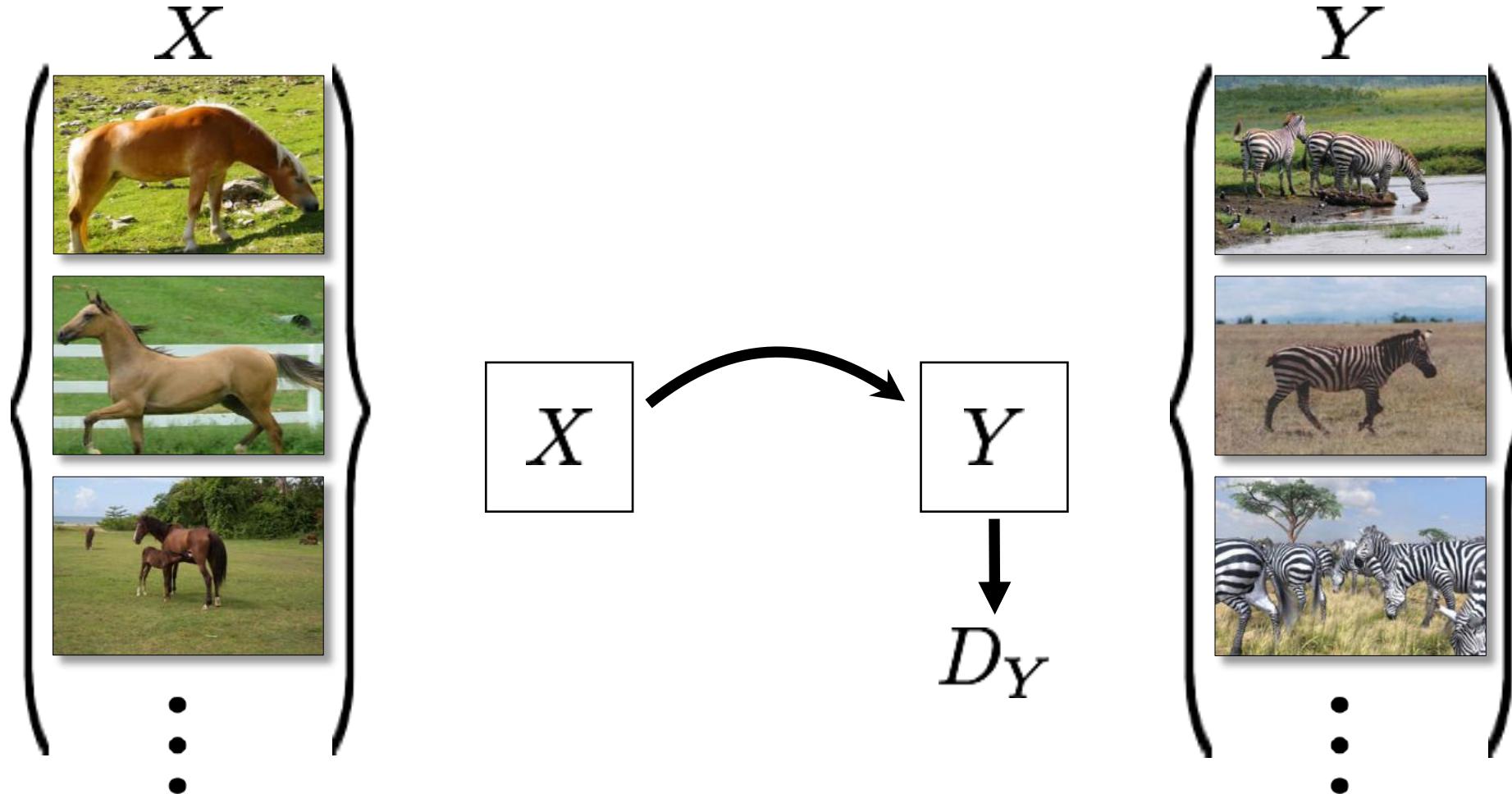


# Cycle-Consistent Adversarial Networks



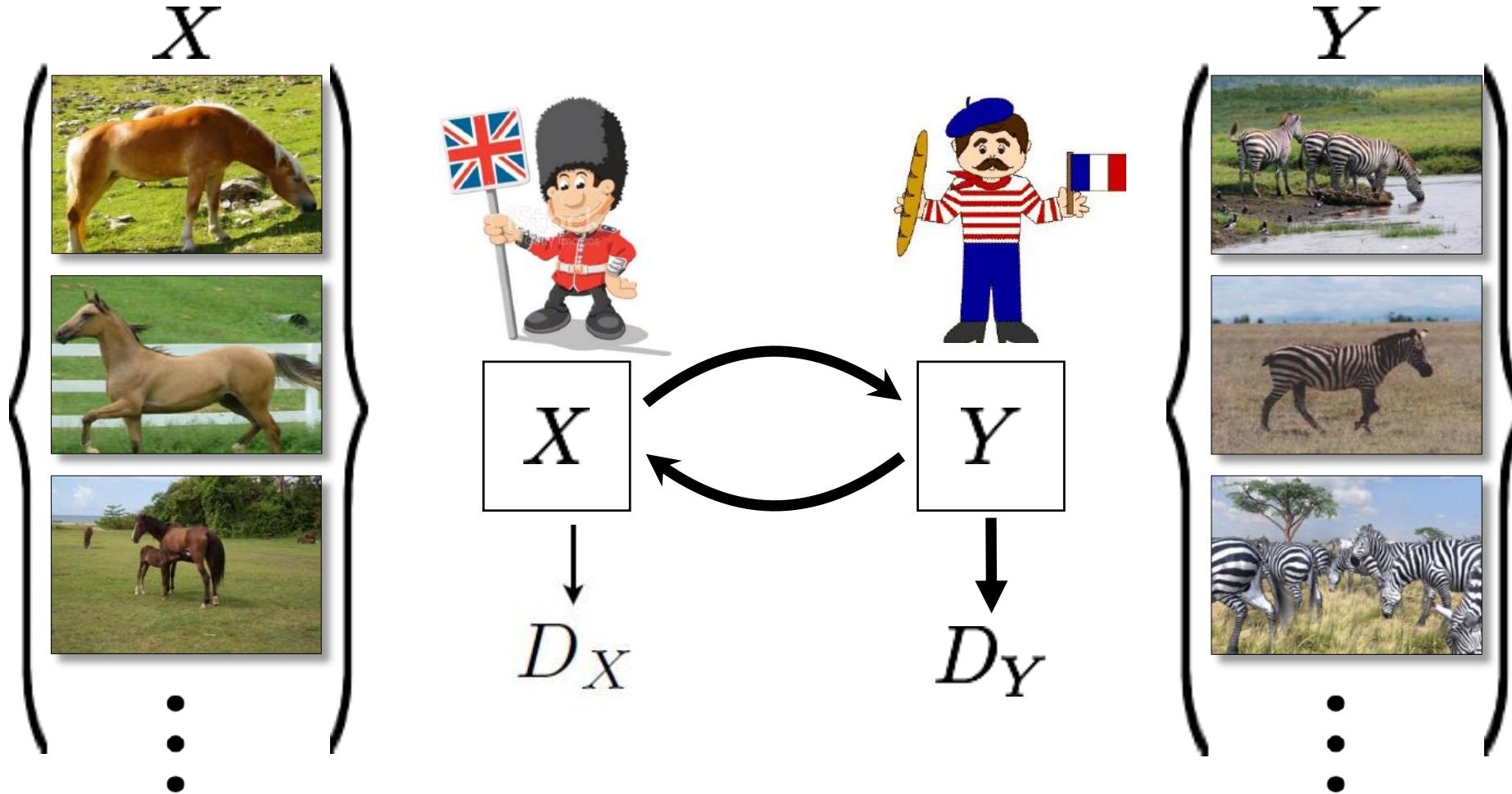
Nothing to force output to correspond to input

# Cycle-Consistent Adversarial Networks

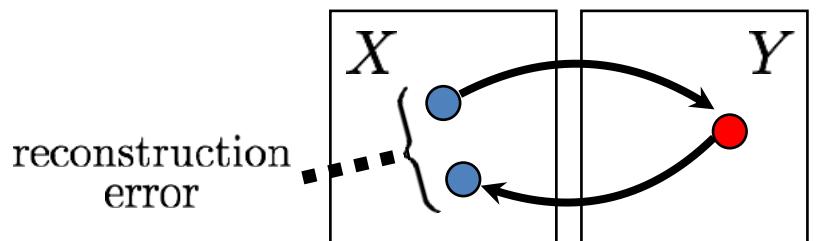
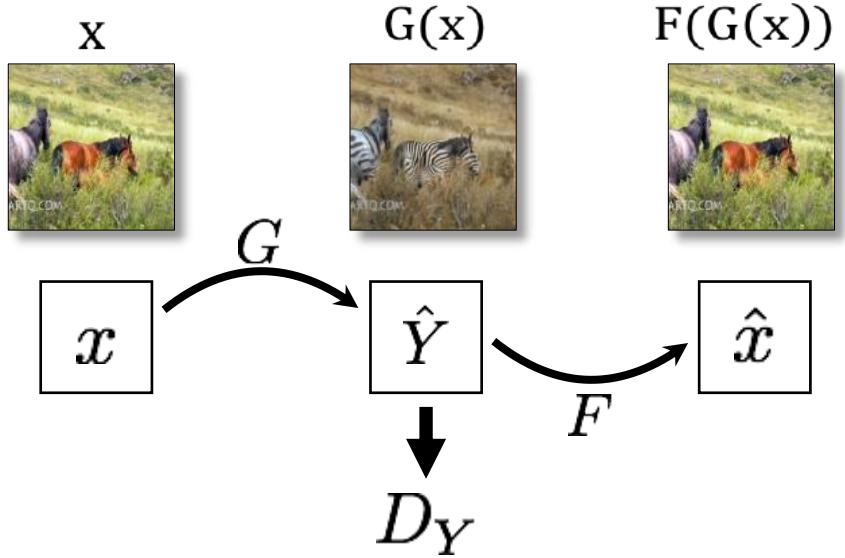


[Zhu et al. 2017], [Yi et al. 2017], [Kim et al. 2017]

# Cycle-Consistent Adversarial Networks

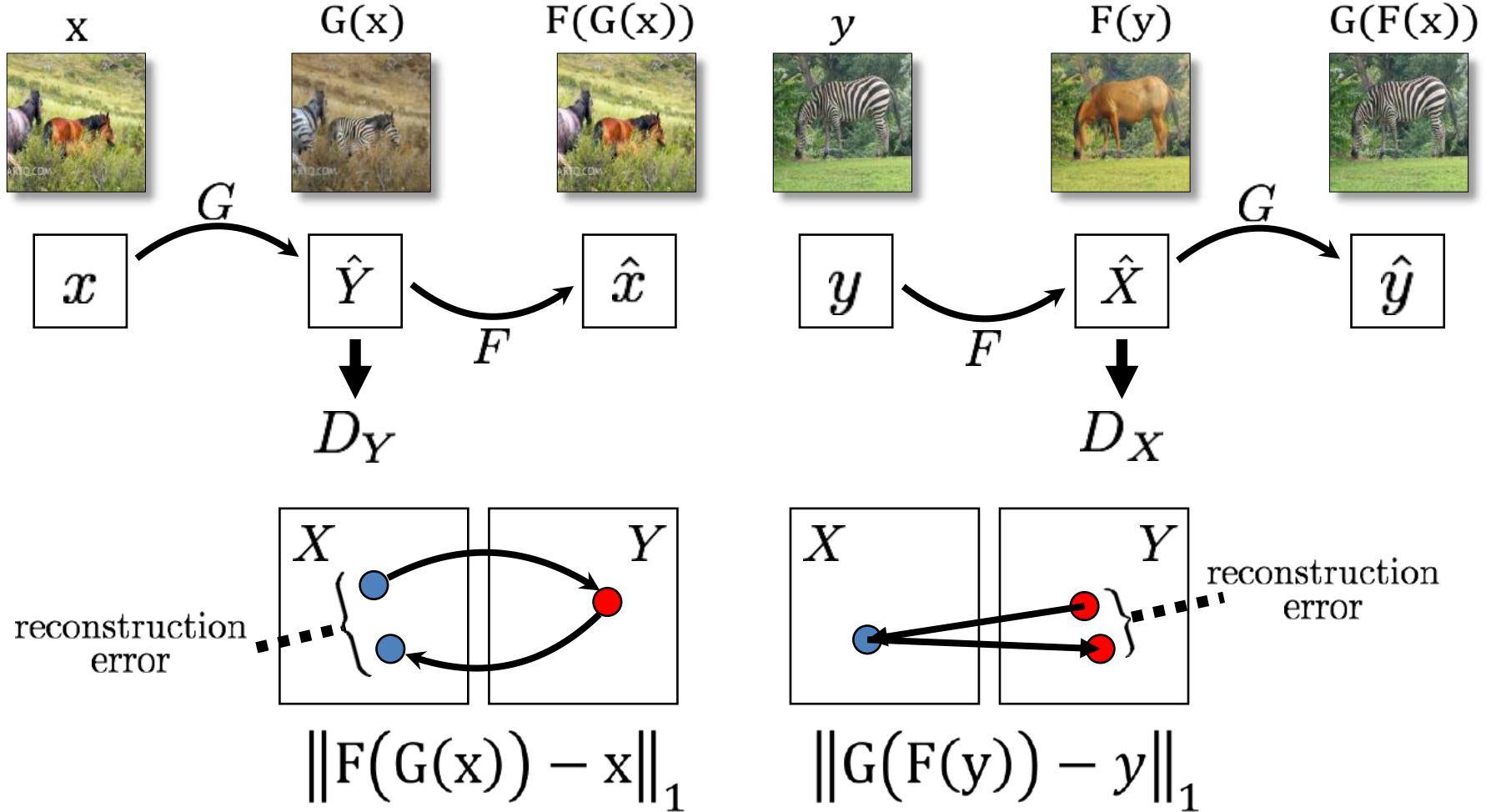


# Cycle Consistency Loss



$$\|F(G(x)) - x\|_1$$

# Cycle Consistency Loss



# Cycle-Consistent Adversarial Networks



# Cycle-Consistent Adversarial Networks



# Cycle-Consistent Adversarial Networks



Photograph  
@ Alexei Efros



Monet



Van Gogh



Cezanne



Ukiyo-e

Input



Monet



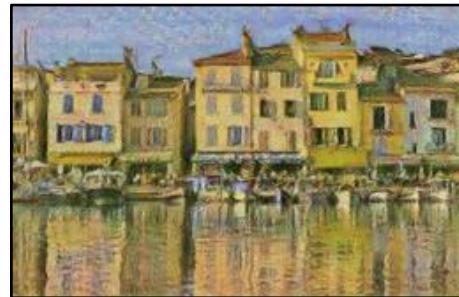
Van Gogh



Cezanne



Ukiyo-e



# Cycle-Consistent Adversarial Networks



# Cycle-Consistent Adversarial Networks



# Cycle-Consistent Adversarial Networks



# Cycle-Consistent Adversarial Networks



# Lecture overview

- Motivation and Definition of Implicit Models
- Original GAN (Goodfellow et al, 2014)
- Evaluation: Parzen, Inception, Frechet
- Theory of GANs
- GAN Progression
- Conditional GANs, Cycle-Consistent Adversarial Networks
- **GANs and Representations**
- Applications

# GANs for unsupervised feature learning

- InfoGAN (Information Maximizing GAN)
- BiGAN (Bidirectional Generative Adversarial Networks)
  - BigBiGAN (Big Bidirectional Generative Adversarial Networks)

# InfoGAN



```
array([[151, 157, 250, ..., 20, 0, 0],  
       [148, 161, 242, ..., 15, 0, 0],  
       [235, 228, 255, ..., 3, 0, 0],  
       ...,  
       [252, 254, 176, ..., 240, 253, 253],  
       [253, 253, 253, ..., 253, 200, 200],  
       [253, 253, 253, ..., 253, 200, 200]]  
     , dtype=uint8)
```

# InfoGAN

```
array([[151, 157, 250, ..., 20, 0, 0],  
       [148, 161, 242, ..., 15, 0, 0],  
       [235, 228, 255, ..., 3, 0, 0],  
       ...,  
       [252, 254, 176, ..., 240, 253, 253],  
       [253, 253, 253, ..., 253, 200, 200],  
       [253, 253, 253, ..., 253, 200, 200]]  
, dtype=uint8)
```

Data: x

Simple factors interact to create complex observations.

Digit type: “5”

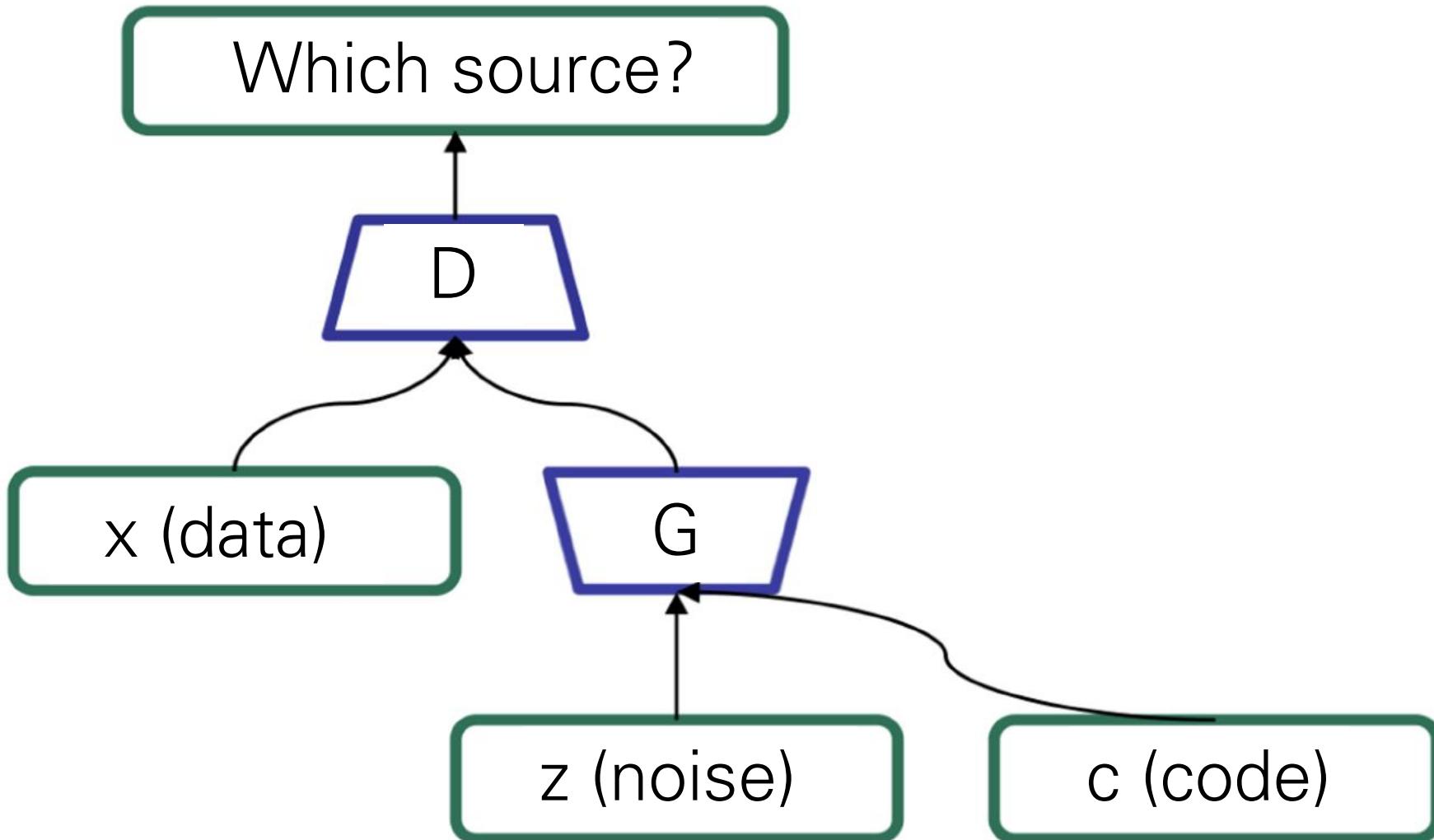
Rotation: Tilting to the right

Width: Medium

.....

Latent code: c

# InfoGAN



# InfoGAN

- Simple idea: Independent factors in latent code should maximally explain variations in generated images
- Formally: We want to maximize the mutual information between latent code and generated images:

$$\begin{aligned}\max_G I(c; x) &= H(x) - H(x|c) \\ &= H(c) - H(c|x)\end{aligned}$$

where  $x = G(z, c)$

# InfoGAN

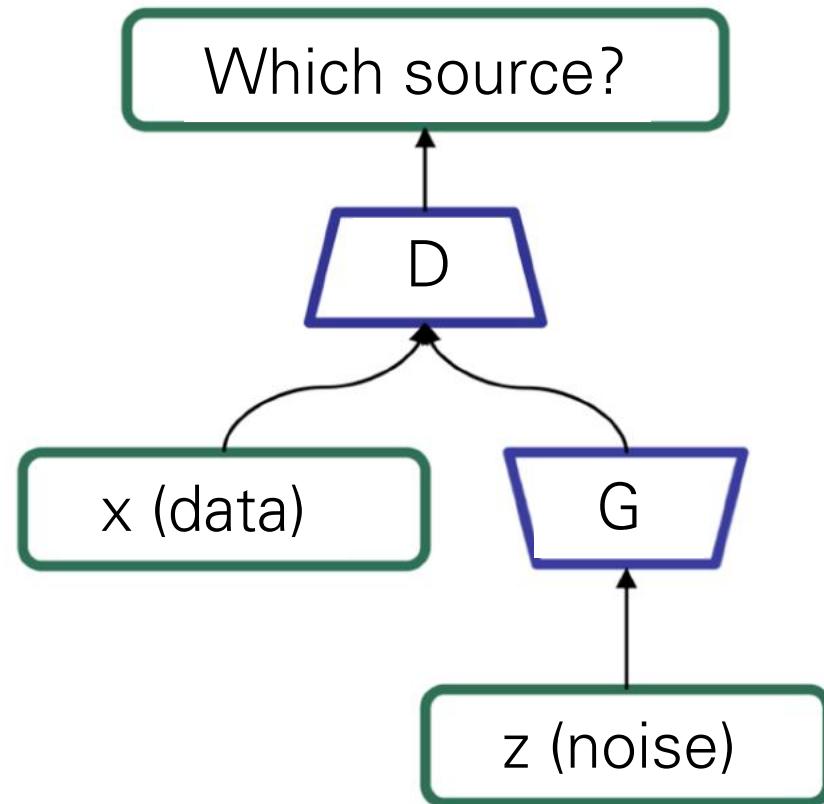
- Mutual information can be maximized easily with a variational lower bound:

$$\begin{aligned} I(c; G(z, c)) &= H(c) - H(c|G(z, c)) \\ &= H(c) + \mathbb{E}_{x \sim G(z, c)} [\mathbb{E}_{c' \sim P(c|x)} [\log P(c'|x)]] \\ &= H(c) + \mathbb{E}_{x \sim G(z, c)} [\mathbb{E}_{c' \sim P(c|x)} [\log Q(c'|x)]] + \underbrace{D_{\text{KL}}(P(\cdot|x) \parallel Q(\cdot|x))}_{\geq 0} \\ &\geq H(c) + \mathbb{E}_{x \sim G(z, c)} [\mathbb{E}_{c' \sim P(c|x)} [\log Q(c'|x)]] \end{aligned}$$

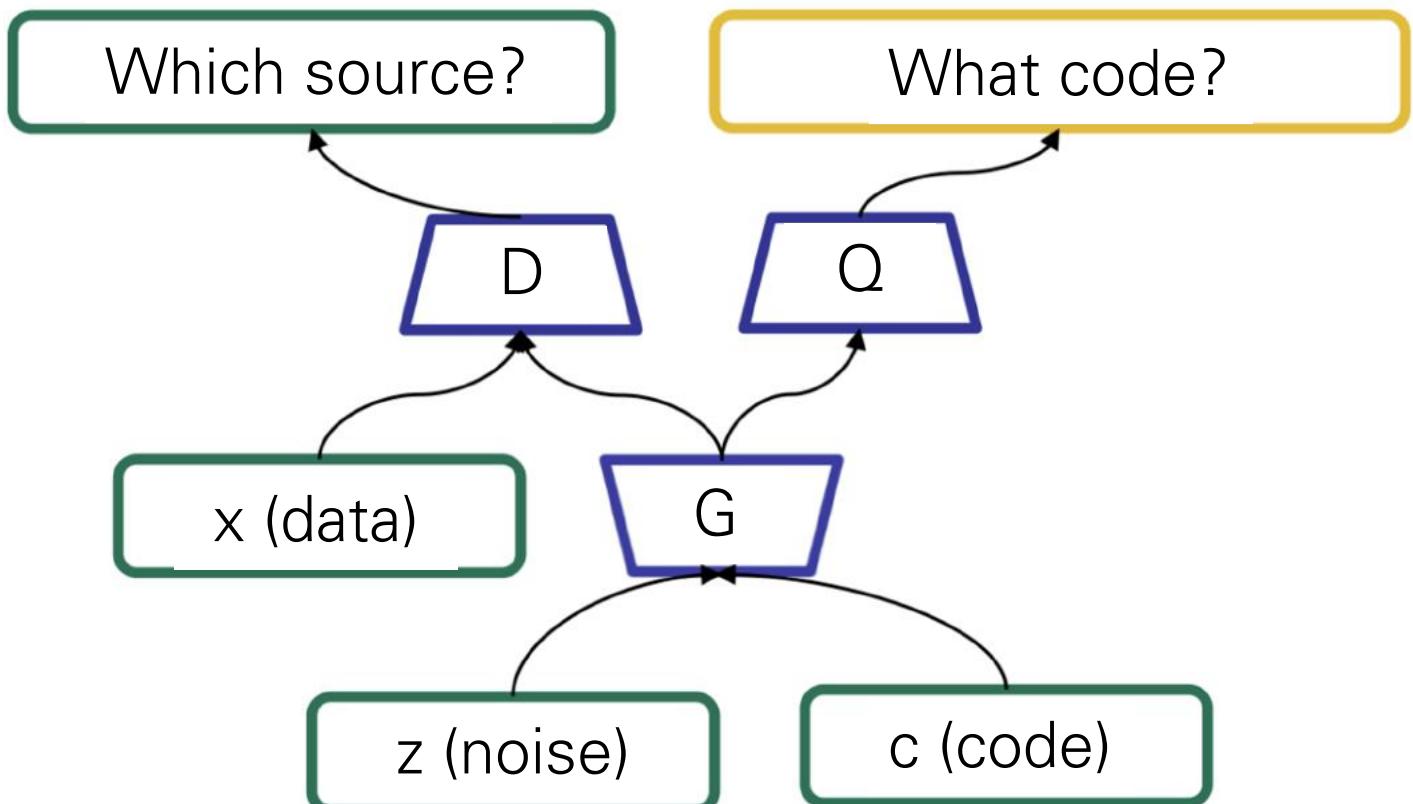


Simply MLE for a classifier/regressor

# InfoGAN

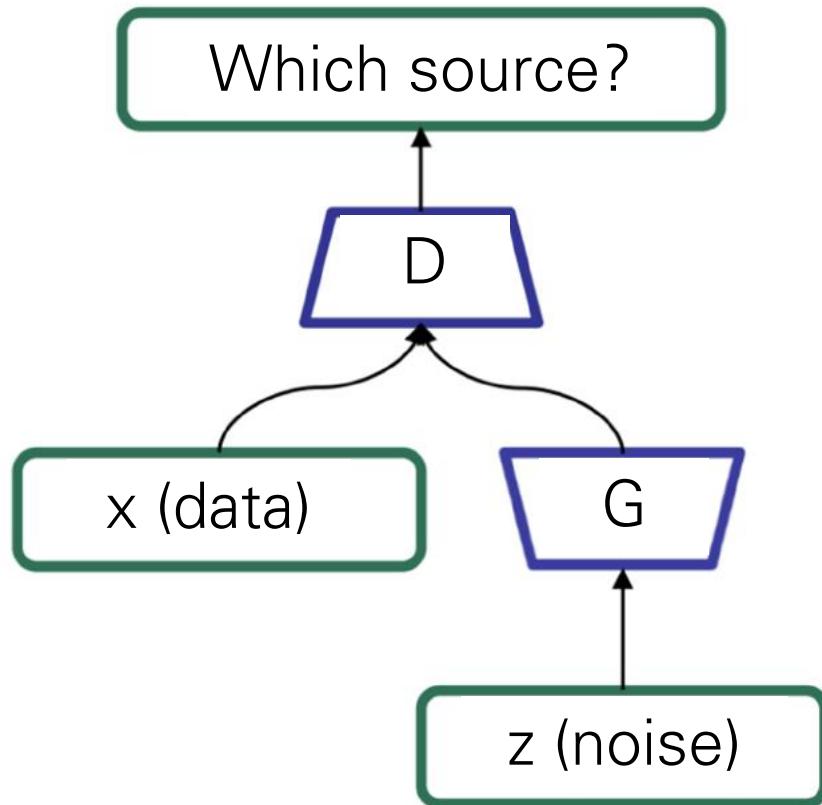


GAN

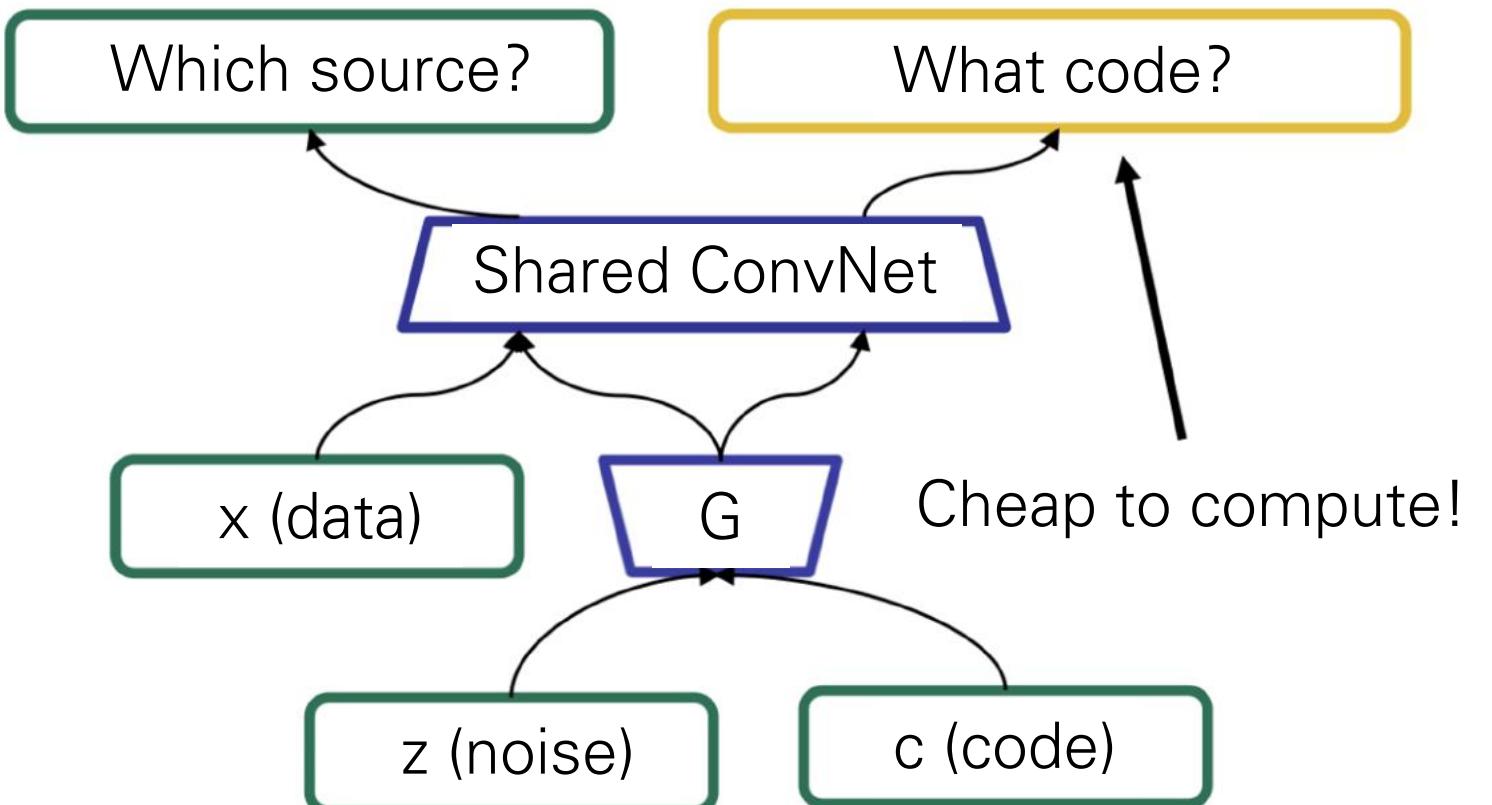


InfoGAN

# InfoGAN

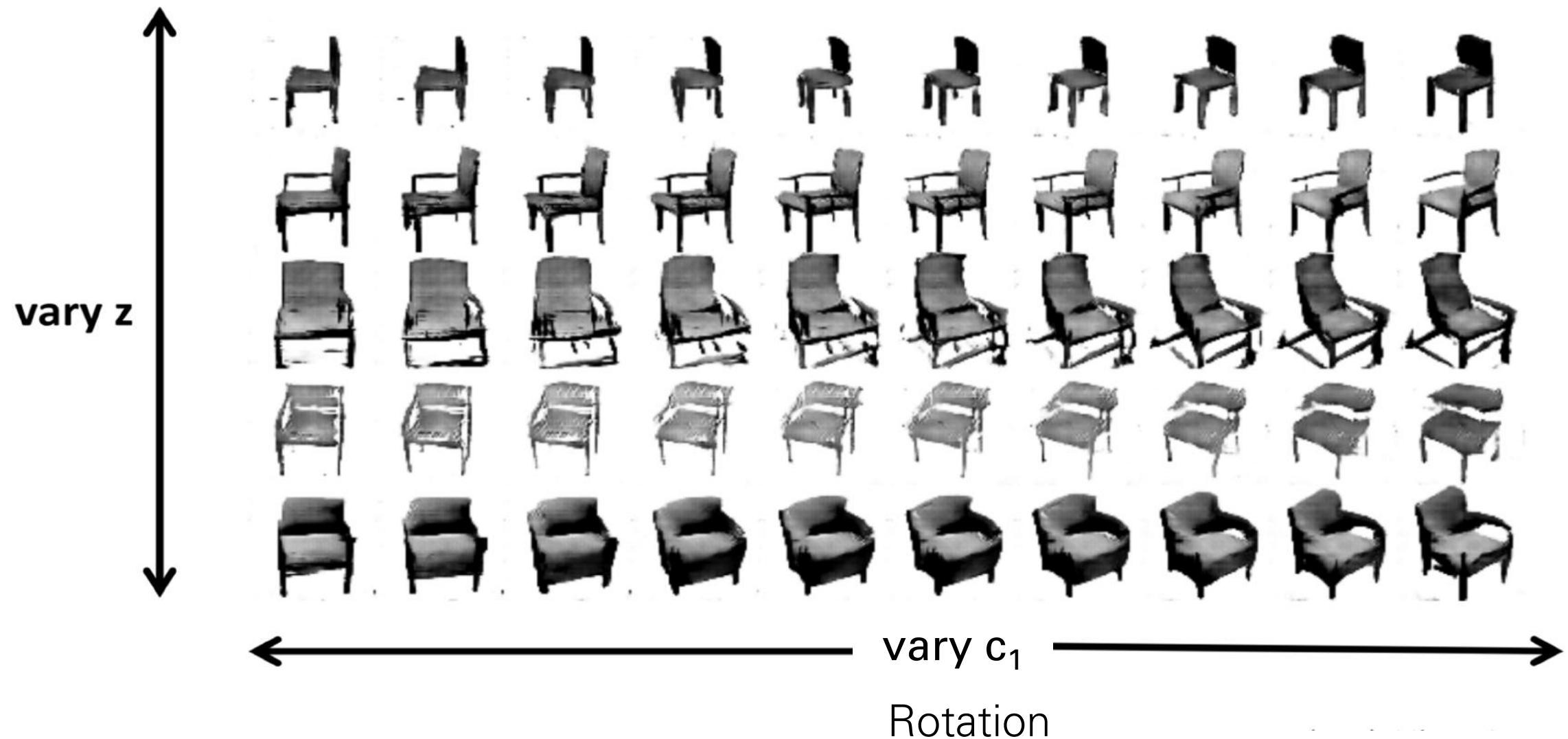


GAN

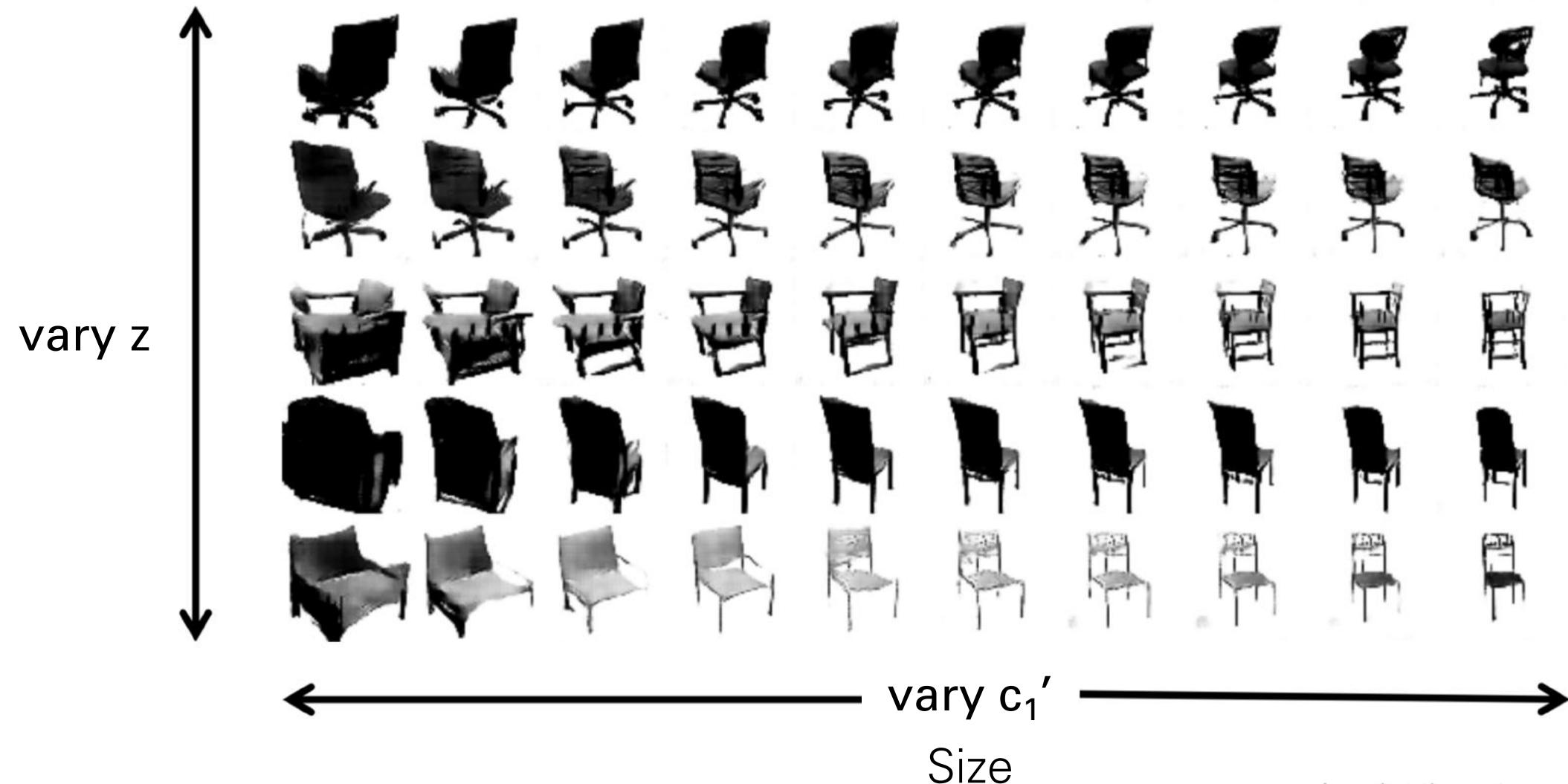


InfoGAN

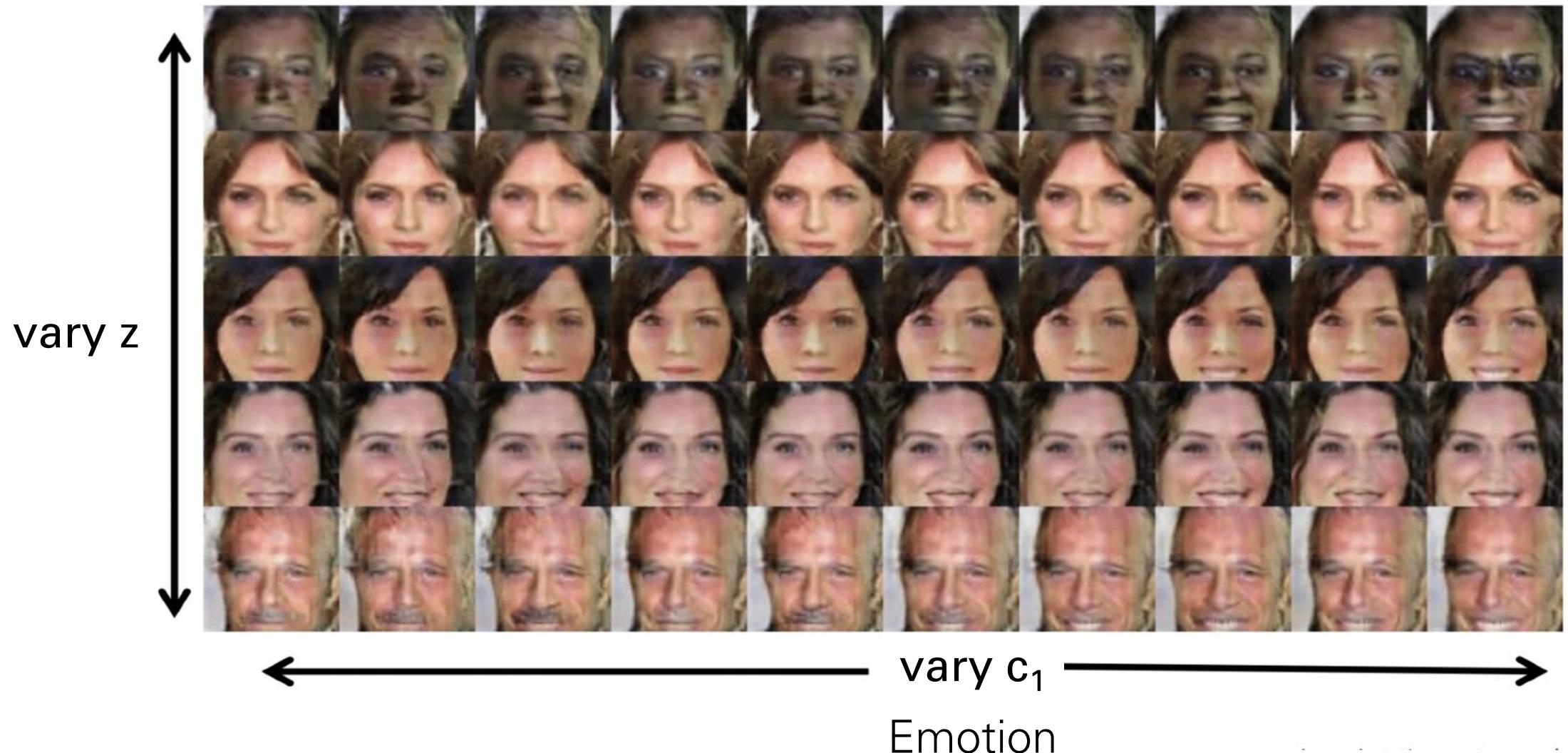
# InfoGAN



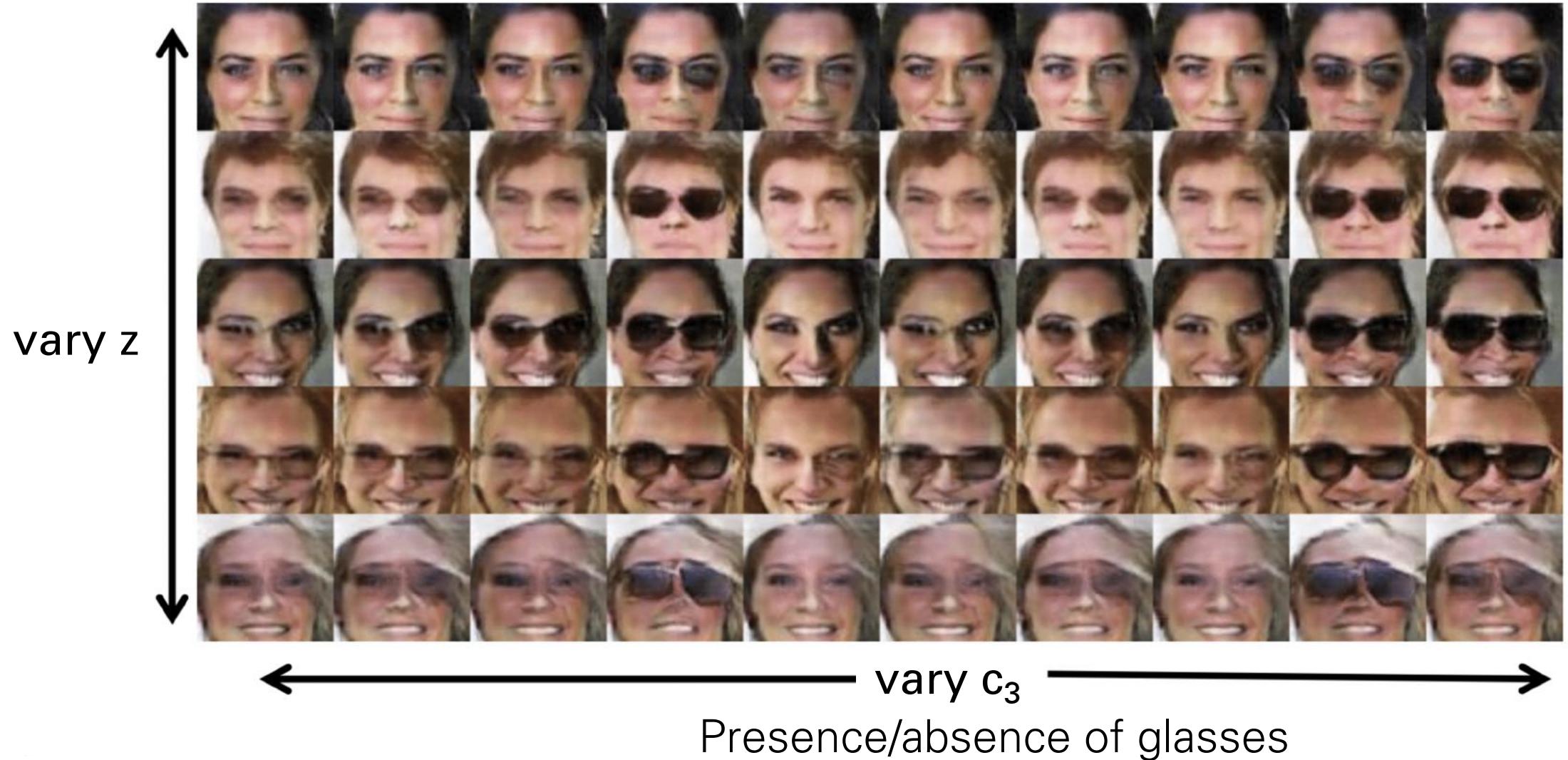
# InfoGAN



# InfoGAN



# InfoGAN



# Unsupervised Category Discovery - BigGAN

- Trained with no labels!

$\mathbf{z} = \text{concat}([$

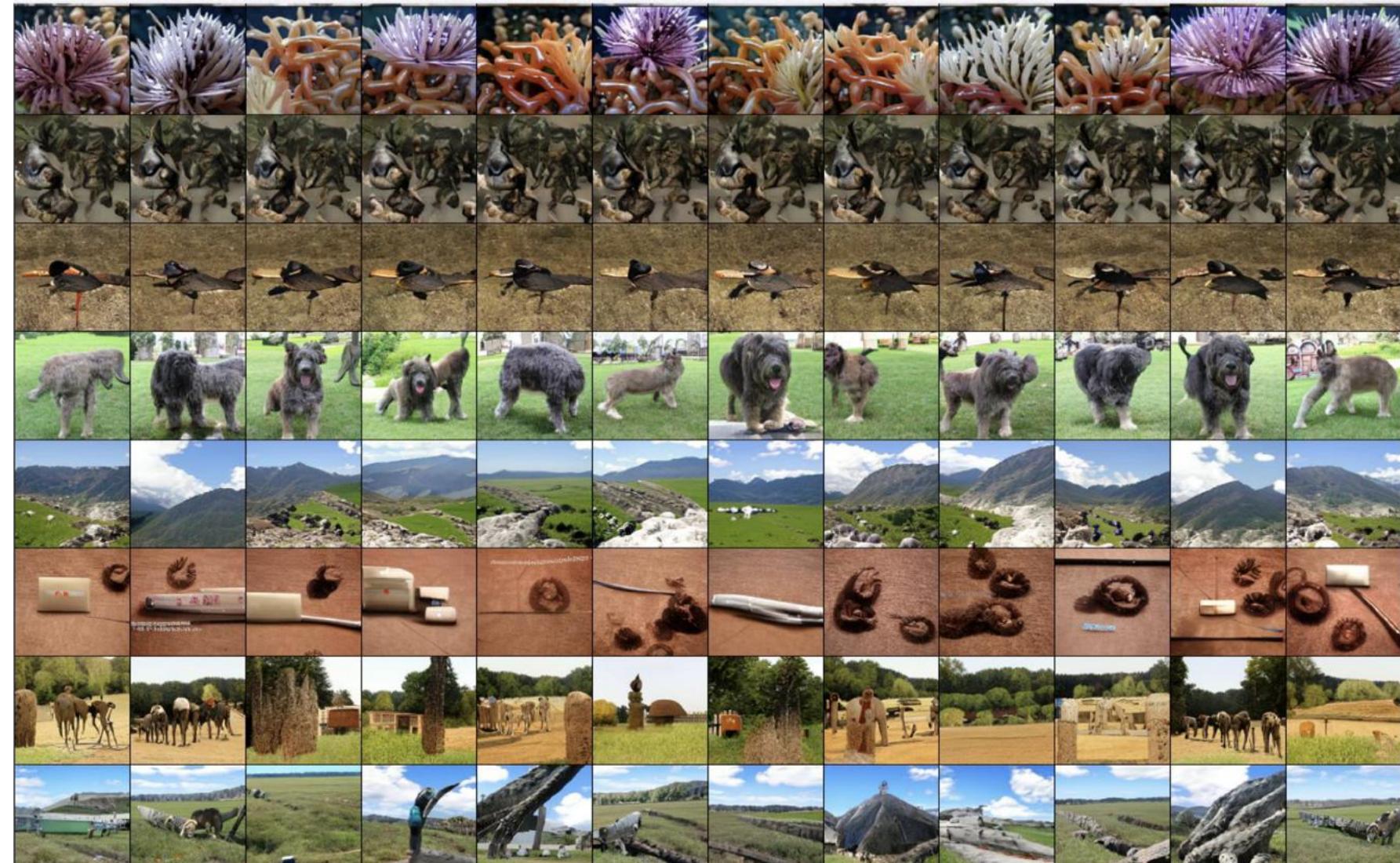
(a)  $[\mathcal{N}(0, I)]^{120}$ ,

(b)

UniformCateg(1024)

])

- Each row is one value of the categorical (b); columns are Gaussian samples (a)



# Unsupervised Category Discovery - BigGAN

- Trained with no labels!  
 $\mathbf{z} = \text{concat}([$   
    (a)  $[\mathcal{N}(0, I)]^{120},$   
    (b)  
    UniformCateg(1024)  
    ])
- Each row is one value  
of the categorical (b);  
columns are Gaussian  
samples (a)



# But what about inference...

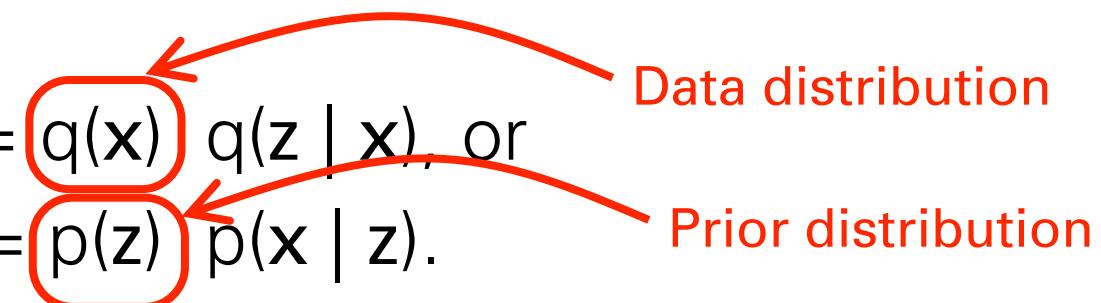
- How can we use generative models?
  - GANs can generate content, but sometimes you want to make inference about observed data.
- Can we incorporate an inference mechanism into GANs?
- Can we learn an inference mechanism using an adversarial training paradigm?

# Two papers, one model

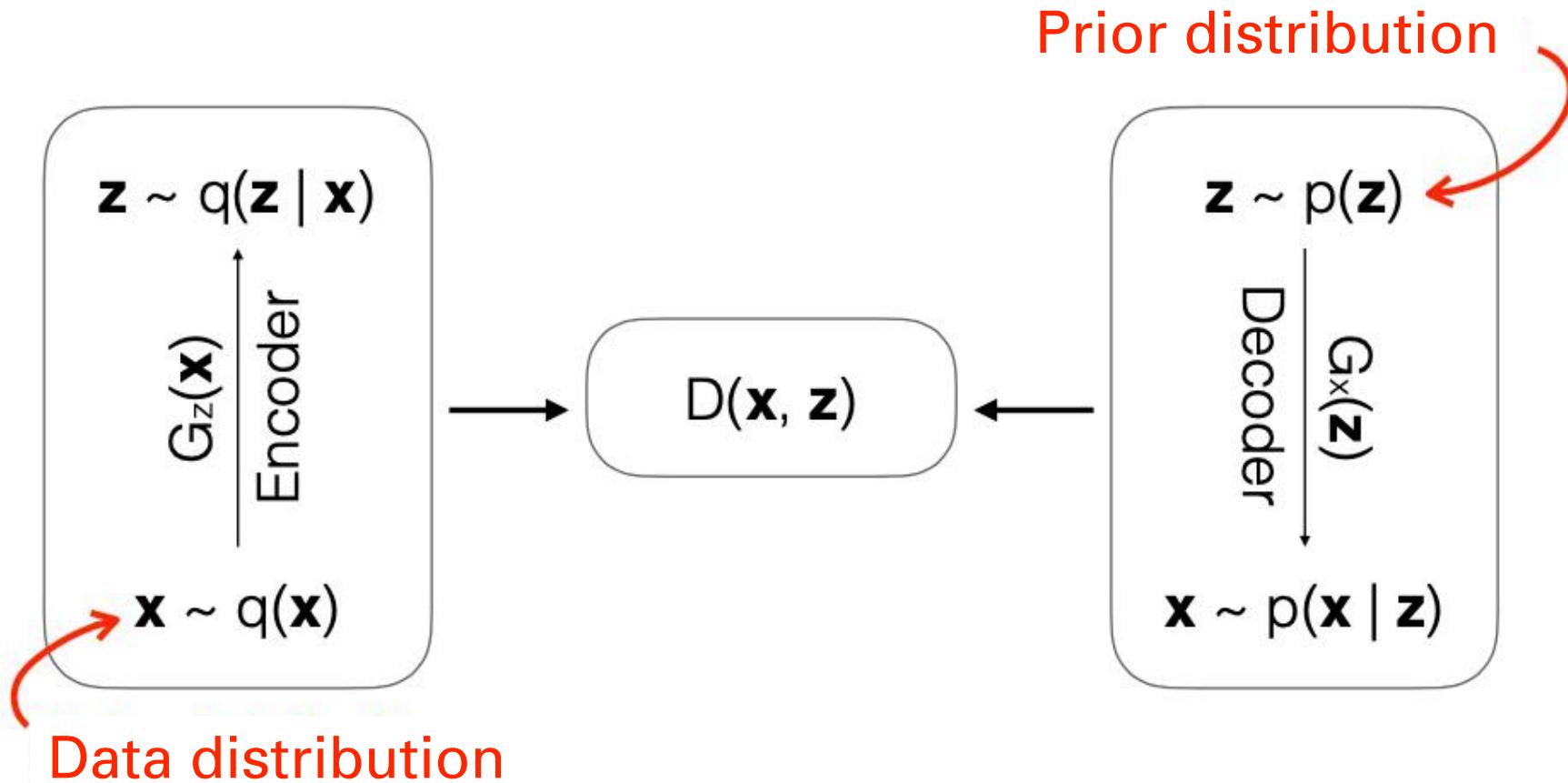
- **ALI:** Vincent Dumoulin, Ishmael Belghazi, Olivier Mastropietro  
ADVERSARIALLY LEARNED INFERENCE, ICLR 2017  
Ben Poole, Alex Lamb, Martin Arjovsky
- **BiGAN:** Donahue, Krähenbühl and Darrell (2016), ADVERSARIAL  
FEATURE LEARNING, ICLR 2017

# Adversarially learned inference: Main idea

- Cast the learning of both an inference model (encoder) and a generative model (decoder) in a GAN-like adversarial framework
- Discriminator is trained to discriminate between joint samples  $(x, z)$  from:
  - Encoder distribution  $q(x, z) = q(x) q(z | x)$ , or
  - Decoder distribution  $p(x, z) = p(z) p(x | z)$ .
- Generator learns conditionals  $q(z | x)$  and  $p(x | z)$  to fool the discriminator.



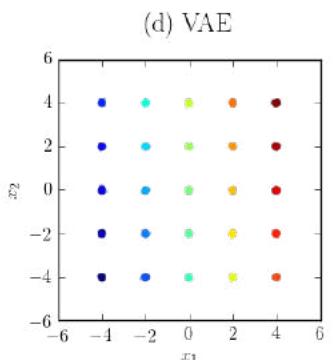
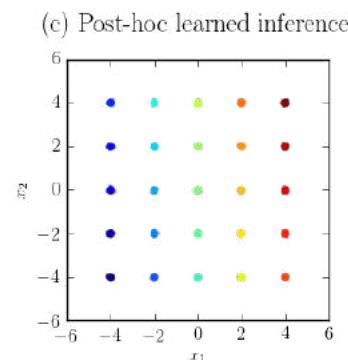
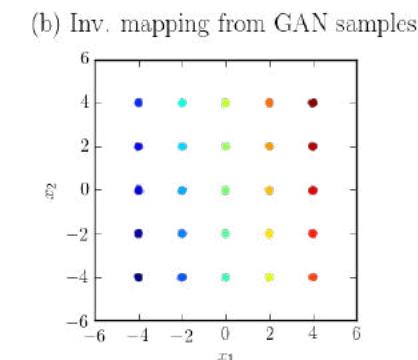
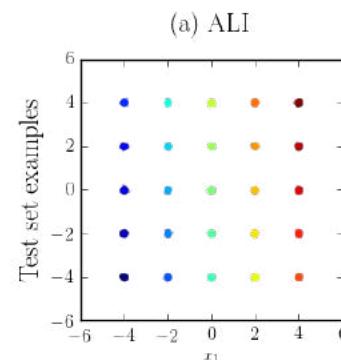
# ALI: Model Diagram



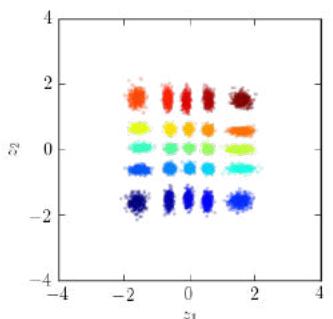
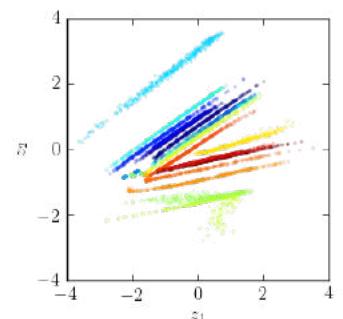
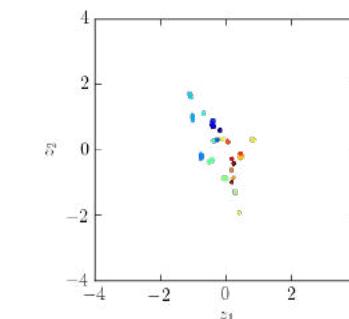
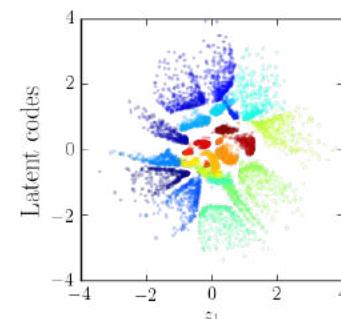
In analogy with GAN, under an ideal discriminator, the generator minimizes the Jensen-Shannon divergence between  $p(\mathbf{x}, \mathbf{z})$  and  $q(\mathbf{x}, \mathbf{z})$ .

# Alternative inference mechanisms:

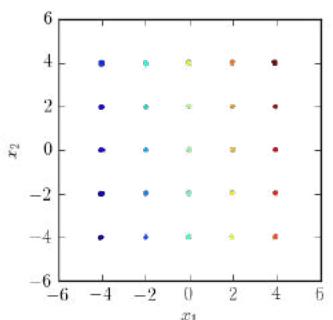
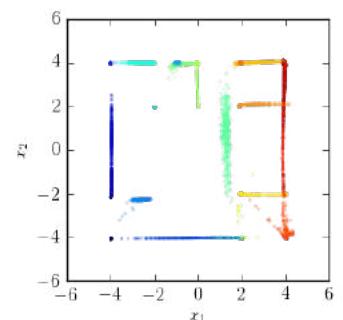
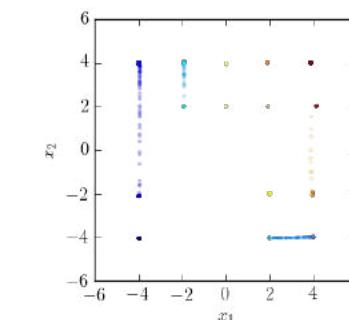
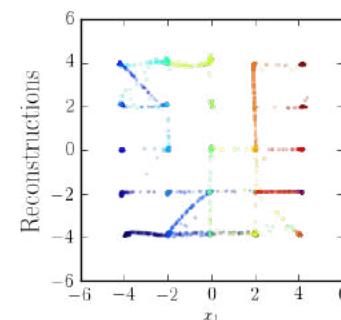
(a) ALI (ours)



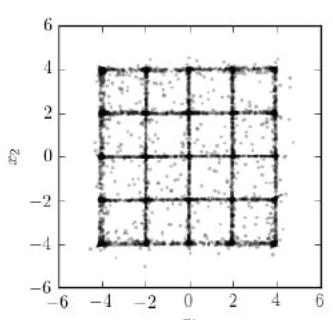
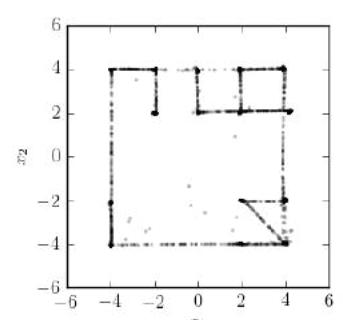
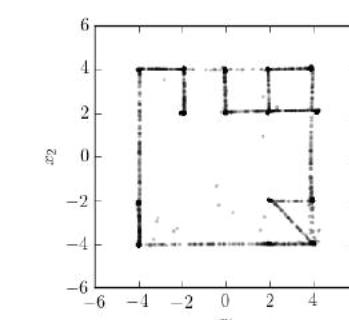
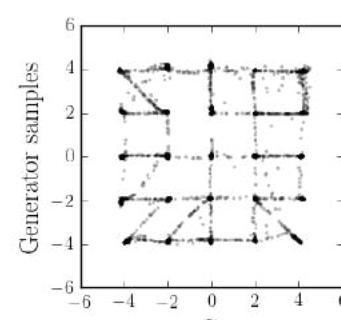
(b) Learn encoder via z reconstruction



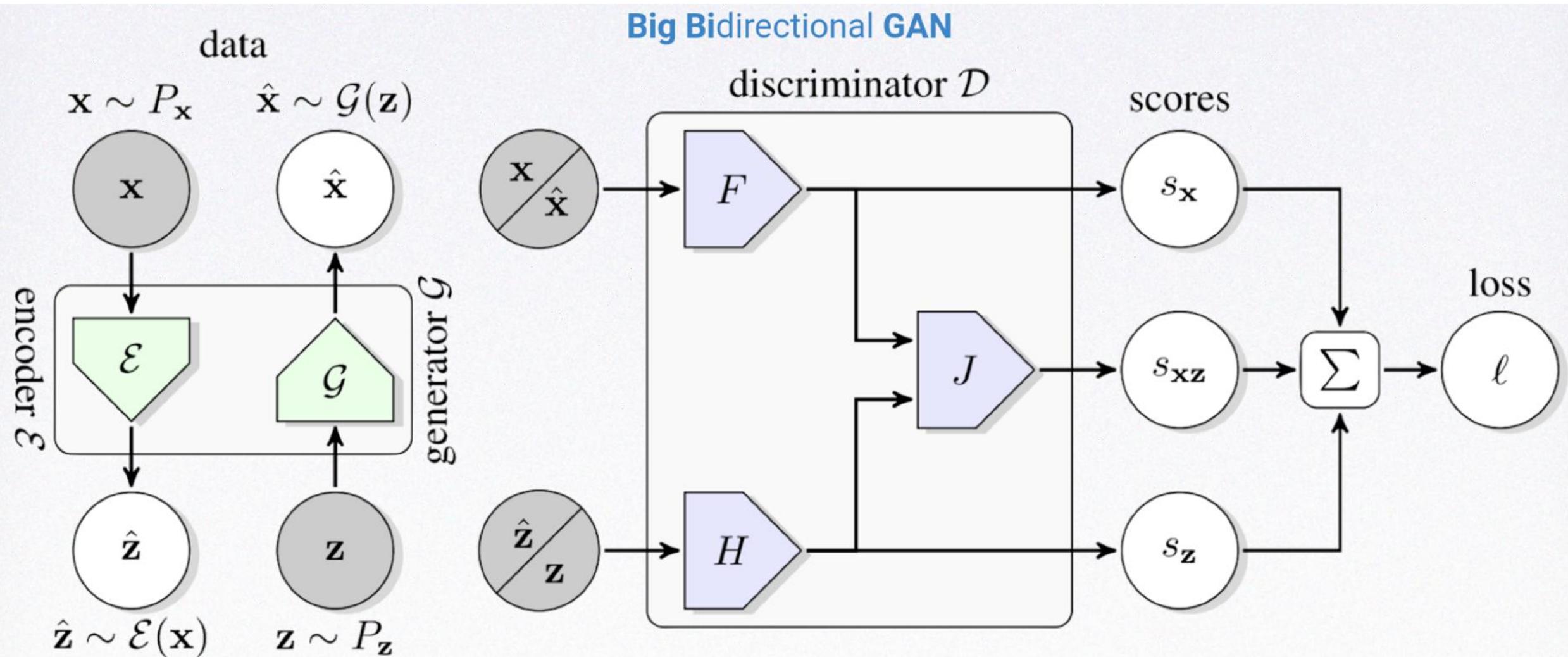
(c) Post hoc encoder learning (ALI-style)



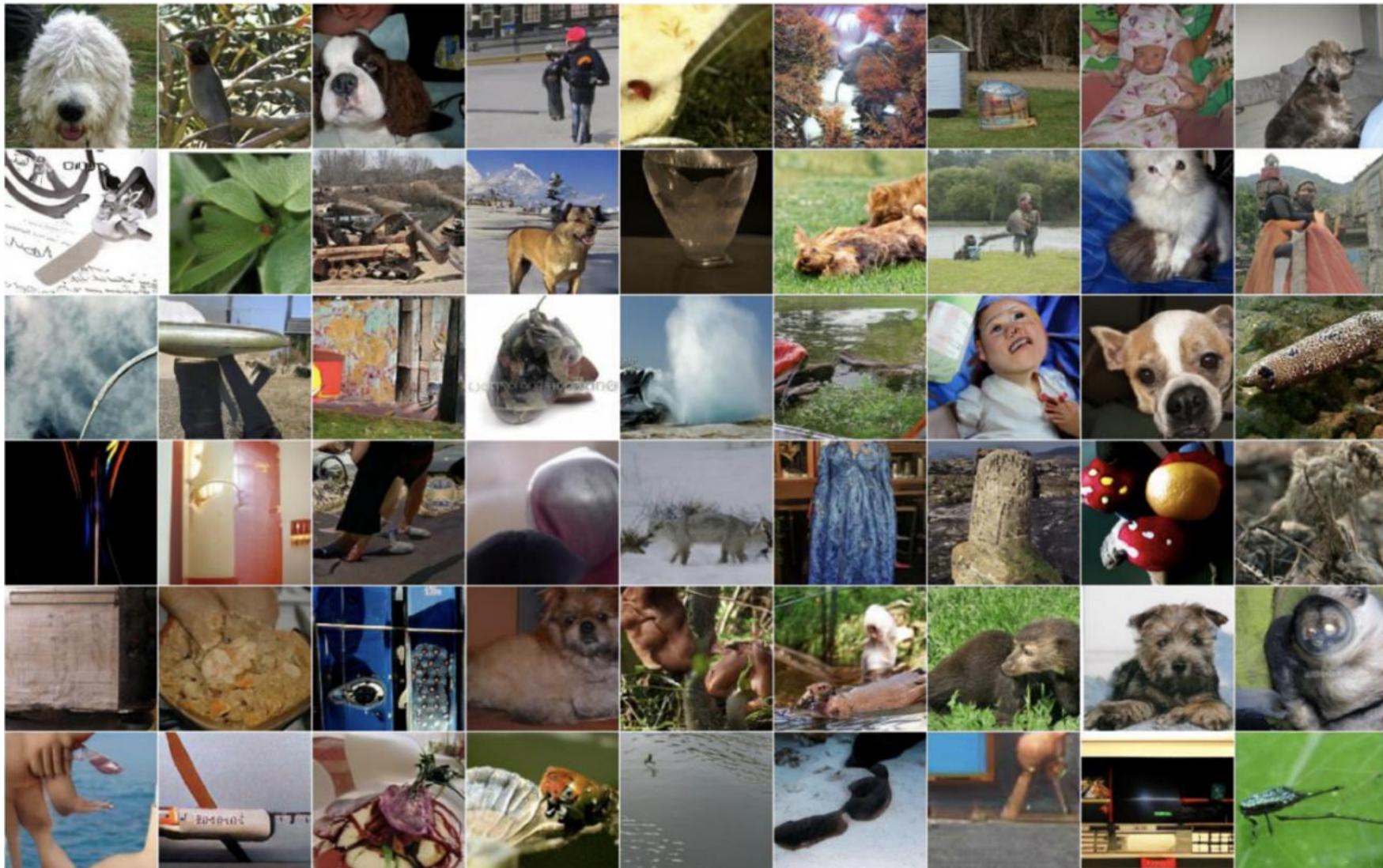
(d) Variational Autoencoder (VAE)



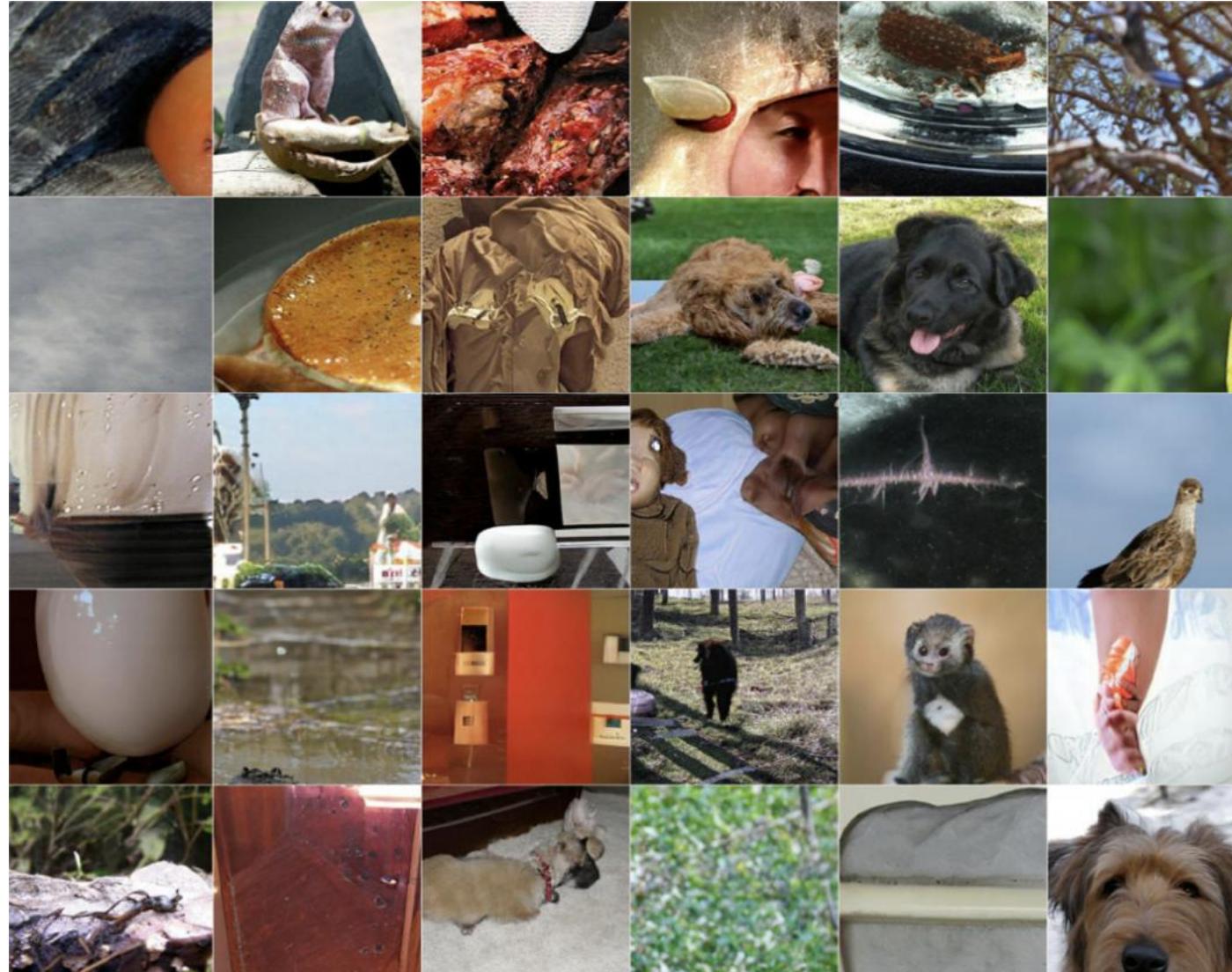
# Big Bidirectional GAN (BigBiGAN)



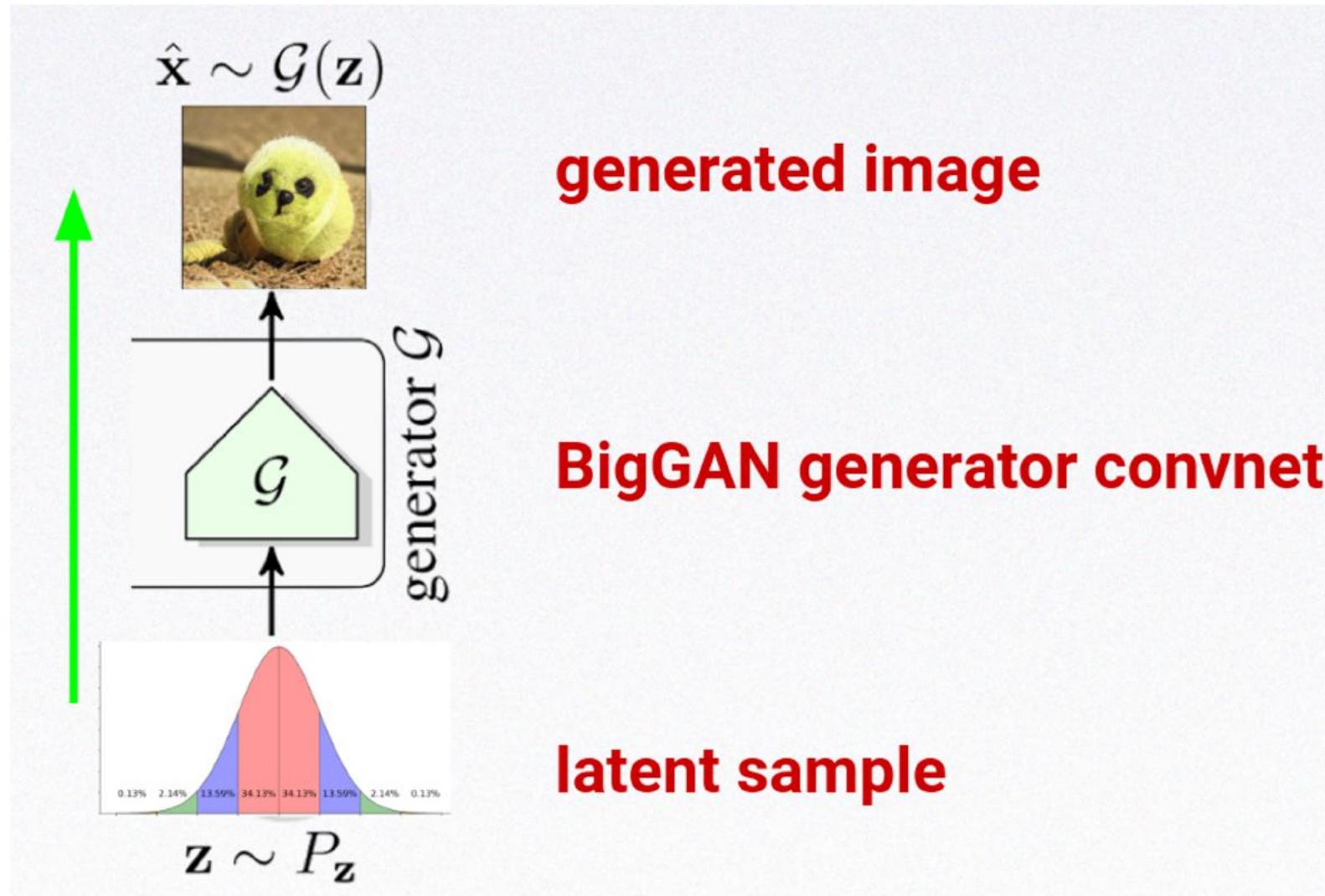
# BigBiGAN: Unconditional Image Generation



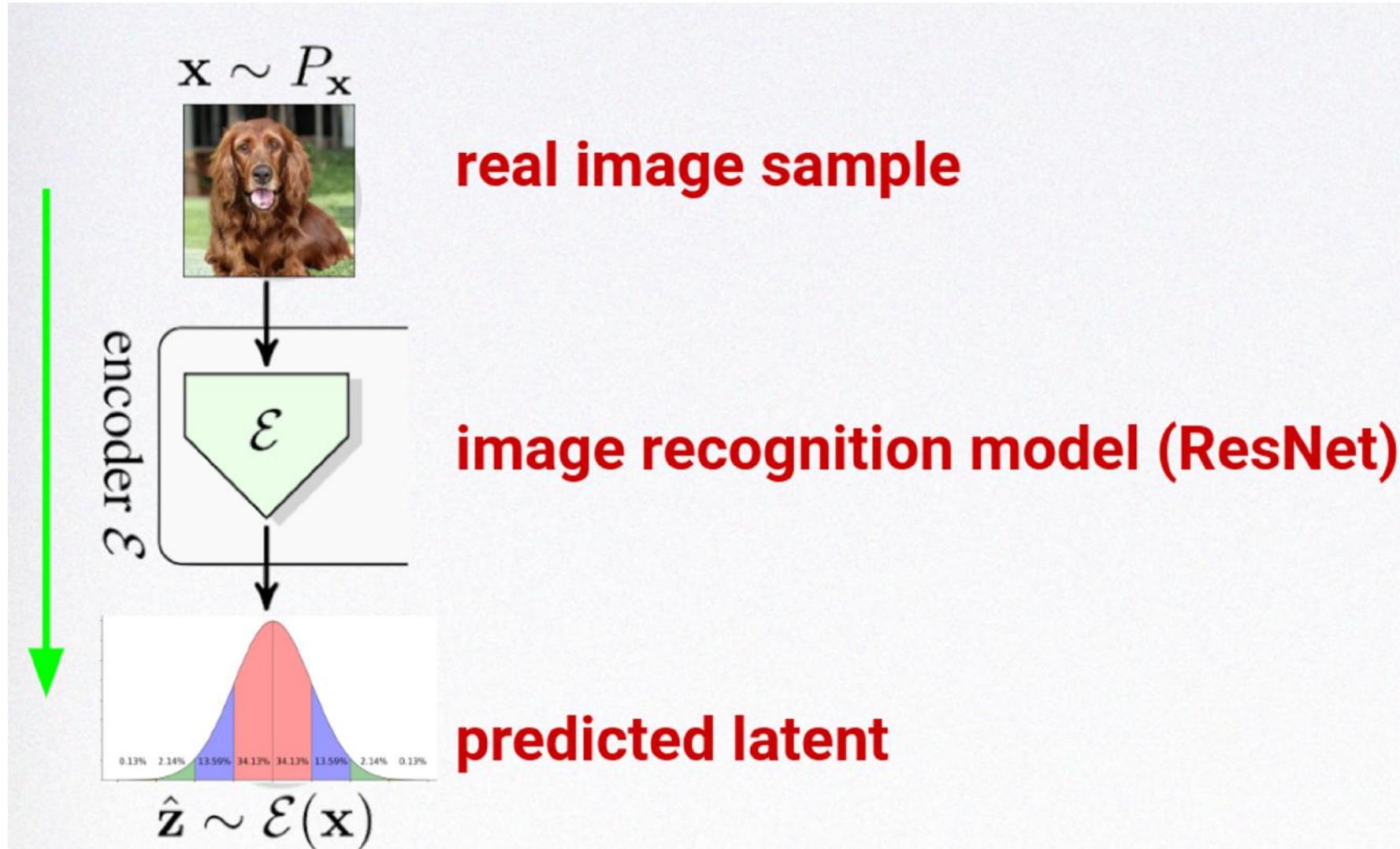
# BigBiGAN: Unconditional Image Generation



# BigBiGAN



# BigBiGAN



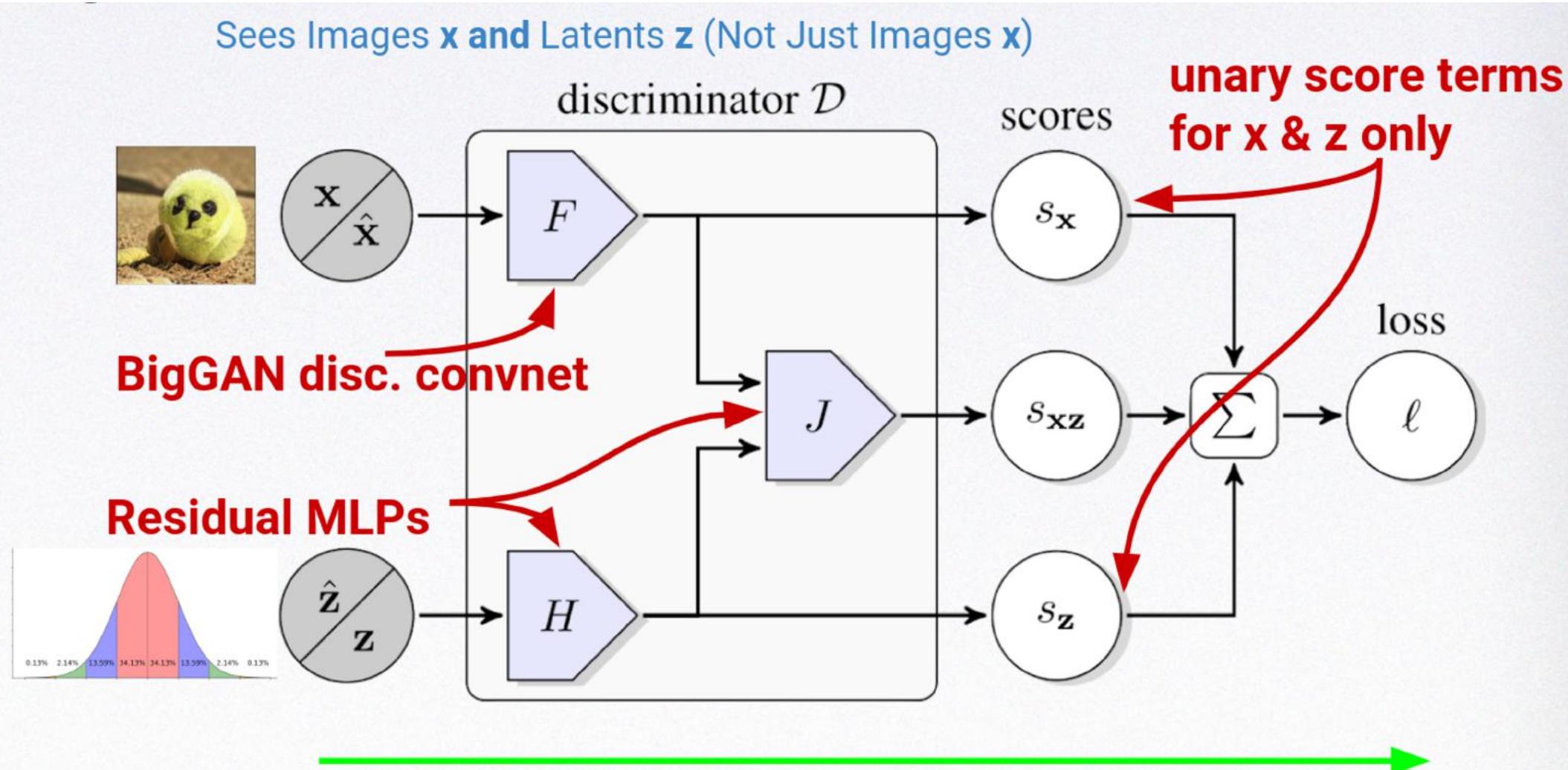
# BigBiGAN

Discriminates between input pairs:

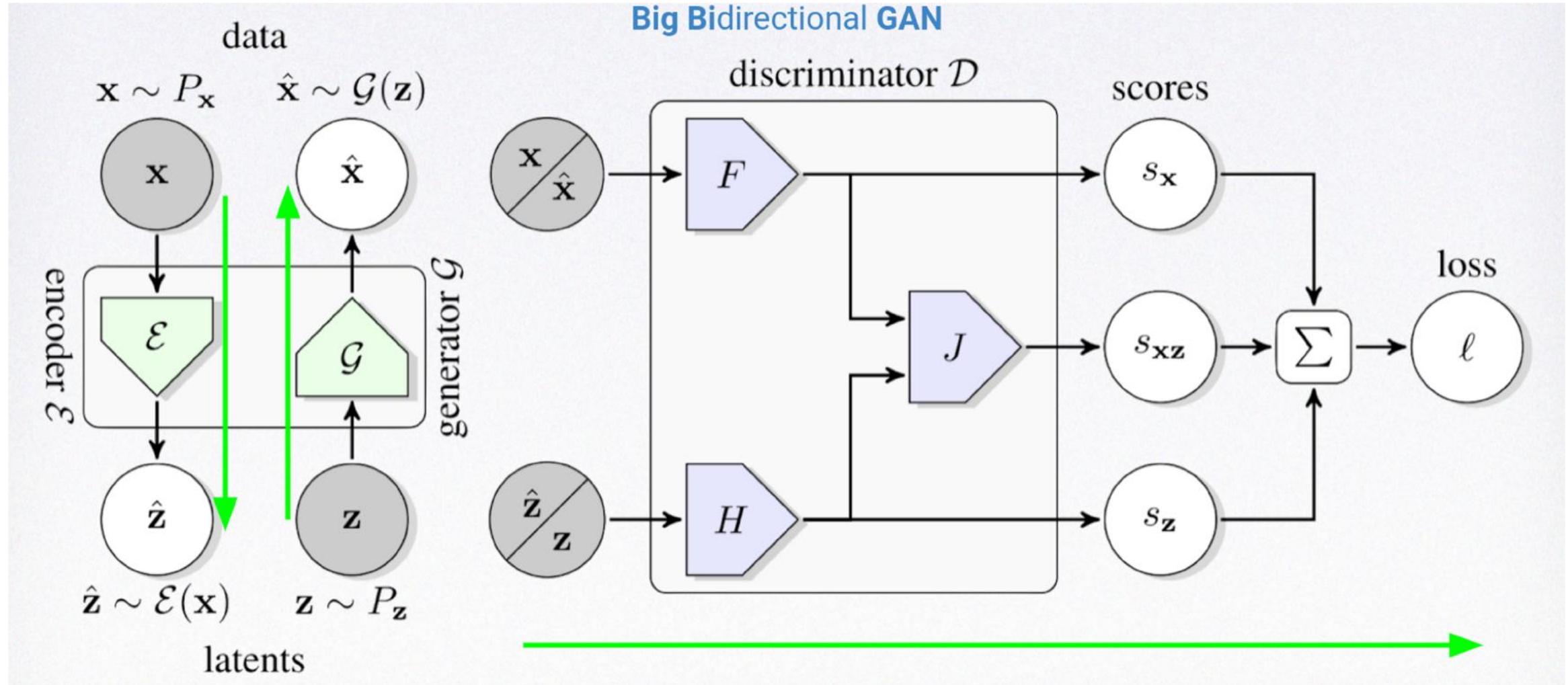
Encoder pair ( $x, z' = E(x)$ )

vs.

Generator pair ( $x' = G(z), z$ )



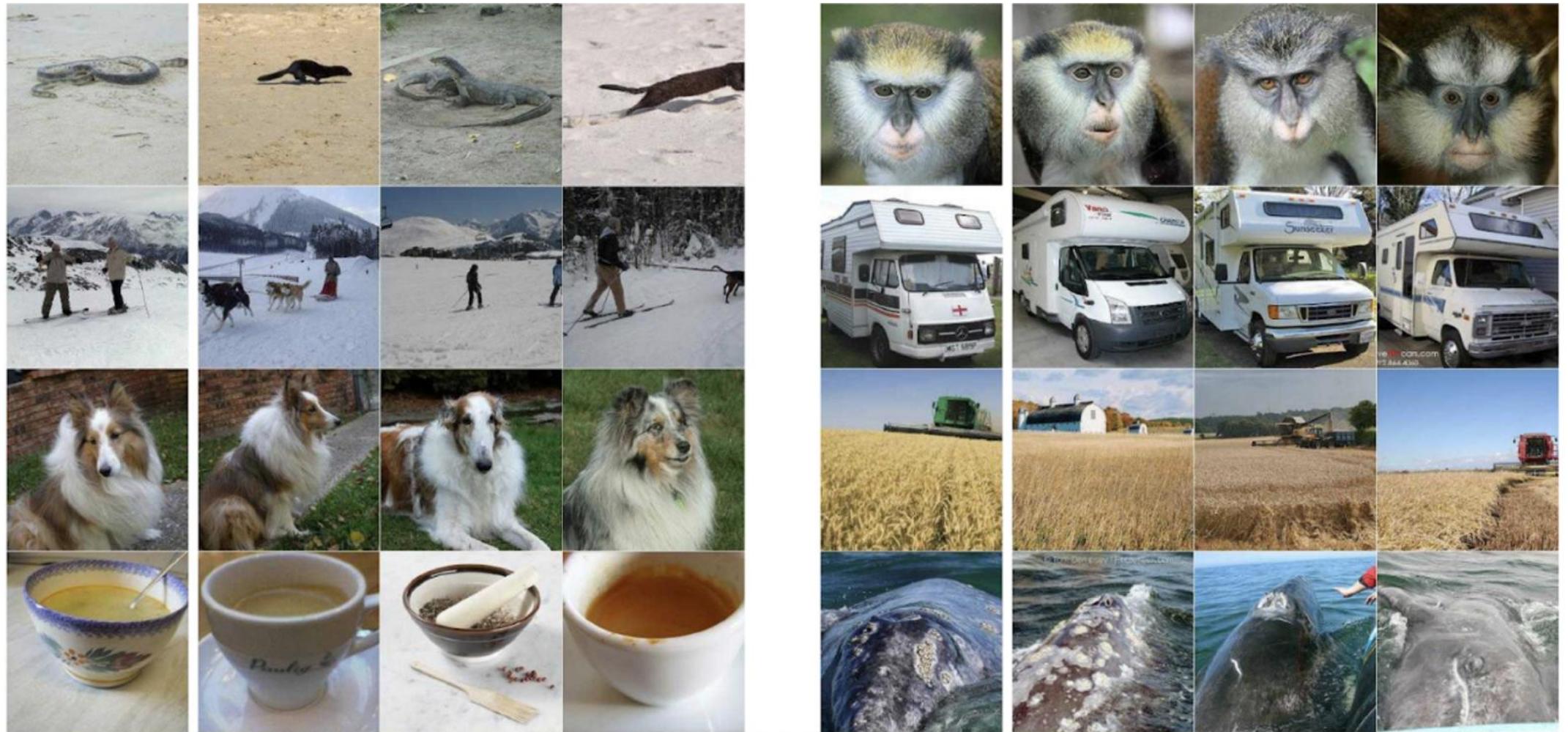
# BigBiGAN



# BigBiGAN: Representation Learning

Method	Architecture	Feature	Top-1	Top-5
BiGAN [7, 42]	AlexNet	Conv3	31.0	-
SS-GAN [4]	ResNet-19	Block6	38.3	-
Motion Segmentation (MS) [30, 6]	ResNet-101	AvePool	27.6	48.3
Exemplar (Ex) [8, 6]	ResNet-101	AvePool	31.5	53.1
Relative Position (RP) [5, 6]	ResNet-101	AvePool	36.2	59.2
Colorization (Col) [41, 6]	ResNet-101	AvePool	39.6	62.5
Combination of MS+Ex+RP+Col [6]	ResNet-101	AvePool	-	69.3
CPC [39]	ResNet-101	AvePool	48.7	73.6
Rotation [11, 24]	RevNet-50 $\times$ 4	AvePool	55.4	-
Efficient CPC [17]	ResNet-170	AvePool	61.0	83.0
BigBiGAN (ours)	ResNet-50	AvePool	55.4	77.4
	ResNet-50	BN+CReLU	56.6	78.6
	RevNet-50 $\times$ 4	AvePool	60.8	81.4
	RevNet-50 $\times$ 4	BN+CReLU	61.3	81.9

# BigBiGAN: Latent Space NNs



# BigBiGAN Reconstructions

Computing a reconstruction  $\mathbf{x}' = G(E(\mathbf{x}))$ :

- (1) Sample a real image  $\mathbf{x} \sim P_x$
- (2) Encoder predicts latents  $\mathbf{z}' = E(\mathbf{x})$
- (3) Generator predicts reconstruction  $\mathbf{x}' = G(\mathbf{z}')$

**(Big)BiGAN is not directly trained for reconstruction!**

Arises out of the objective: approx. reconstruction  $\mathbf{x}' \cong G(E(\mathbf{x}))$  optimally confuses the joint data-latent discriminator.

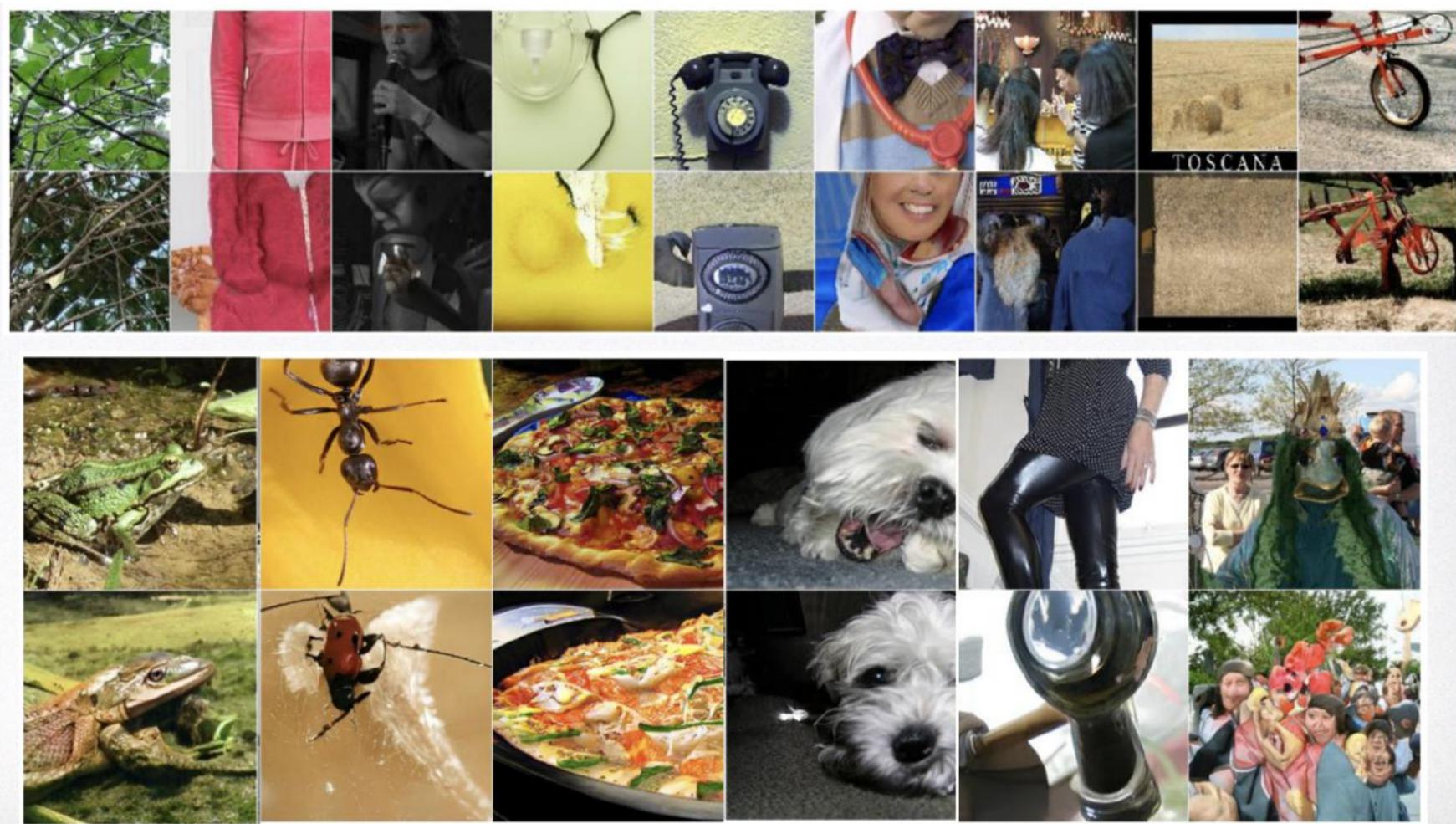
Reconstructions give insight into the semantics modeled.

real images  $\mathbf{x}$



reconstructions  $\mathbf{x}' = G(E(\mathbf{x}))$

# BigBiGAN Reconstructions



# Lecture overview

- Motivation and Definition of Implicit Models
- Original GAN (Goodfellow et al, 2014)
- Evaluation: Parzen, Inception, Frechet
- Theory of GANs
- GAN Progression
- Conditional GANs, Cycle-Consistent Adversarial Networks
- GANs and Representations
- Applications

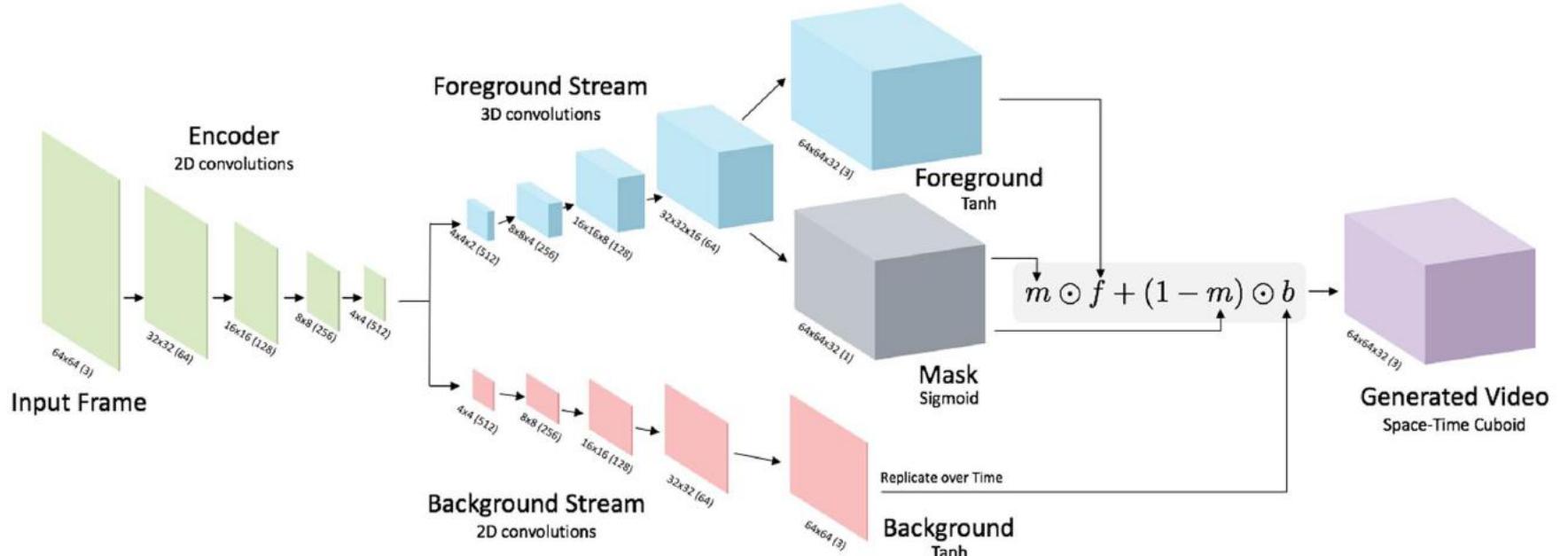
# Semi-supervised Classification

(Salimans et al., 2016;  
Dumoulin et al., 2016)

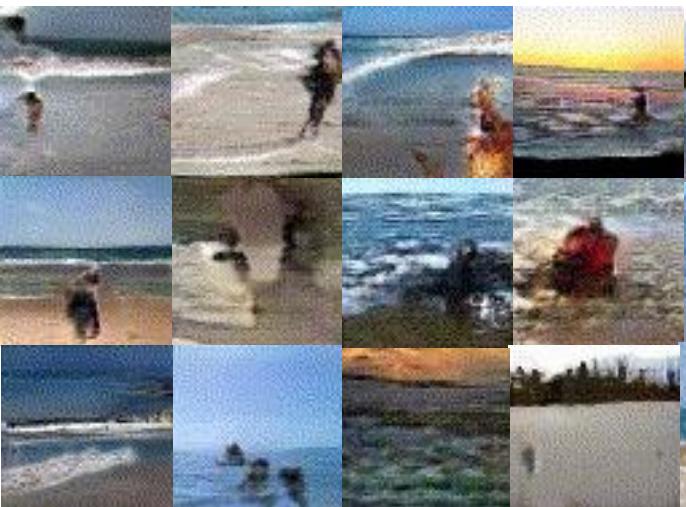
## SVNH

Model	Misclassification rate
VAE (M1 + M2) (Kingma et al., 2014)	36.02
SWWAE with dropout (Zhao et al., 2015)	23.56
DCGAN + L2-SVM (Radford et al., 2015)	22.18
SDGM (Maaløe et al., 2016)	16.61
<b>GAN (feature matching) (Salimans et al., 2016)</b>	<b><math>8.11 \pm 1.3</math></b>
ALI (ours, L2-SVM)	$19.14 \pm 0.50$
<b>ALI (ours, no feature matching)</b>	<b><math>7.42 \pm 0.65</math></b>

# Video Generation (Vondrick et al., 2016)



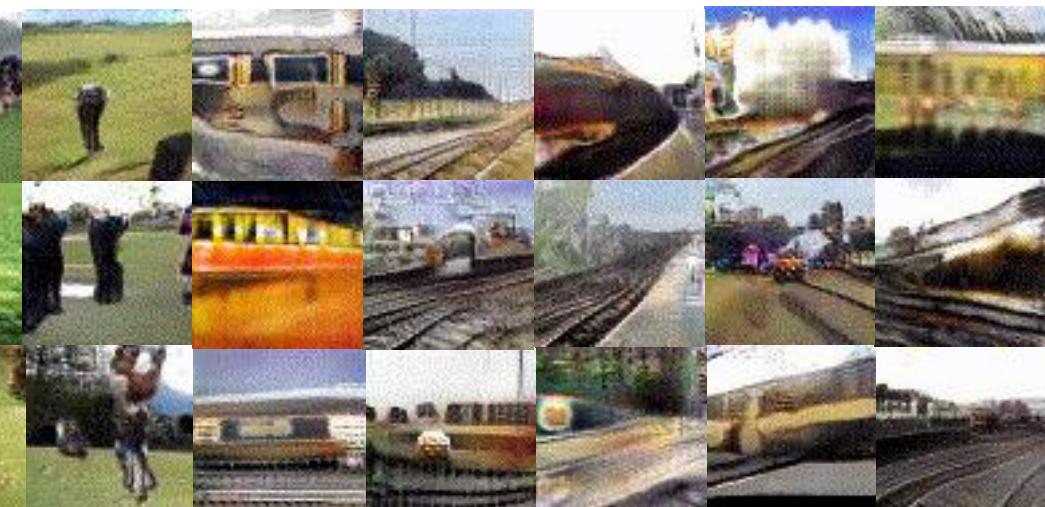
Beach



Golf

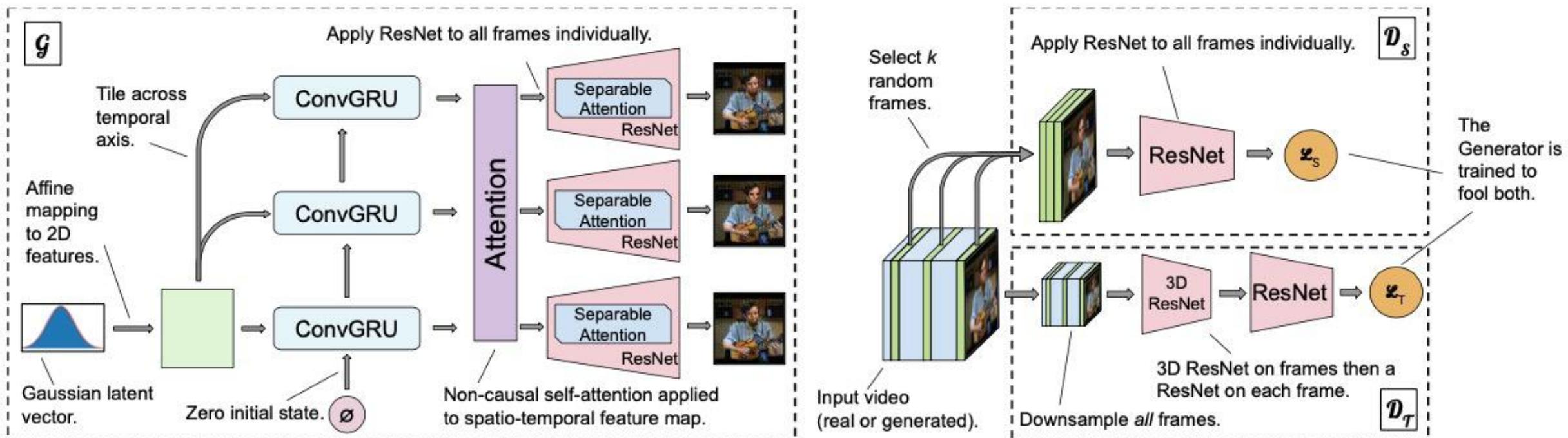


Train Station



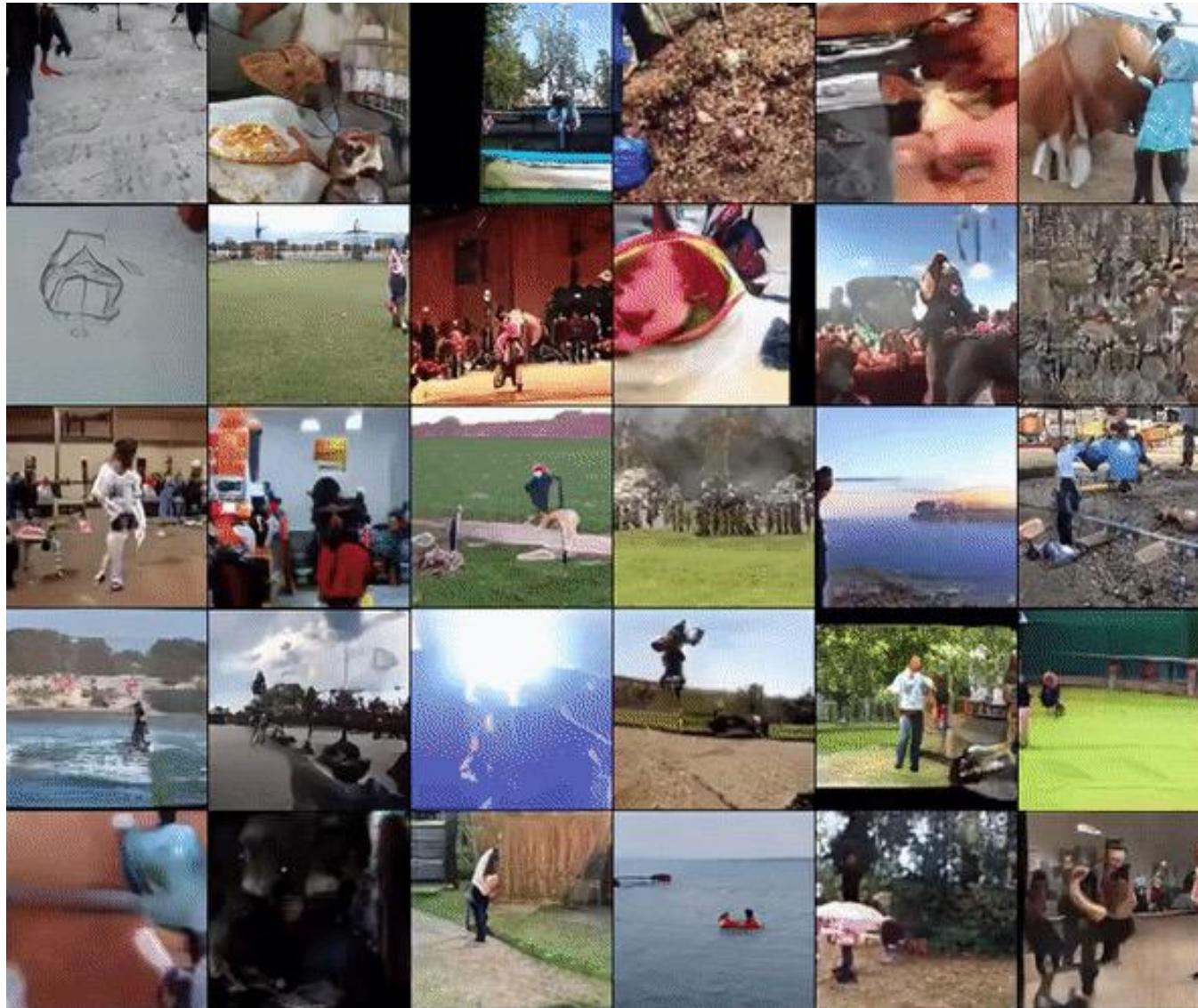
# DVD-GAN: Efficient Video Generation

(Clark et al., 2019)



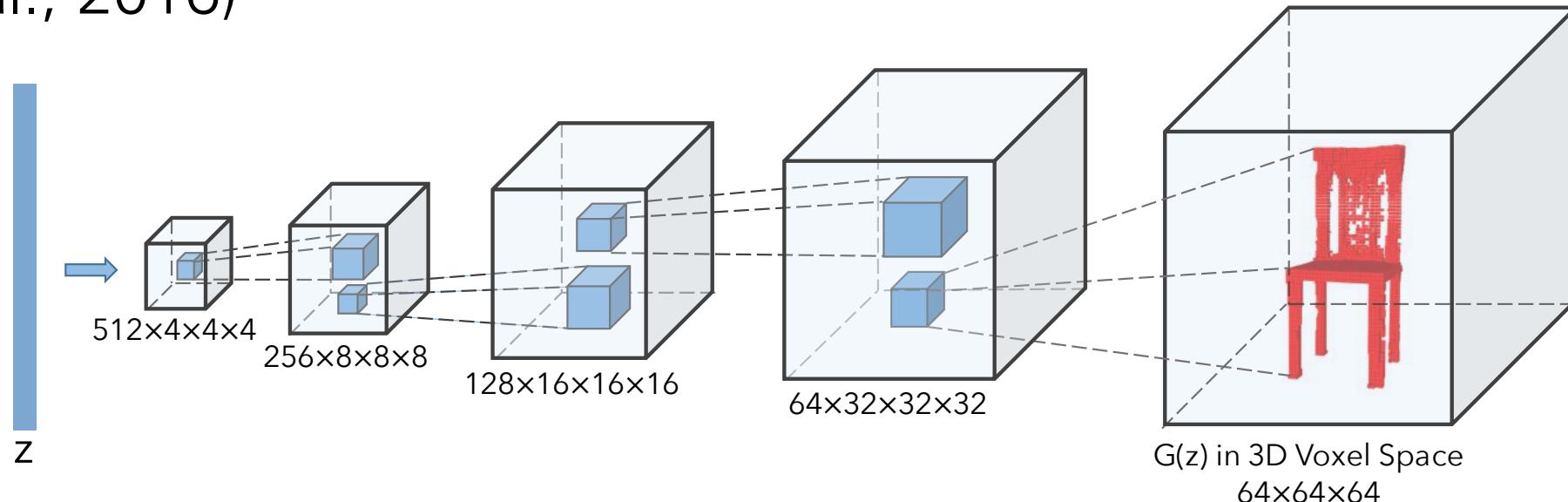
# DVD-GAN: Efficient Video Generation

(Clark et al., 2019)

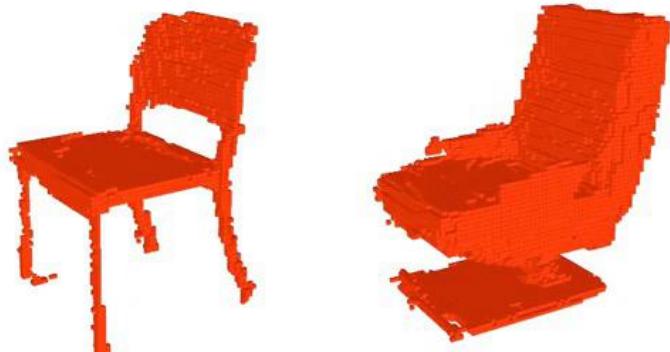


# 3DGAN: Generative Shape Modeling

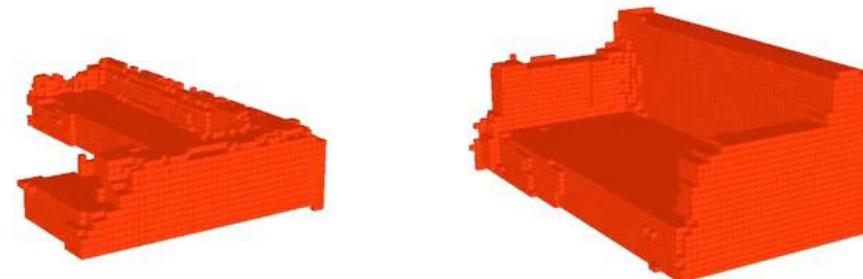
(Wu et al., 2016)



Chairs

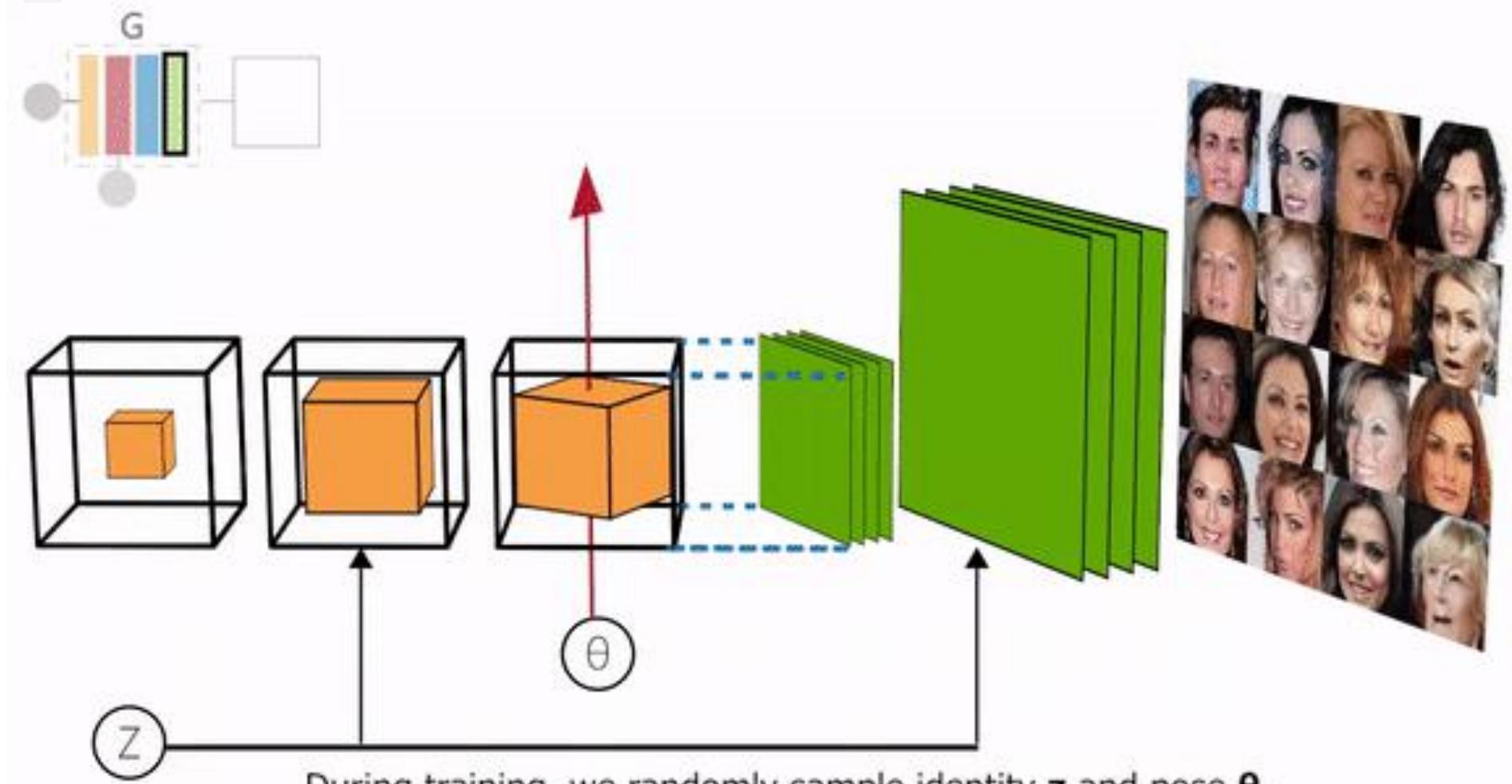


Sofas



# HoloGAN: Learning 3D Representations from Images

(Nguyen-Phuoc et al., 2020)



# HoloGAN: Learning 3D Representations from Images

(Nguyen-Phuoc et al., 2020)



# Vid2Vid: Video to Video Synthesis



# Motion Transfer: Everybody Dance Now



# StackGAN: Text-to-Image Synthesis (Zhang et al.'16)

The small bird has a red head with feathers that fade from red to gray from head to tail



The petals of this flower are white with a large stigma

A unique yellow flower with no visible pistils protruding from the center

This flower is pink and yellow in color, with petals that are oddly shaped

This is a light colored flower with many different petals on a green stem

This flower is yellow and green in color, with petals that are ruffled

The flower have large petals that are pink with yellow on some of the petals

A flower that has white petals with some tones of yellow and green filaments



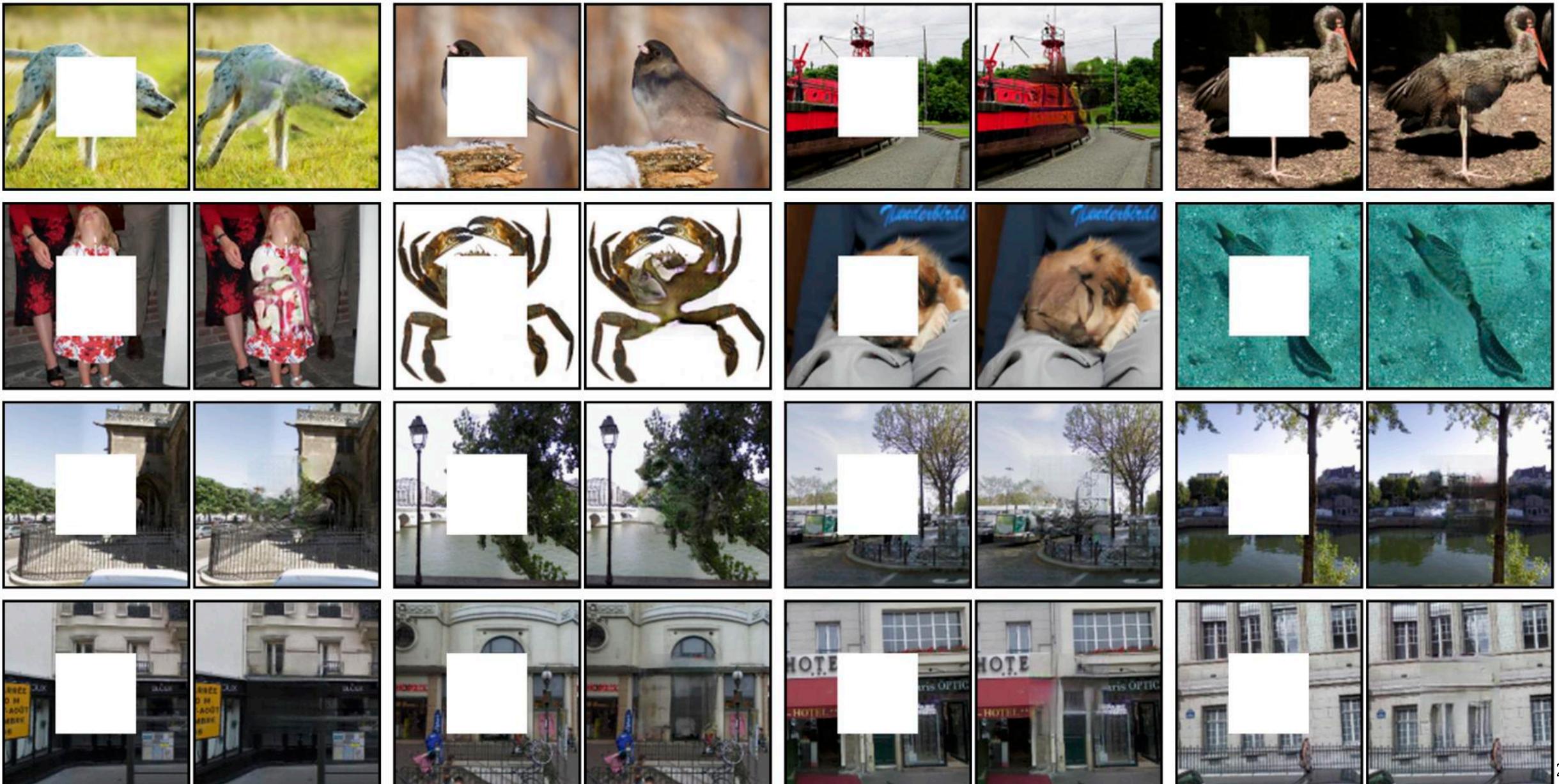
# SRGAN: Single Image Super-Resolution

(Ledig et al., 2017)

- Combine content loss with adversarial loss



# Image Inpainting (Pathak et al., 2016)



# Unsupervised Domain Adaptation (Bousmalis et al., 2016)

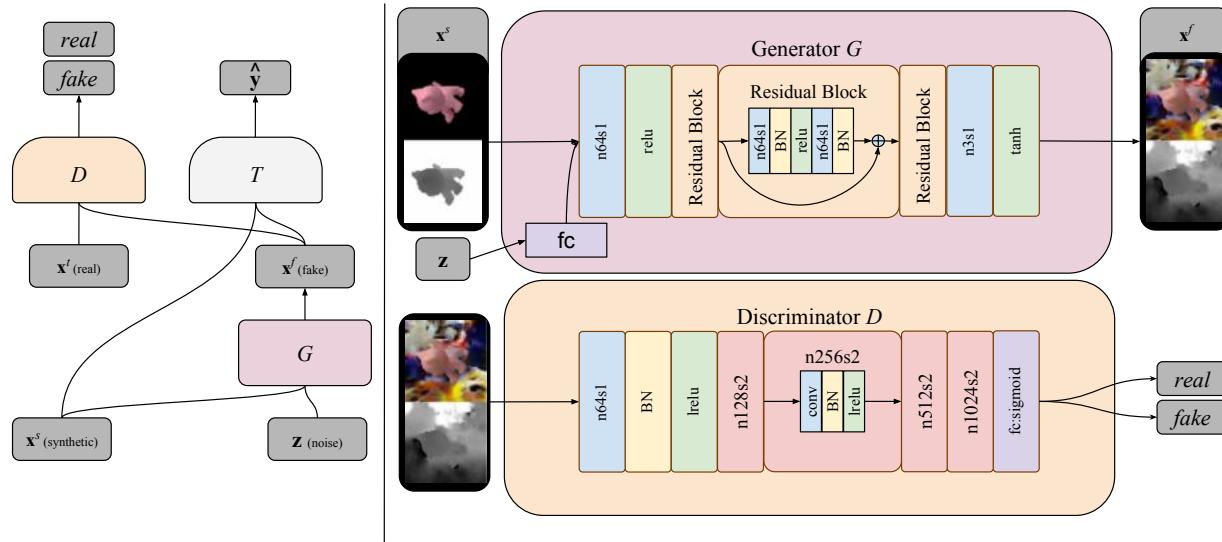
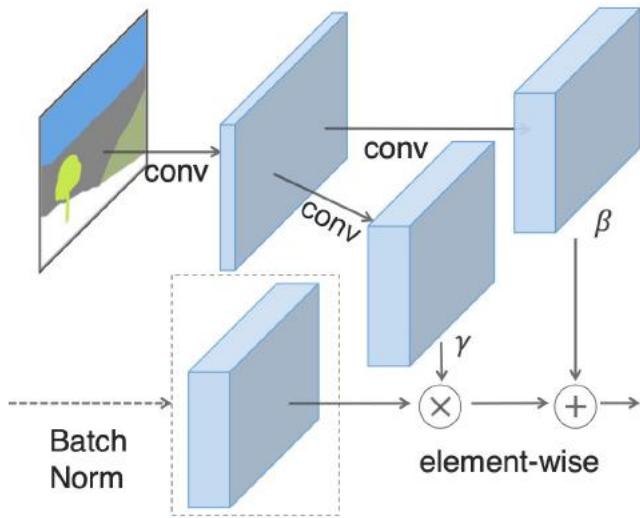


Image examples from the Linemod dataset



RGDB image samples  
(conditioned on a synthetic image)

# Semantic Image Editing: GauGAN

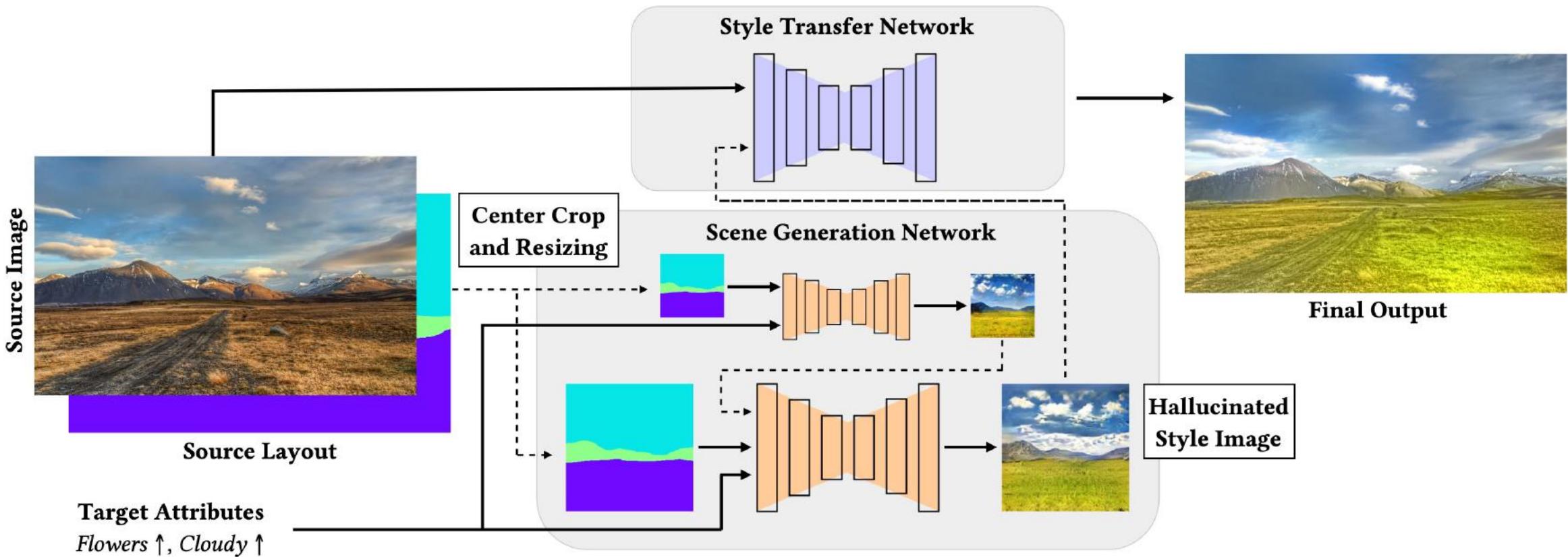


(Park et al. 2019)

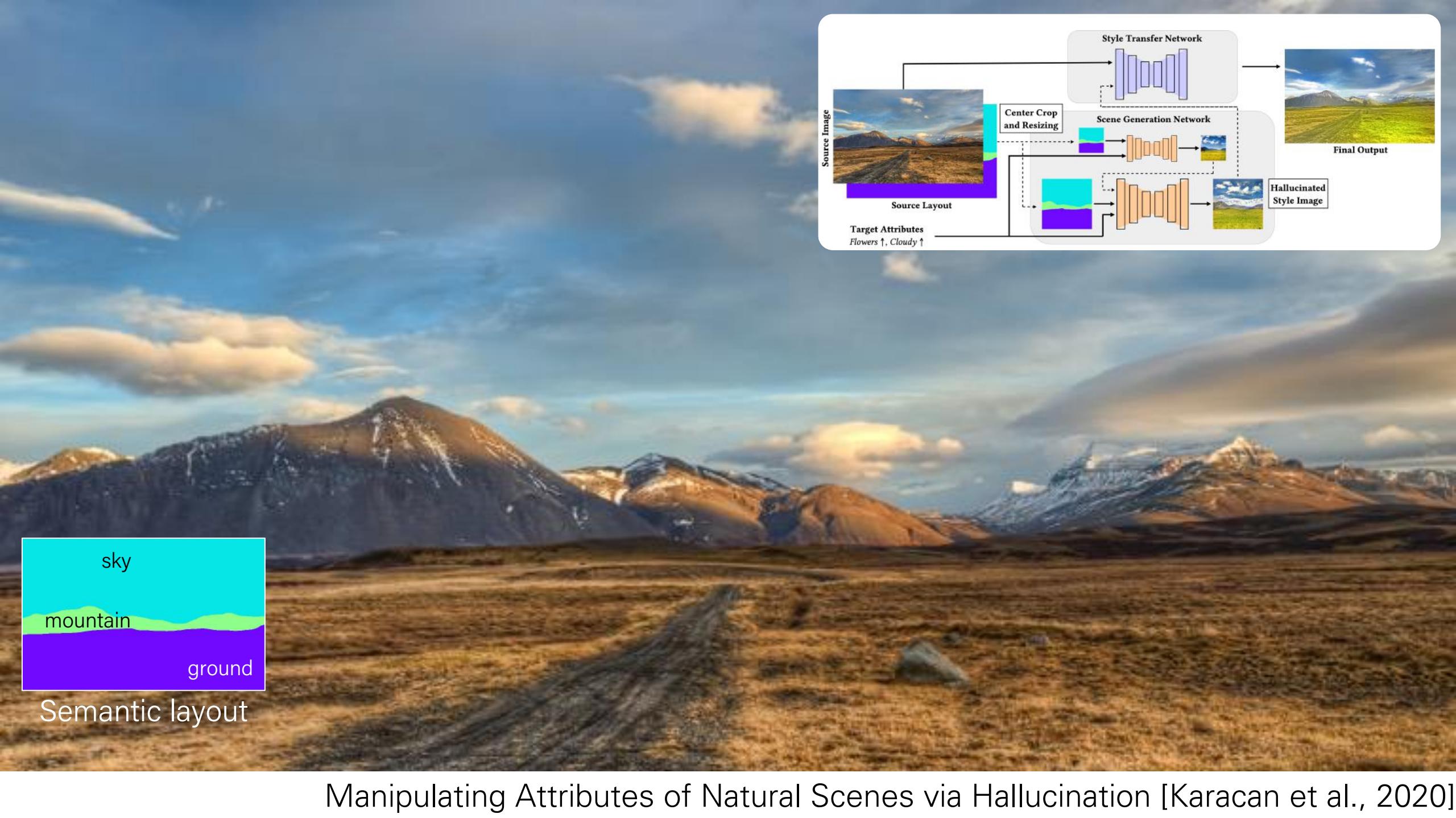


# Semantic Image Editing

(Karacan et al. 2020)



[https://hucvl.github.io/attribute\\_hallucination/](https://hucvl.github.io/attribute_hallucination/)





Manipulating Attributes of Natural Scenes via Hallucination [Karacan et al., 2020]



night

prediction

A wide-angle photograph of a sunset over a mountain range. The sky is filled with warm, orange and yellow hues, with scattered clouds. In the foreground, there is a dark, flat landscape, possibly a plain or a large body of water. The mountains in the background are silhouetted against the bright sky.

sunset





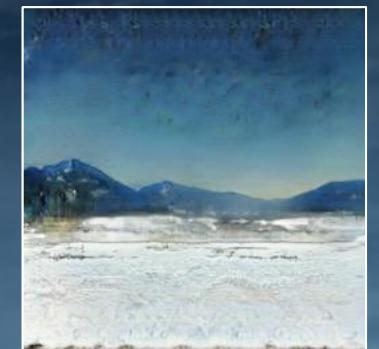
snow



prediction



winter



prediction

Spring and clouds



prediction





Moist, rain and fog



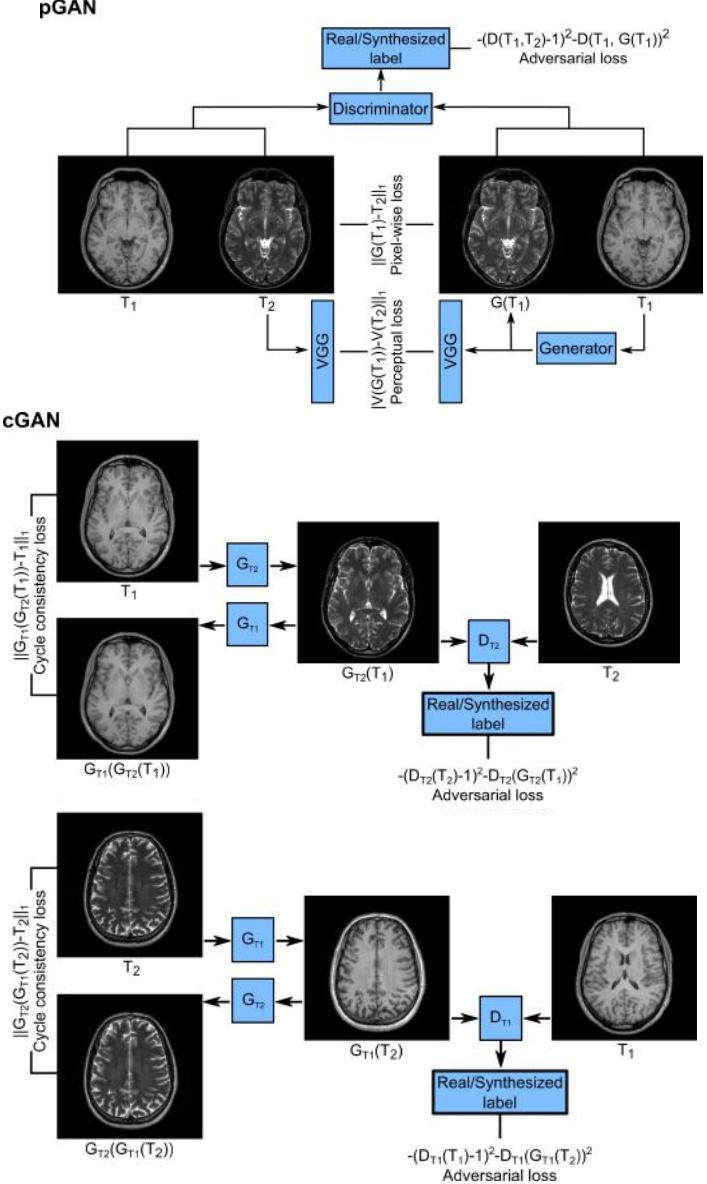
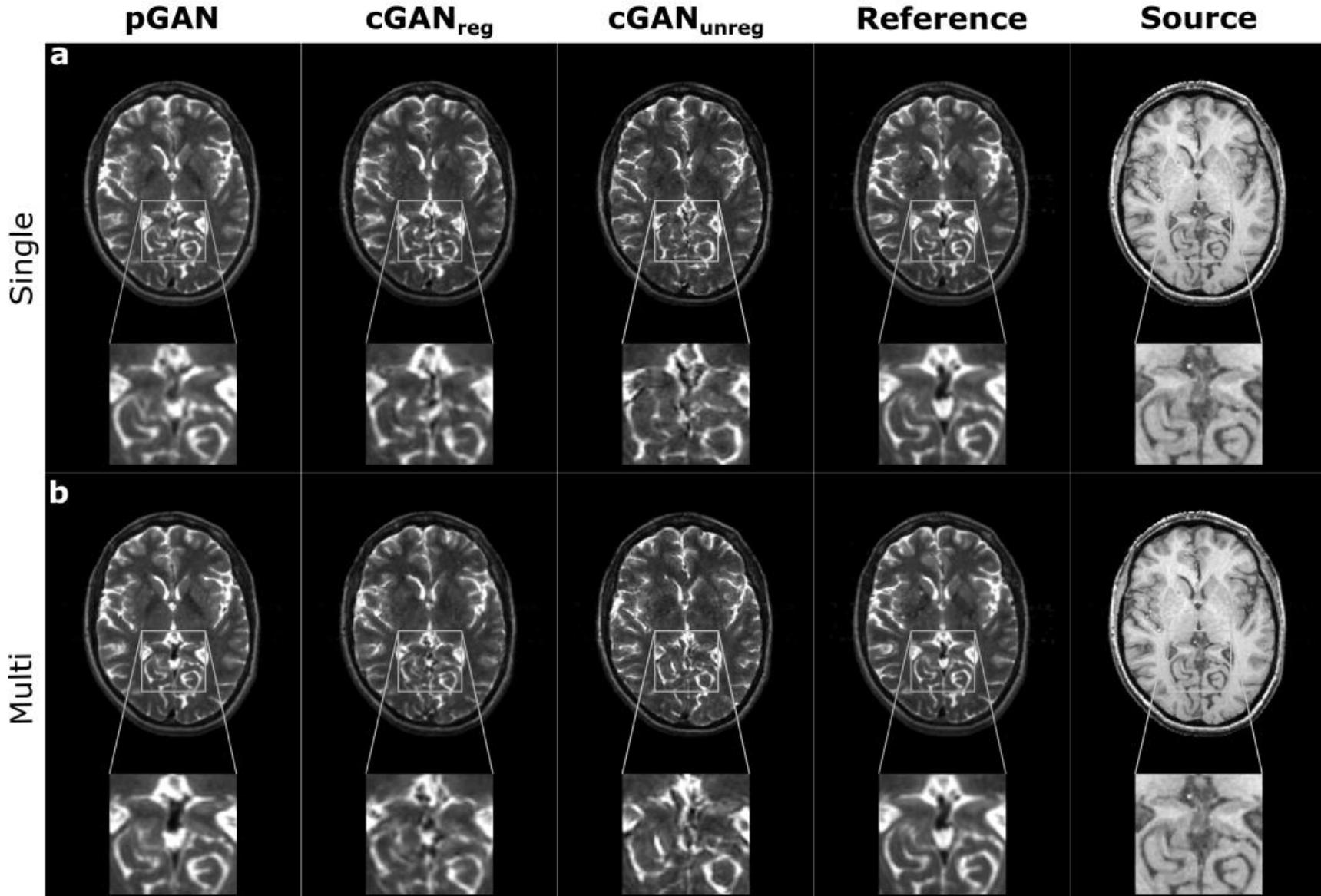
prediction



flowers

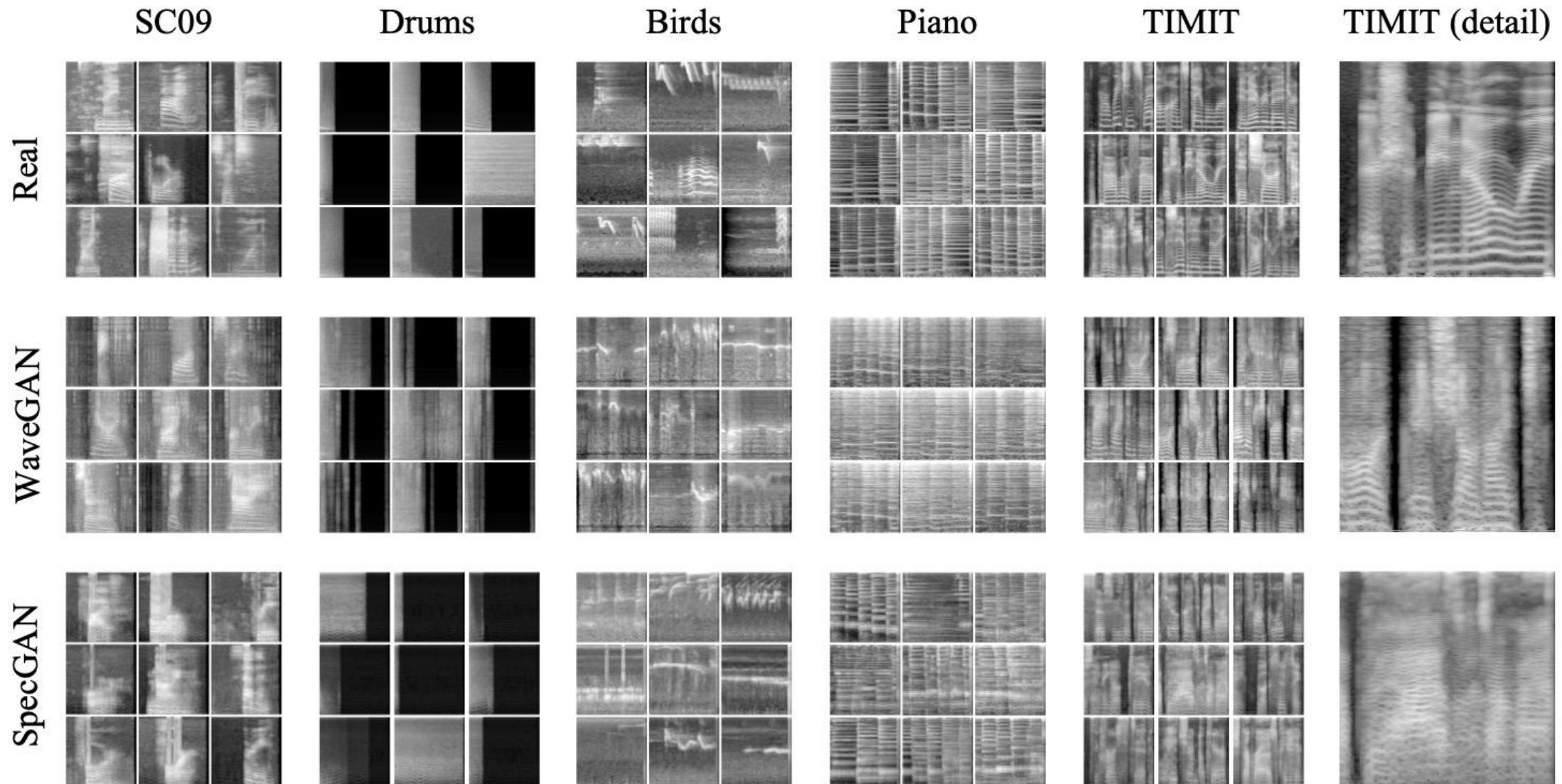


prediction



- Image Synthesis in Multi-Contrast MRI [UI Hassan Dar et al. 2019]

# Audio Synthesis: WaveGAN (Donahue et al. 2020)



# Text Generation: MaskGAN (Fedus et al. 2018)

<b>Ground Truth</b>	Pitch Black was a complete shock to me when I first saw it back in 2000 In the previous years I
MaskGAN	Pitch Black was a complete shock to me when I first saw it back in <u>1979</u> I was really looking forward
MaskMLE	Black was a complete shock to me when I first saw it back in <u>1969</u> I live in New Zealand

Table 3: Conditional samples from IMDB for both MaskGAN and MaskMLE models.

**Next lecture:**  
**Discrete Latent Variable Models**