(W)GANs

Danica J. Sutherland



(from thispersondoesnotexist.com)

MLCC 2019

Generative models

- Start with a bunch of examples: $X_1, \ldots, X_n \sim \mathbb{P}$
- Want a model for the data: $\mathbb{Q} \approx \mathbb{P}$

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 - Find outliers, anomalies, ...
 - Discover underlying structure of the data
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Why produce samples?



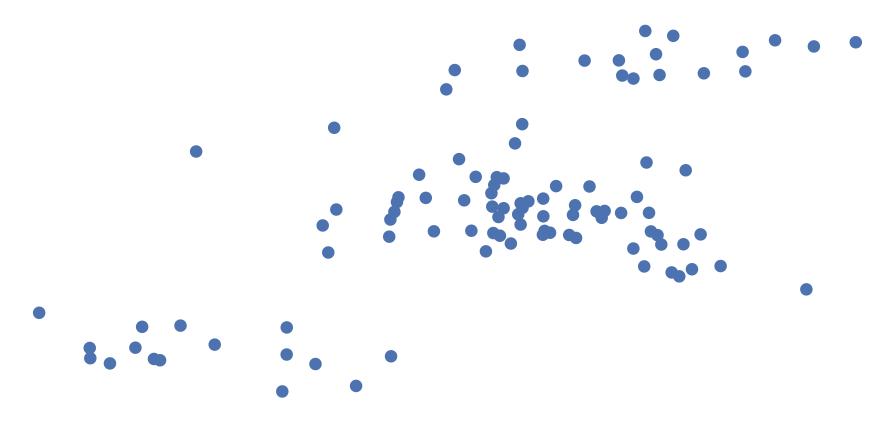
Is artificial intelligence set to become art's next medium?

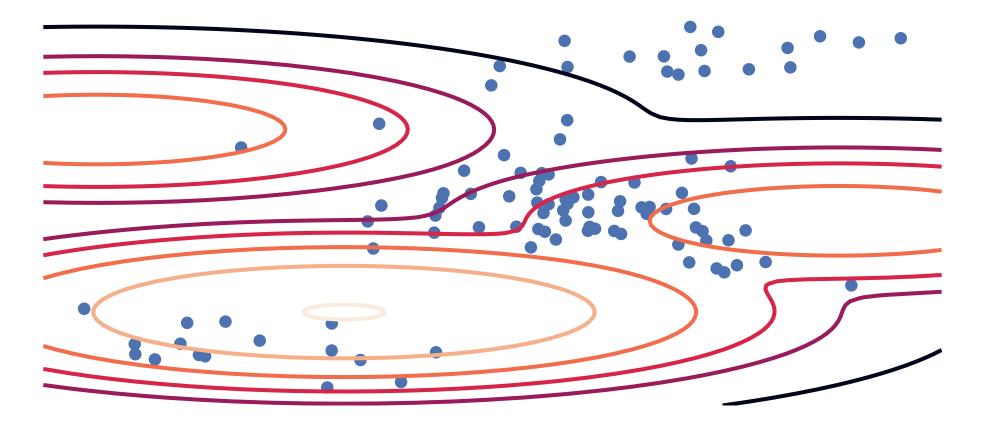
Al artwork sells for \$432,500 — nearly 45 times its high estimate — as Christie's becomes the first auction house to offer a work of art created by an algorithm

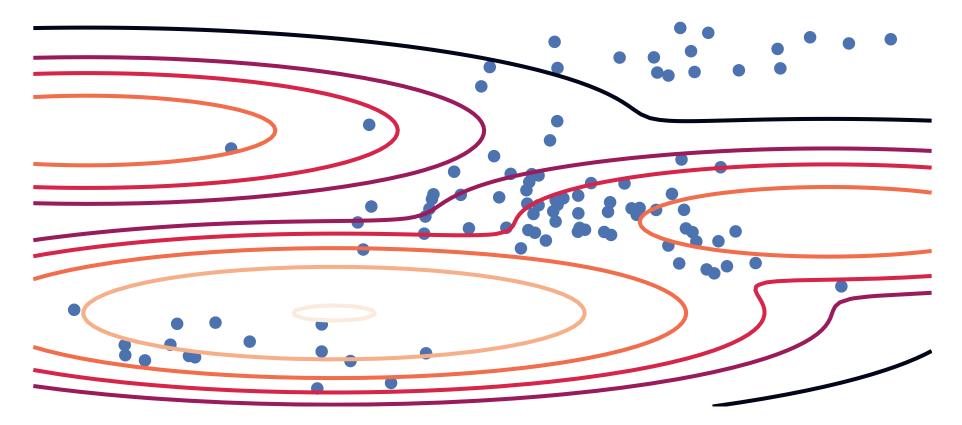
The portrait in its gilt frame depicts a portly gentleman, possibly French and — to judge by his dark frockcoat and plain white collar — a man of the church. The work appears unfinished: the facial features are somewhat indistinct and there are blank areas of canvas. Oddly, the whole composition is displaced slightly to the north-west. A label on the wall states that the sitter is a man named Edmond Belamy, but the giveaway clue as to the origins of the work is the artist's signature at the bottom right. In cursive Gallic script it reads:

 $\min_{G} \max_{D} \mathbb{E}_{x}[\log(D(x))] + \mathbb{E}_{z}[\log(1 - D(G(z)))]$

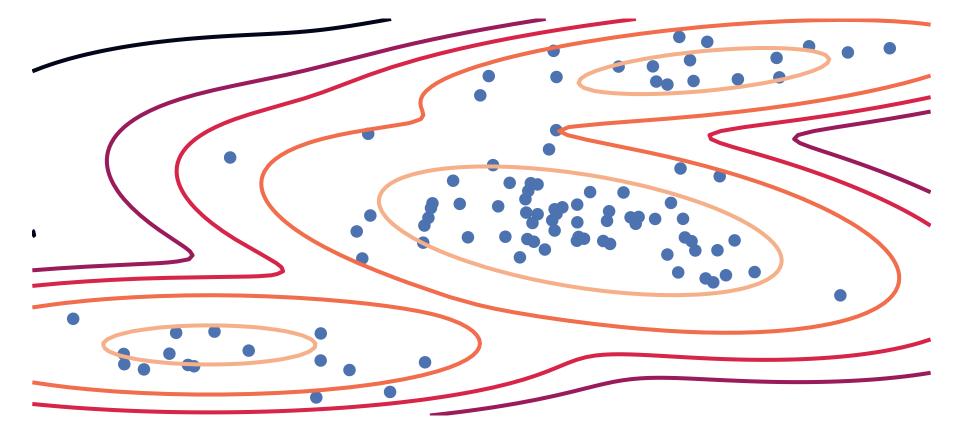
Image © Obvious



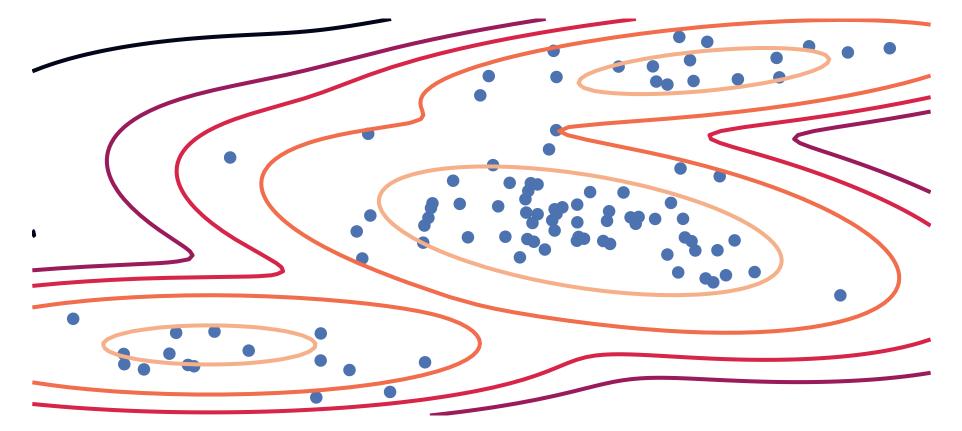




• Maximum likelihood: $\max_{ heta} \mathbb{E}_{X \sim \mathbb{P}}[\log q_{ heta}(X)]$



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- Maximum likelihood: $\max_{ heta} \mathbb{E}_{X \sim \mathbb{P}}[\log q_{ heta}(X)]$
- Equivalent: $\min_{\theta} \operatorname{KL}(\mathbb{P} \| \mathbb{Q}_{\theta}) = \min_{\theta} \int p(x) \log \frac{p(x)}{q_{\theta}(x)} \mathrm{d}x$

Traditional models for images

• 1987-style generative model of faces (Eigenface via Alex Egg)



Traditional models for images

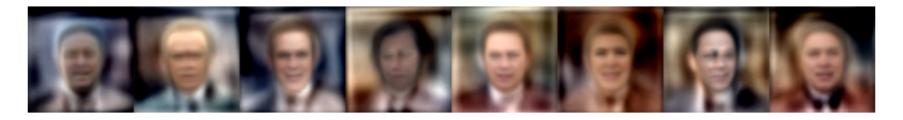
• 1987-style generative model of faces (Eigenface via Alex Egg)



• Can do fancier versions, of course...

Traditional models for images

• 1987-style generative model of faces (Eigenface via Alex Egg)



- Can do fancier versions, of course...
- Usually based on Gaussian noise $pprox L_2$ loss

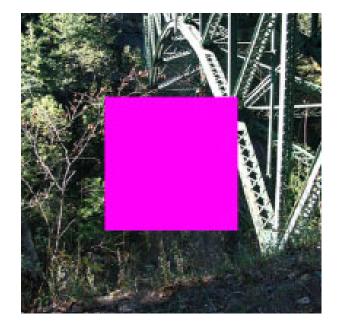
• One use case of generative models is inpainting [Harry Yang]:



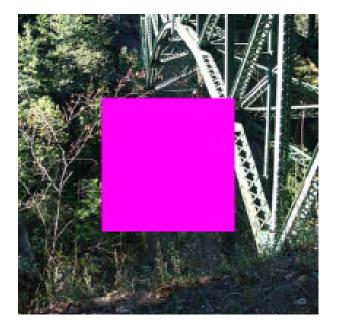


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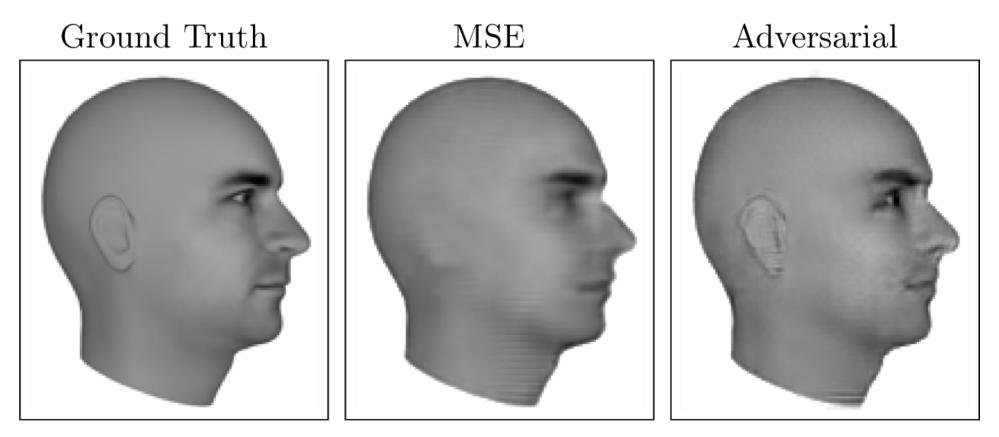
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Next-frame video prediction



[Lotter+ 2016]

Generator (\mathbb{Q}_{θ})





Generator (\mathbb{Q}_{θ})





Target (\mathbb{P})









Target (\mathbb{P})







No way! $\Pr(\text{real}) = 0.03$

Target (P)











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Is this real?







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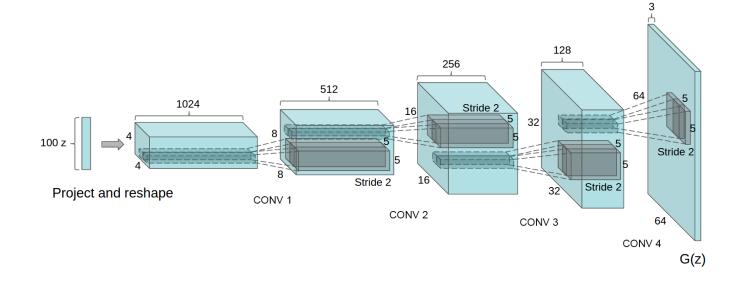


No way! Pr(real) = 0.03

 $\text{Umm...} \Pr(\text{real}) = 0.48$

Generator networks

• How to specify \mathbb{Q}_{θ} ?



[Radford+ ICLR-16]

- $Z \sim \mathbb{Z} = \text{Uniform}\left([-1,1]^{100}
 ight)$
- $G_{m heta}: [-1,1]^{100} o \mathcal{X}$, $G_{m heta}(Z) \sim \mathbb{Q}_{m heta}$

GANs in equations

• Tricking the discriminator:

$$\min_{oldsymbol{ heta}} \max_{\psi} rac{1}{2} \mathop{\mathbb{E}}_{X \sim \mathbb{P}}[\log D_{\psi}(X)] + rac{1}{2} \mathop{\mathbb{E}}_{Y \sim \mathbb{Q}_{oldsymbol{ heta}}}[\log(1 - D_{\psi}(Y))]$$

GANs in equations

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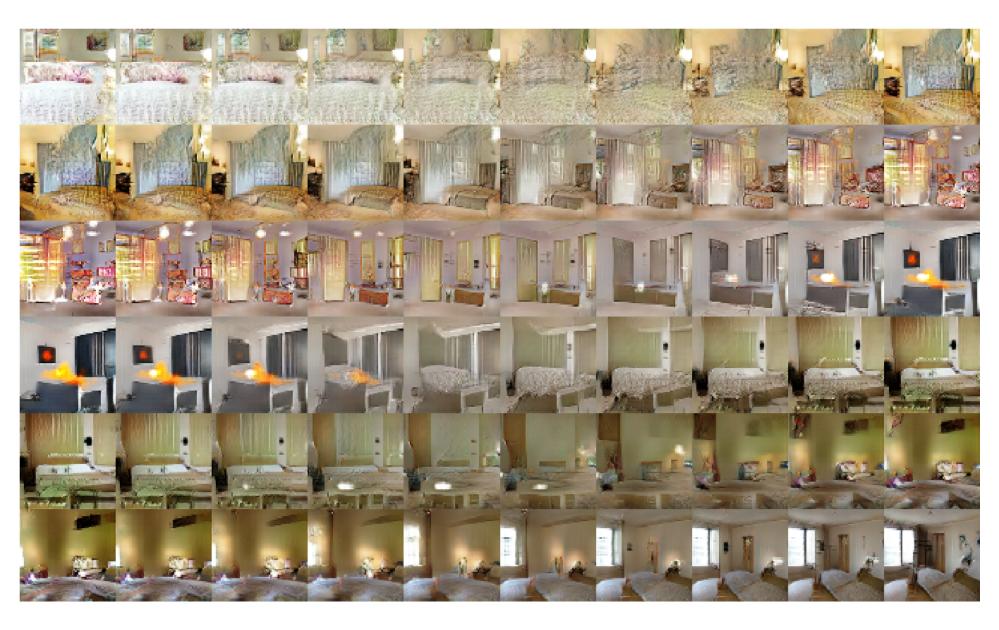
• Can do alternating gradient descent!

Original paper's results [Goodfellow+ NeurIPS-14]





DCGAN results [Radford+ ICLR-16]



Training instability

Running code from [Salimans+ NeurIPS-16]:

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Run 1, epoch 1

Training instability

Running code from [Salimans+ NeurIPS-16]:

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Run 1, epoch 2

Training instability

Running code from [Salimans+ NeurIPS-16]:

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Run 1, epoch 3

Running code from [Salimans+ NeurIPS-16]:



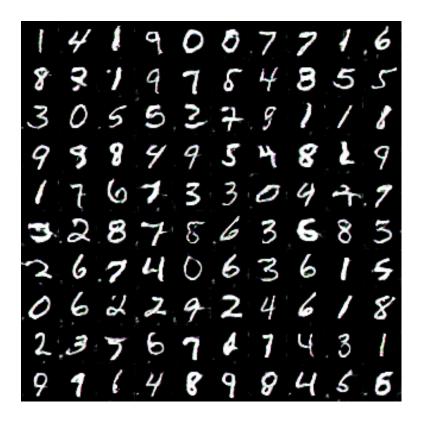
Running code from [Salimans+ NeurIPS-16]:



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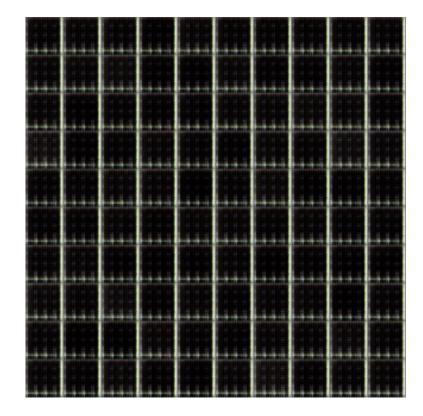


Running code from [Salimans+ NeurIPS-16]:



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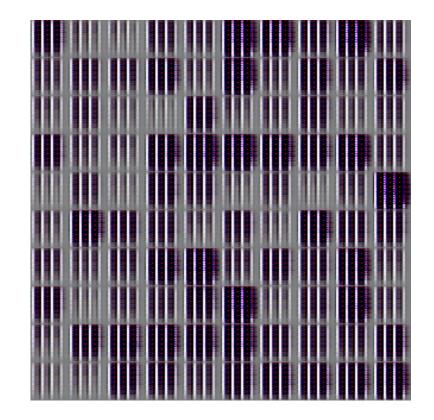




Run 1, epoch 900

Running code from [Salimans+ NeurIPS-16]:

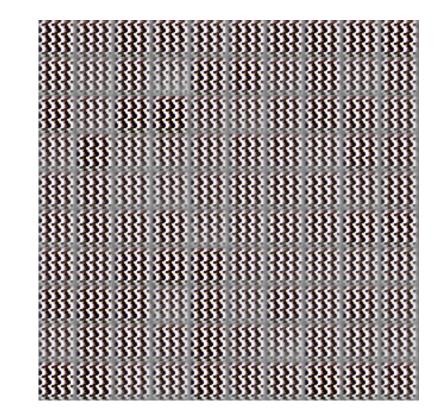




Run 1, epoch 900

Running code from [Salimans+ NeurIPS-16]:

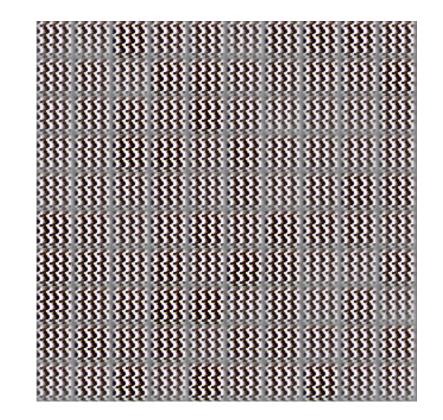




Run 1, epoch 900

Running code from [Salimans+ NeurIPS-16]:

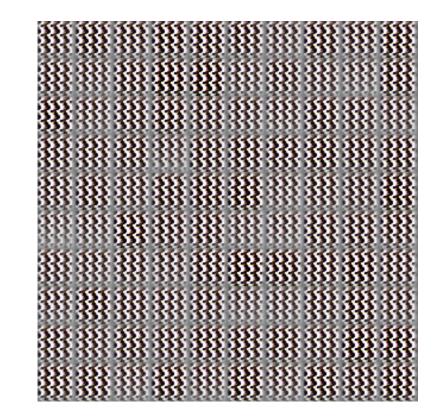




Run 1, epoch 900

Running code from [Salimans+ NeurIPS-16]:





Run 1, epoch 900

One view: distances between distributions

• What happens when D_ψ is at its optimum?

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- What happens when D_ψ is at its optimum?
- If distributions have densities, $D^*_\psi(x) = rac{p(x)}{p(x)+q_ heta(x)}$

One view: distances between distributions

- What happens when D_ψ is at its optimum?
- If distributions have densities, $D^*_\psi(x) = rac{p(x)}{p(x)+q_ heta(x)}$
- If D_ψ stays optimal throughout, heta tries to minimize

$$\frac{1}{2} \mathop{\mathbb{E}}_{X \sim \mathbb{P}} \left[\log \frac{p(X)}{p(X) + q_{\theta}(X)} \right] + \frac{1}{2} \mathop{\mathbb{E}}_{Y \sim \mathbb{Q}_{\theta}} \left[\log \frac{q_{\theta}(X)}{p(X) + q_{\theta}(X)} \right]$$

which is $\mathrm{JS}(\mathbb{P},\mathbb{Q}_{ heta}) - \log 2$

Jensen-Shannon divergence

$$egin{aligned} \mathrm{JS}(\mathbb{P},\mathbb{Q}_{ heta}) &= rac{1}{2}\int p(x)\lograc{p(x)}{rac{1}{2}p(x)+rac{1}{2}q_{ heta}(x)}\mathrm{d}x \ &+ rac{1}{2}\int q_{ heta}(x)\lograc{q_{ heta}(x)}{rac{1}{2}p(x)+rac{1}{2}q_{ heta}(x)}\mathrm{d}x \end{aligned}$$

Jensen-Shannon divergence

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$$egin{aligned} \mathrm{JS}(\mathbb{P},\mathbb{Q}_{ heta}) &= rac{1}{2}\int p(x)\lograc{p(x)}{rac{1}{2}p(x)+rac{1}{2}q_{ heta}(x)}\mathrm{d}x \ &+ rac{1}{2}\int q_{ heta}(x)\lograc{q_{ heta}(x)}{rac{1}{2}p(x)+rac{1}{2}q_{ heta}(x)}\mathrm{d}x \end{aligned}$$

• If \mathbb{P} and \mathbb{Q}_{θ} have (almost) disjoint support

$$rac{1}{2}\int p(x)\lograc{p(x)}{rac{1}{2}p(x)}\mathrm{d}x$$

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$$\frac{1}{2} \int p(x) \log \frac{p(x)}{\frac{1}{2}p(x)} dx = \frac{1}{2} \int p(x) \log(2) dx = \frac{1}{2} \log 2$$

so $\mathrm{JS}(\mathbb{P},\mathbb{Q}_{\theta}) = \log 2$

Generator (\mathbb{Q}_{θ})



Discriminator



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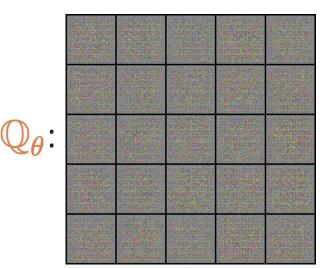






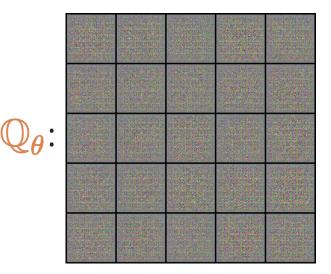
:(I don't know how to do any better...





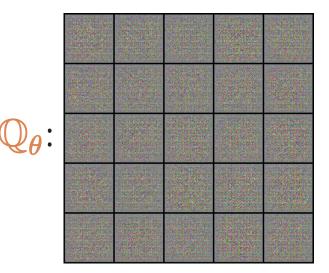
• At initialization, pretty reasonable:





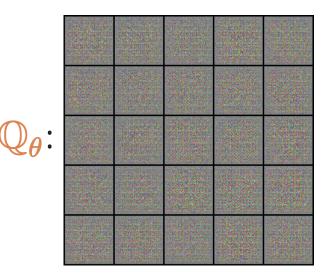
• Remember we might have $G_ heta: \mathbb{R}^{100} o \mathbb{R}^{64 imes 64 imes 3}$





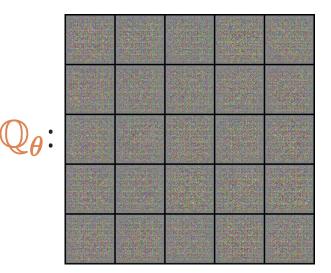
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- No chance that they'd align at init, so $\mathrm{JS}(\mathbb{P},\mathbb{Q}_{ heta}) = \log 2$

A heuristic partial workaround

• Original GANs almost never use the minimax game

 $\min_{\theta} \max_{\psi} \frac{1}{2} \mathop{\mathbb{E}}_{X \sim \mathbb{P}} [\log D_{\psi}(X)] + \frac{1}{2} \mathop{\mathbb{E}}_{Y \sim \mathbb{Q}_{\theta}} [\log(1 - D_{\psi}(Y))]$

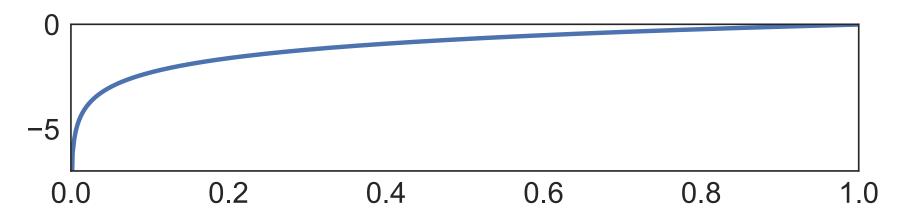
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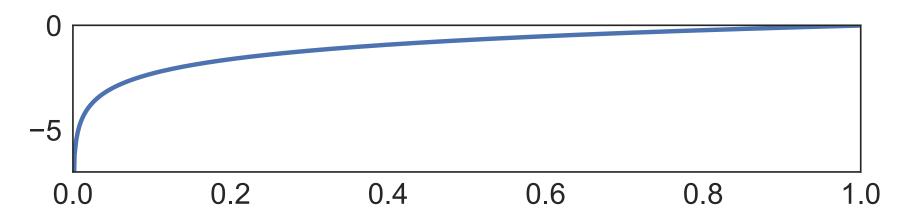


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- When D_ψ is near-perfect, makes it unstable instead of stuck

Better Solution 1: Optimal Transport to the rescue

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• Especially because of Kantorovich-Rubinstein duality:

$$\mathcal{W}_1(\mathbb{P},\mathbb{Q}) = \sup_{f:\|f\|_{ ext{Lip}} \leq 1} \mathbb{E}_{X \sim \mathbb{P}}[f(X)] - \mathbb{E}_{Y \sim \mathbb{Q}}[f(Y)]$$

The Wasserstein distance

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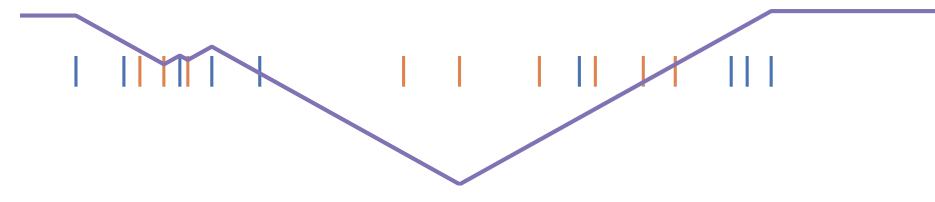
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- This turns out not to be a great idea.

WGAN-GP [Gulrajani+ NeurlPS-17]

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- Works well! But...does it really estimate Wasserstein?

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- Can also simplify to e.g. [Mescheder+ ICML-18]

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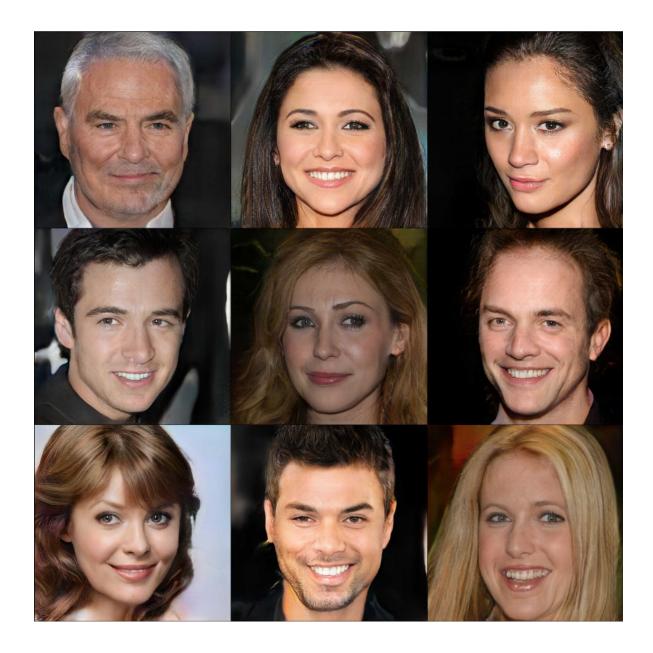
Solution 3: Spectral norm [Miyato+ ICLR-18]

- Regular deep nets: $f_\ell = \sigma \left(W_\ell f_{\ell-1}(x) + b_\ell
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New samples [Mescheder+ ICML-18]



How to evaluate?



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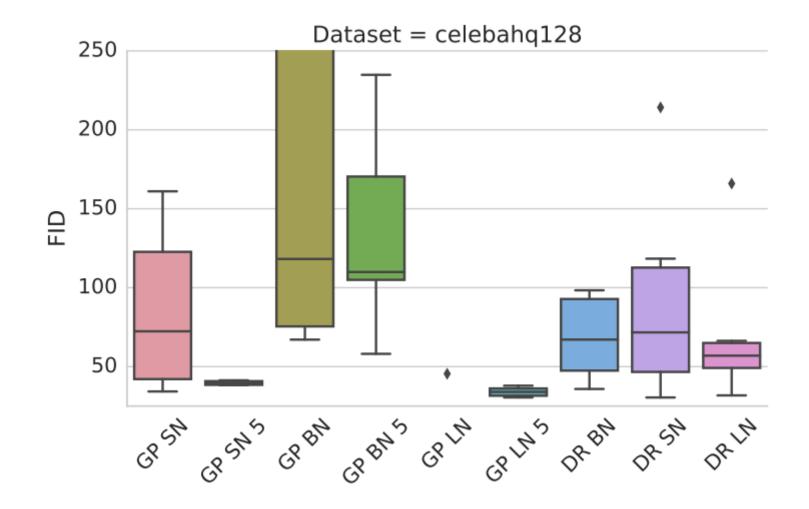
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 - Similar distance with unbiased, ~normal estimator!

Comparing approaches [Kurach+ ICML-19]

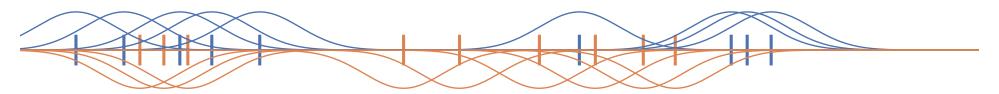


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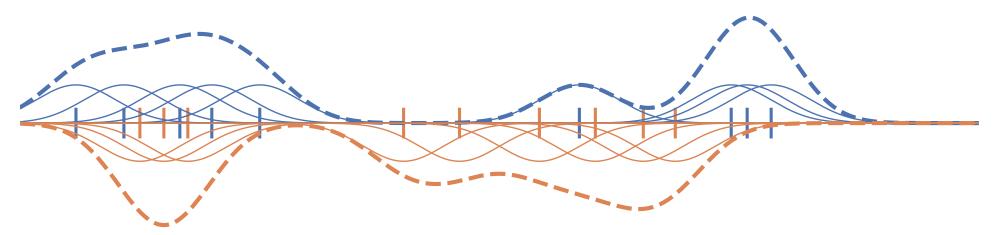
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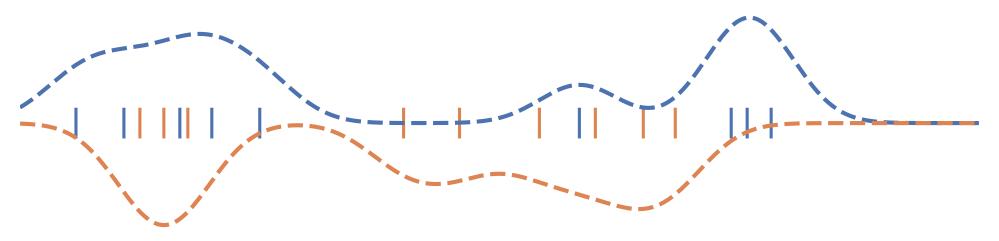
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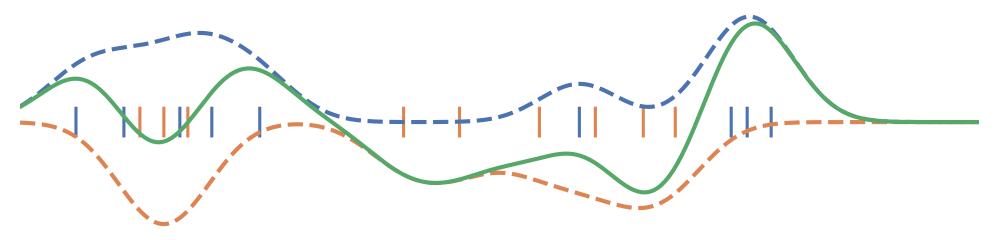
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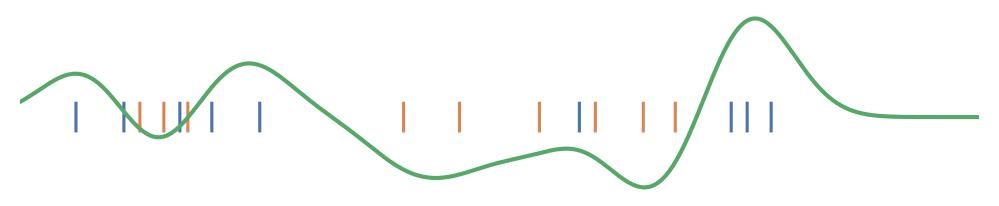


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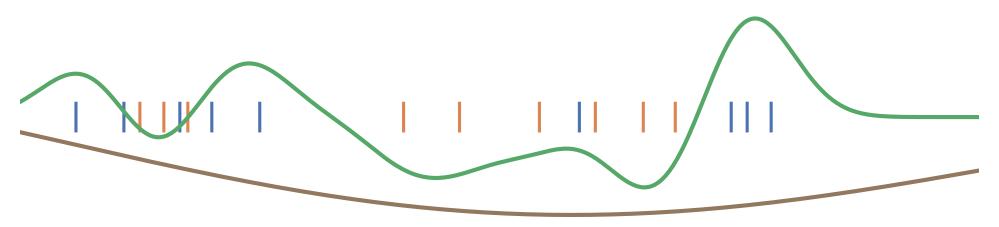
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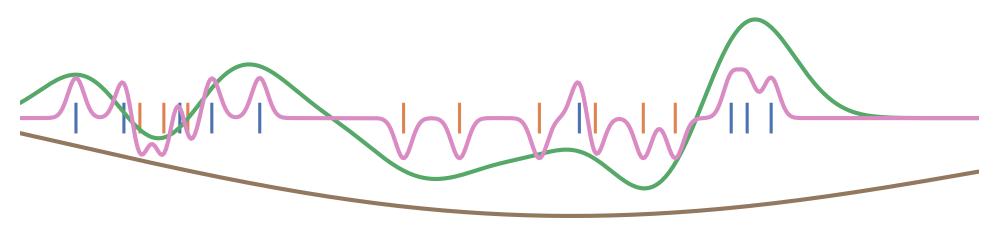
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 $\|f\|_{\mathcal{H}_k}$ is smoothness induced by kernel $k: \mathcal{X} \times \mathcal{X} \to \mathbb{R}$ Optimal f analytically: $f^*(t) \propto \mathbb{E}_{X \sim \mathbb{P}} k(t, X) - \mathbb{E}_{Y \sim \mathbb{Q}} k(t, Y)$

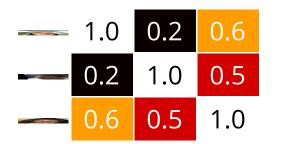
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 K_{XX} K_{YY}

	1.0	0.2	0.6		.0	0.8	0.7
and the second se	0.2	1.0	0.5	0	.8	1.0	0.6
	0.6	0.5	1.0	····· 0	.7	0.6	1.0

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1.0	0.2	0.6	· (~~~~~)/	1.0	0.8	0.7	· (~~~~~~~~)	0.3	0.1	0.2
0.2	1.0	0.5		0.8	1.0	0.6		0.2	0.3	0.3
0.6	0.5	1.0		0.7	0.6	1.0		0.2	0.1	0.4

- No need for a discriminator just minimize $\widetilde{\mathrm{MMD}}_k!$
- Continuous loss

Critic

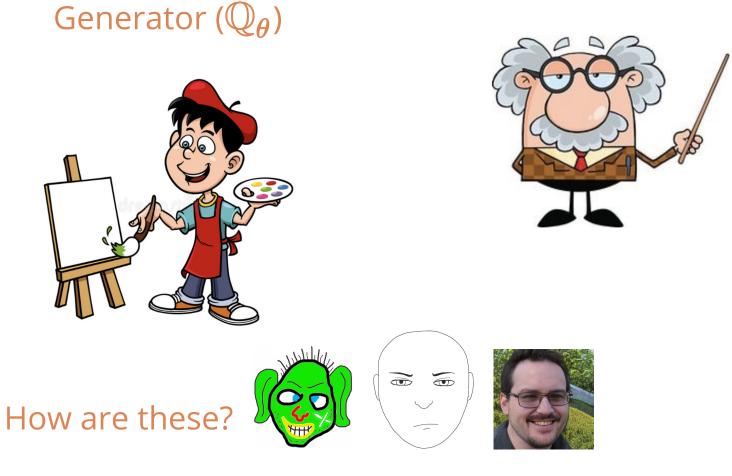






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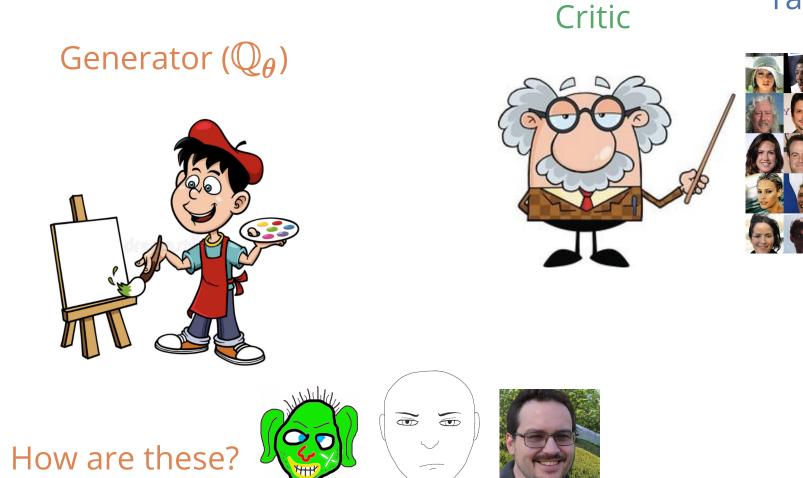




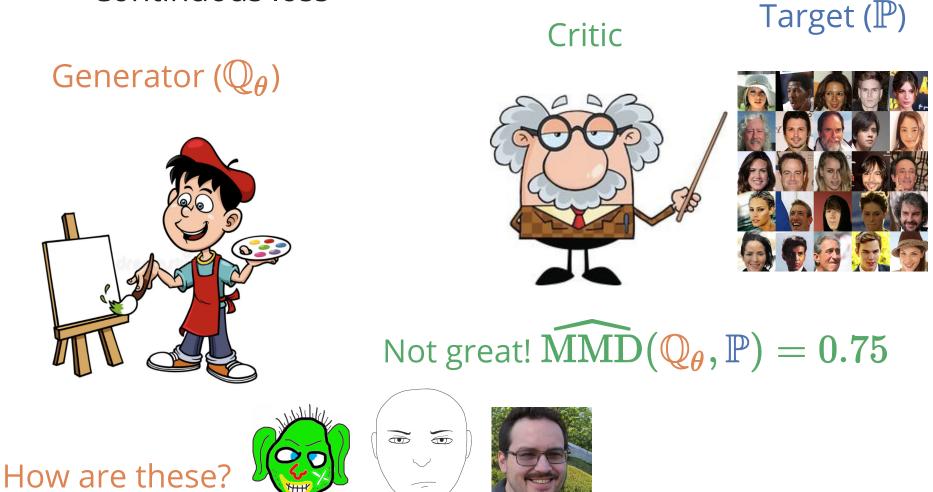
• No need for a discriminator – just minimize $\widetilde{\mathrm{MMD}}_k!$

Target (\mathbb{P})

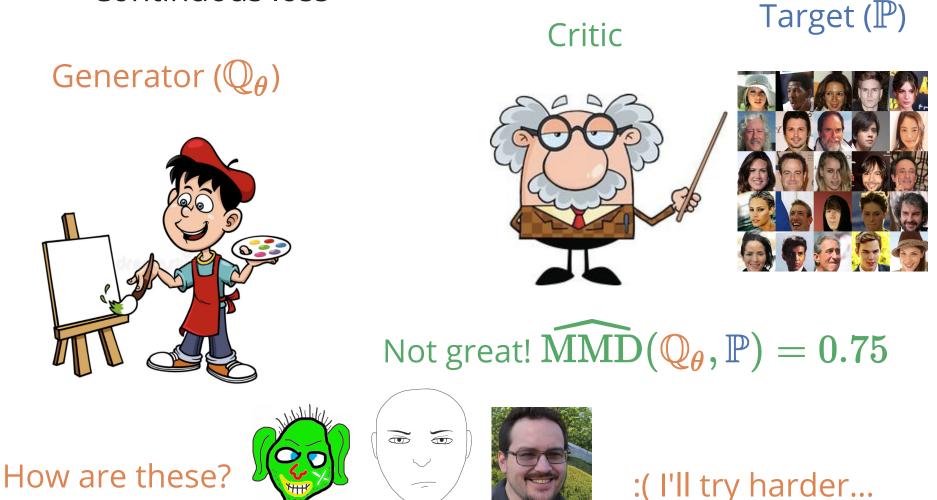
• Continuous loss



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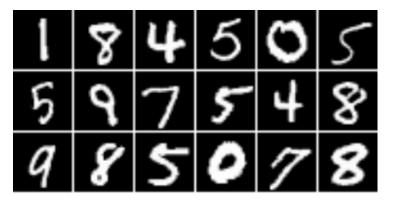
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- Continuous loss



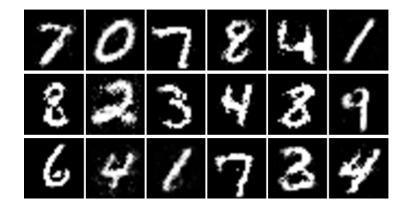
MNIST, mix of Gaussian kernels



 \mathbb{P}

MNIST, mix of Gaussian kernels

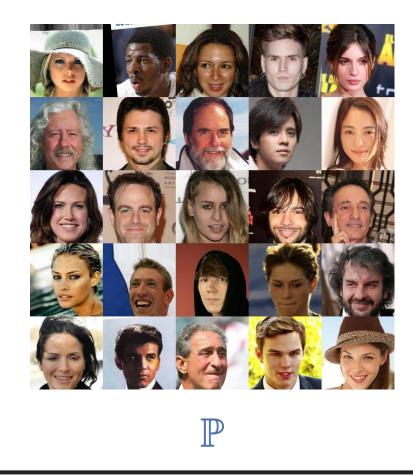




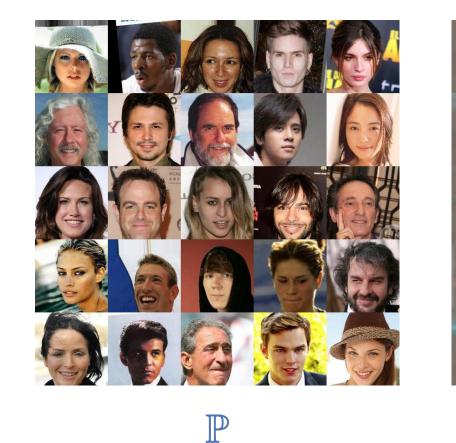
 \mathbb{P}

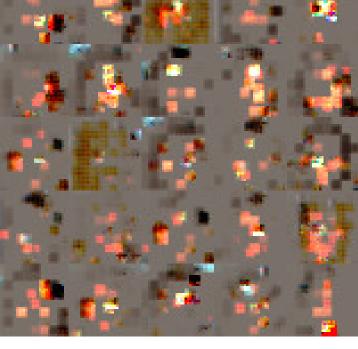
 $\mathbb{Q}_{ heta}$

Celeb-A, mix of rational quadratic + linear kernels



Celeb-A, mix of rational quadratic + linear kernels





 $\mathbb{Q}_{ heta}$

$$k(x,y) = k_{ ext{top}}(\phi(x),\phi(y))$$

- $\phi: \mathcal{X}
 ightarrow \mathbb{R}^{2048}$ from pretrained Inception net
- $k_{
 m top}$ simple: exponentiated quadratic or polynomial

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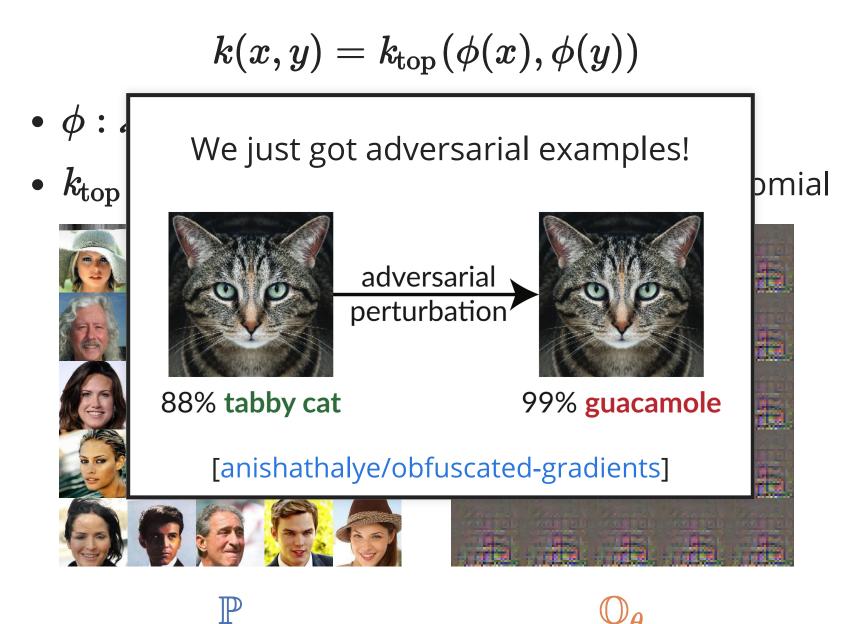
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• Don't just use one kernel, use a *class* parameterized by ψ :

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• Turns out that \mathcal{D}_{MMD} *isn't* continuous: have $\mathbb{Q}_{\theta} \to \mathbb{P}$ but $\mathcal{D}_{MMD}(\mathbb{Q}_{\theta}, \mathbb{P}) \not\rightarrow 0$

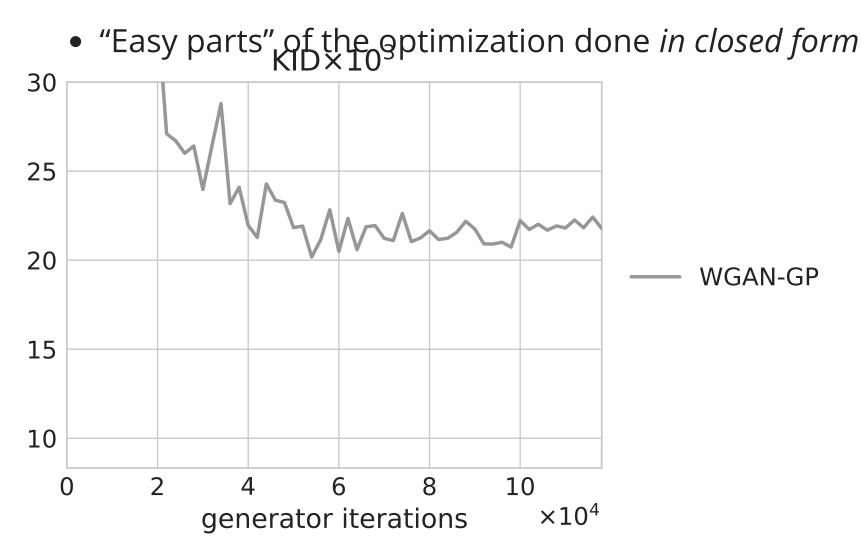
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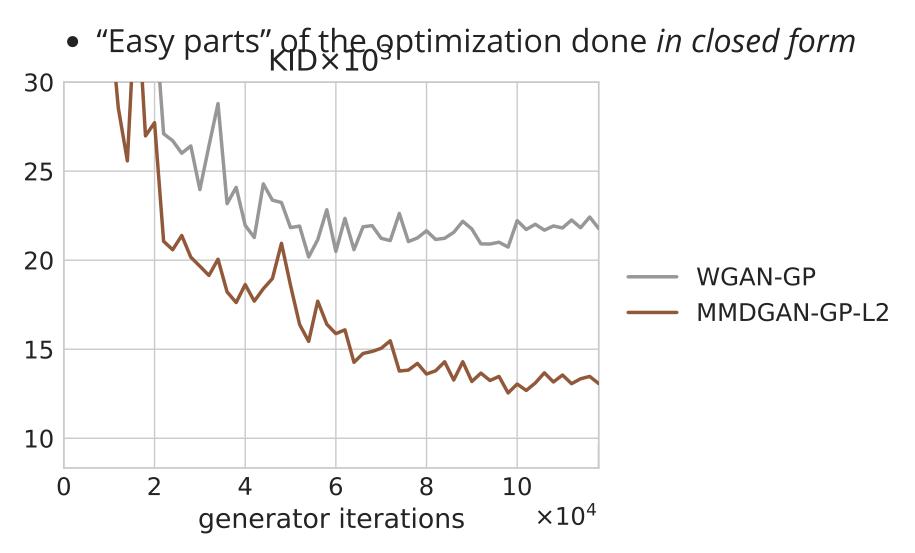
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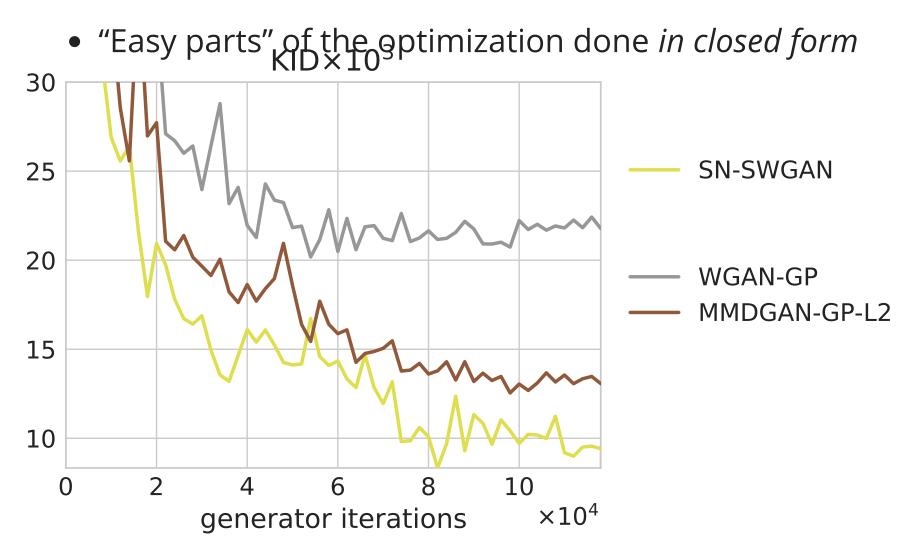
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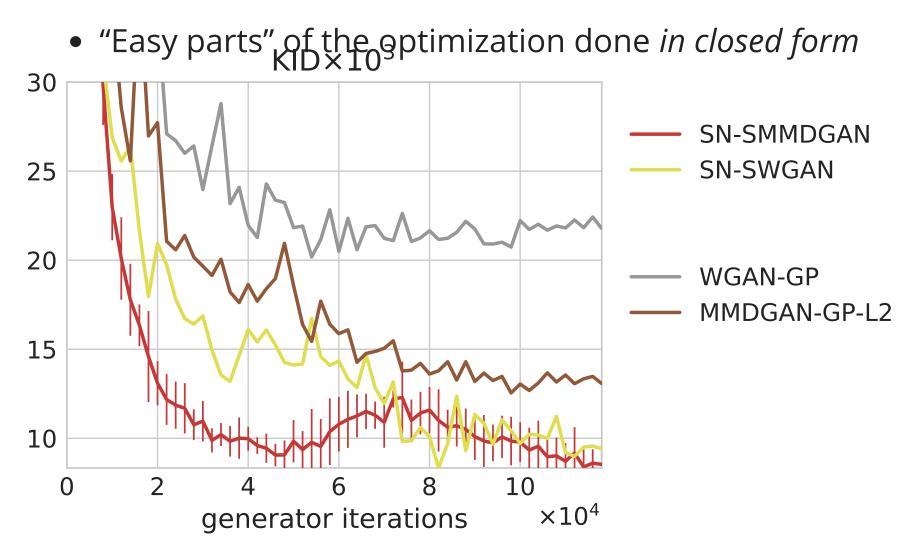
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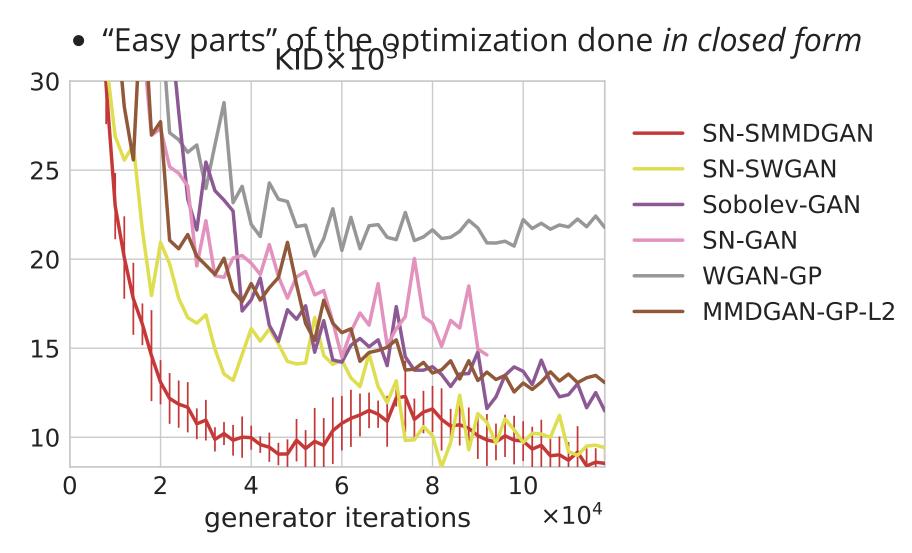
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- Scaled MMD GANs [Arbel+ NeurIPS-18] correct \mathcal{D}_{MMD} with a gradient penalty to make it continuous



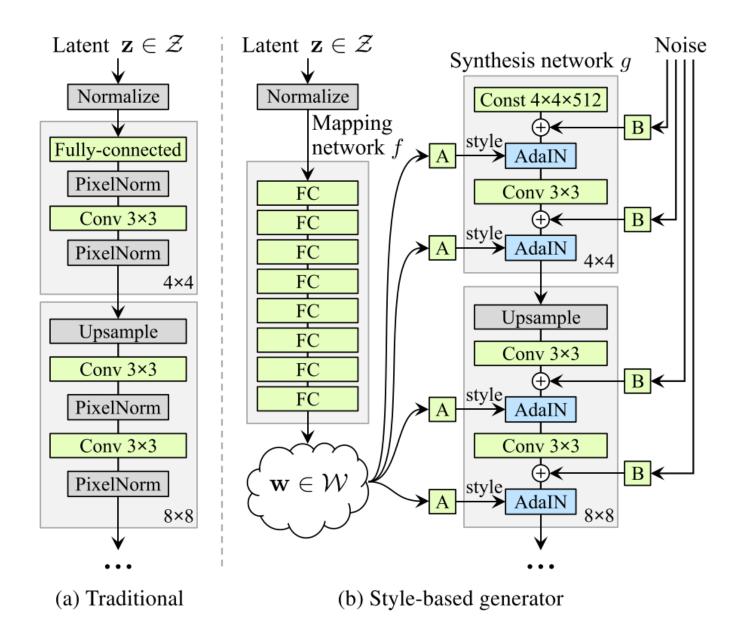








StyleGANs [Karras+ 2018]



StyleGAN: latent structure

StyleGAN: local noise



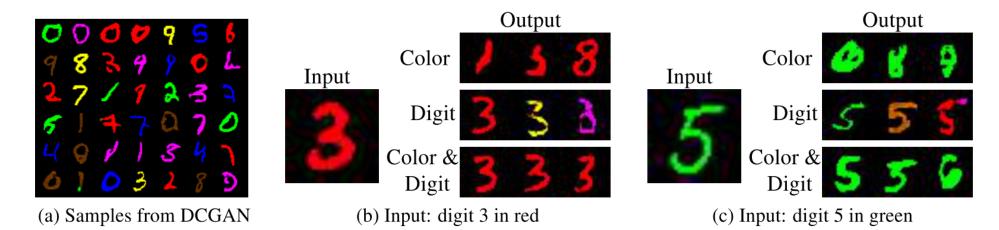
(a) Generated image (b) Stochastic variation (c) Standard deviation

StyleGANs on a different domain [@roadrunning01]

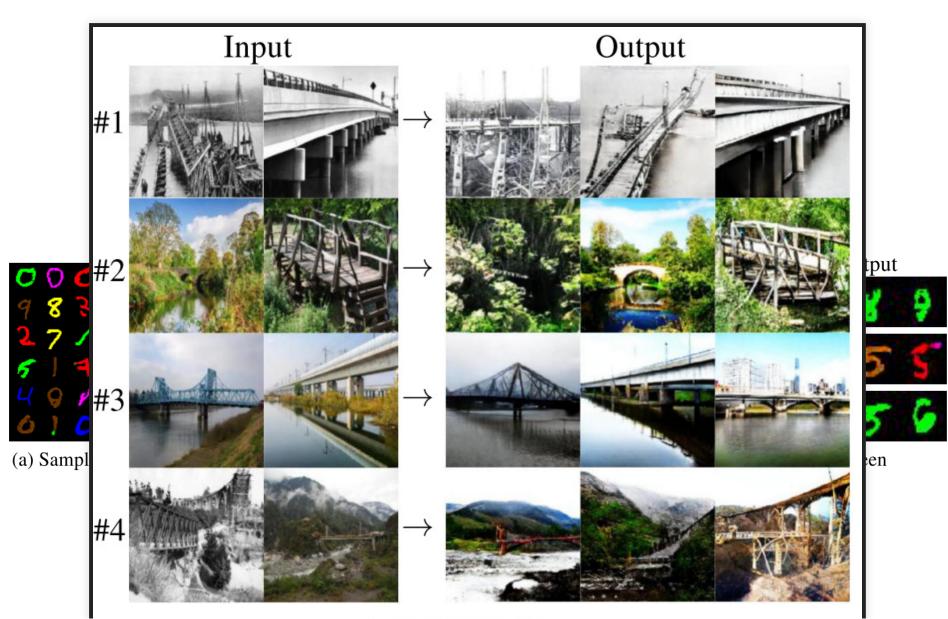
Finding samples you want [Jitkrittum+ ICML-19]

If we want to find "more samples like $\{X\}$ ":

$$\min_{\{Z_1,\ldots,Z_n\}} \widehat{\mathrm{MMD}}_k^2ig(\{X_i\}_{i=1}^m,\{G_{oldsymbol{ heta}}(Z_i)\}_{i=1}^nig)$$



Finding samples you want [Jitkrittum+ ICML-19]



Conditional GANs and BigGAN

- Conditional GANs: [Mirza+ 2014]
 - ullet Just add a class label as input to $G_ heta$ and D_ψ
- BigGAN [Brock+ ICLR-19]: a bunch of tricks to make it huge



Image-to-image translation [Isola+ CVPR-17]

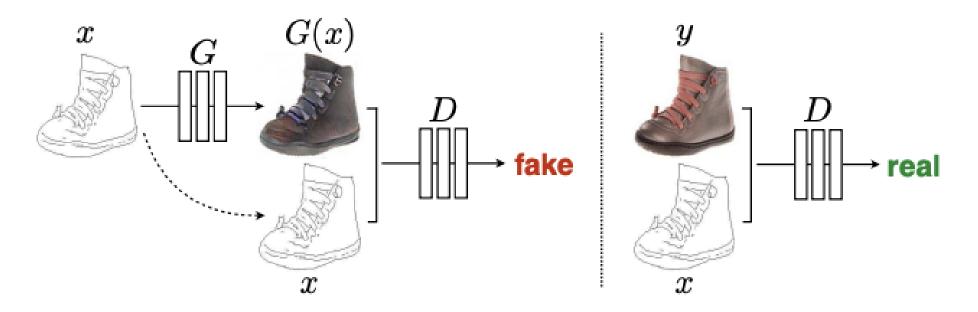
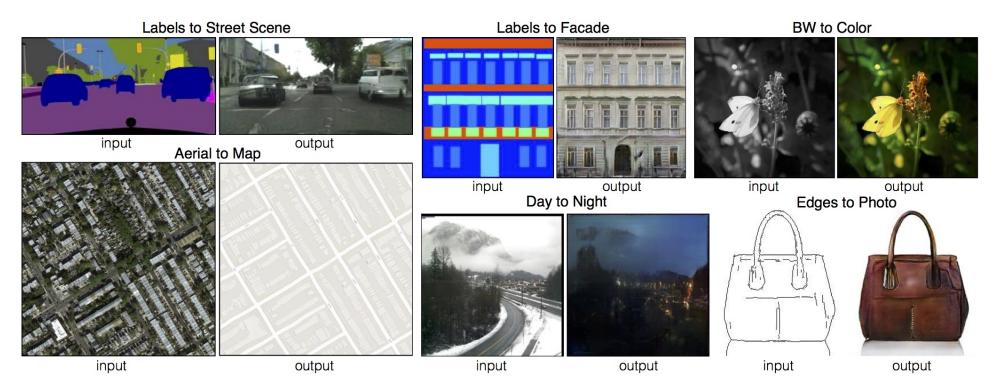
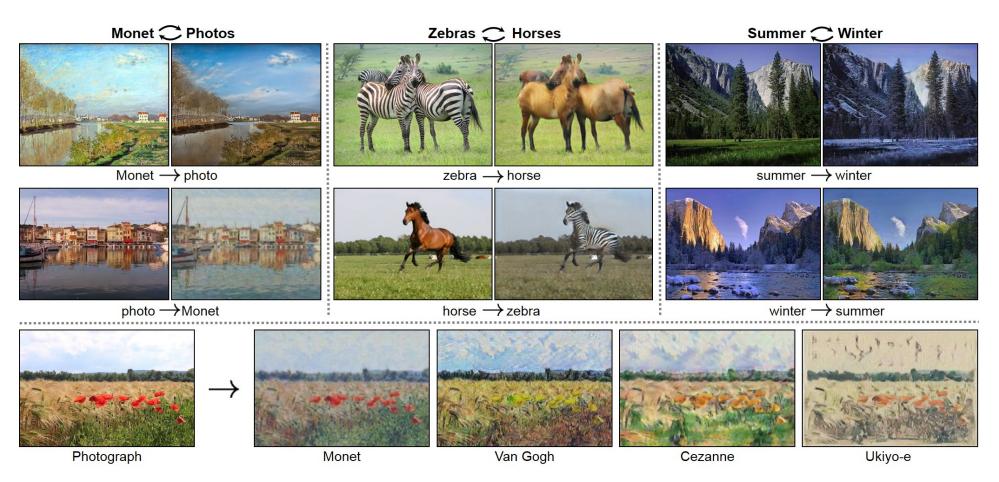


Figure 2: Training a conditional GAN to map edges \rightarrow photo. The discriminator, D, learns to classify between fake (synthesized by the generator) and real {edge, photo} tuples. The generator, G, learns to fool the discriminator. Unlike an unconditional GAN, both the generator and discriminator observe the input edge map.

Image-to-image translation [Isola+ CVPR-17]



CycleGAN [Zhu+ ICCV-17]



Pose-to-image translation [Chan+ 2018]

DeepFakes

More

- Optimal transport stuff:
 - Gabriel Peyré: Optimal transport for machine learning talk
 - Peyré and Cuturi, Computational Optimal Transport book
 - Kantorovich Initiative: kantorovich.org
 - Pacific Interdisciplinary Hub on Optimal Transport
- GANs / generative models...so much.