Taxonomy of generative models

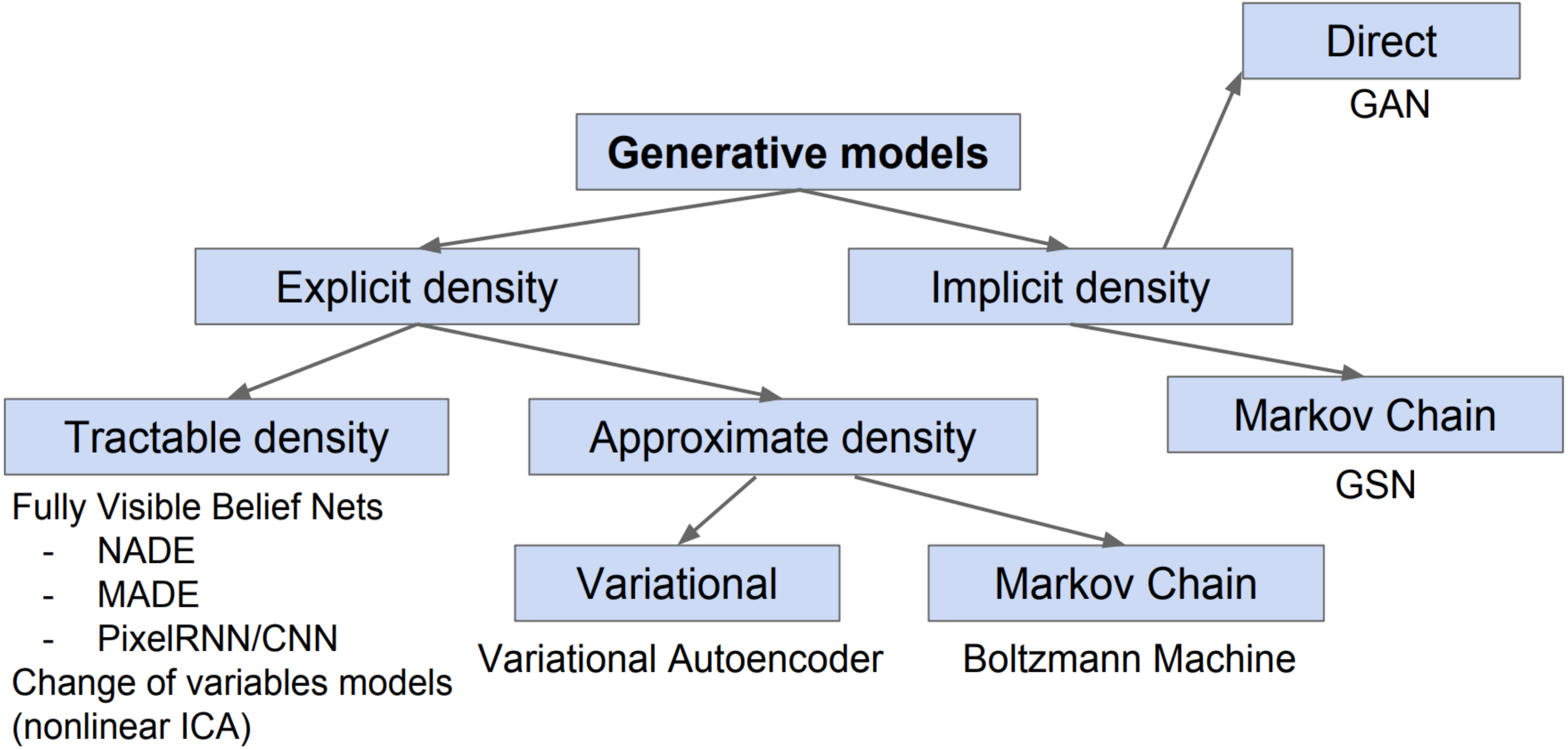


Figure from Ian Goodfellow, Tutorial on Generative Adversarial /networks, 2017

Taxonomy of generative models

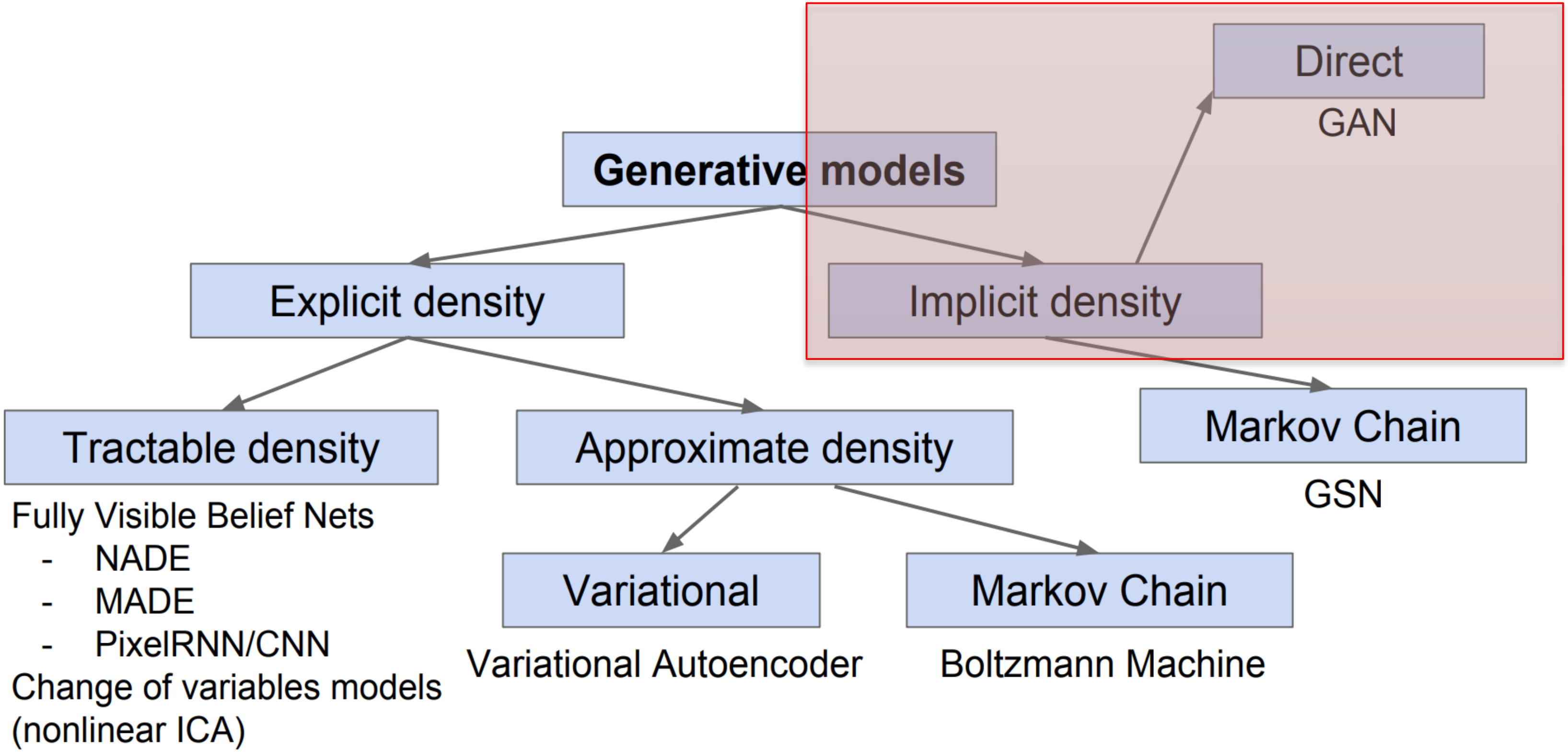
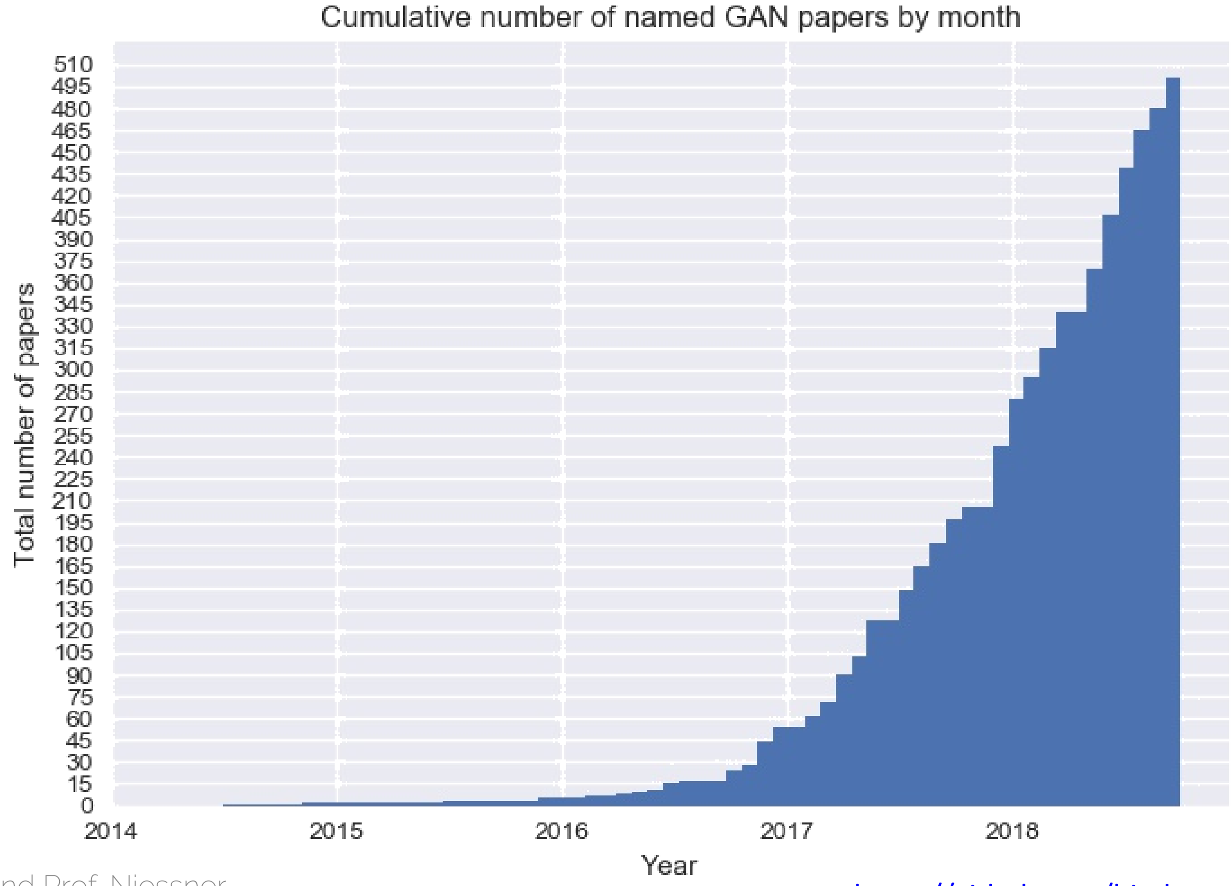


Figure from Ian Goodfellow, Tutorial on Generative Adversarial /networks, 2017

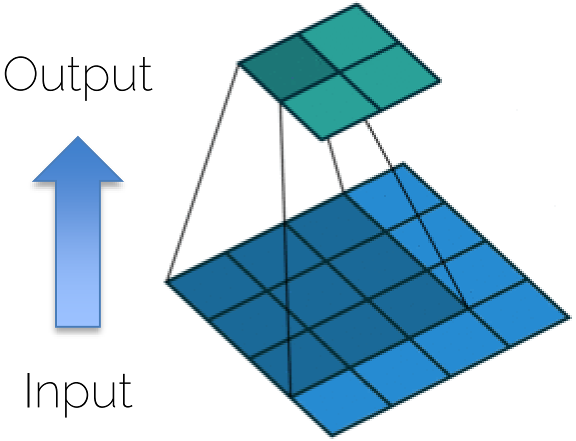
Generative Adversarial Networks

Generative Adversarial Networks (GANs)

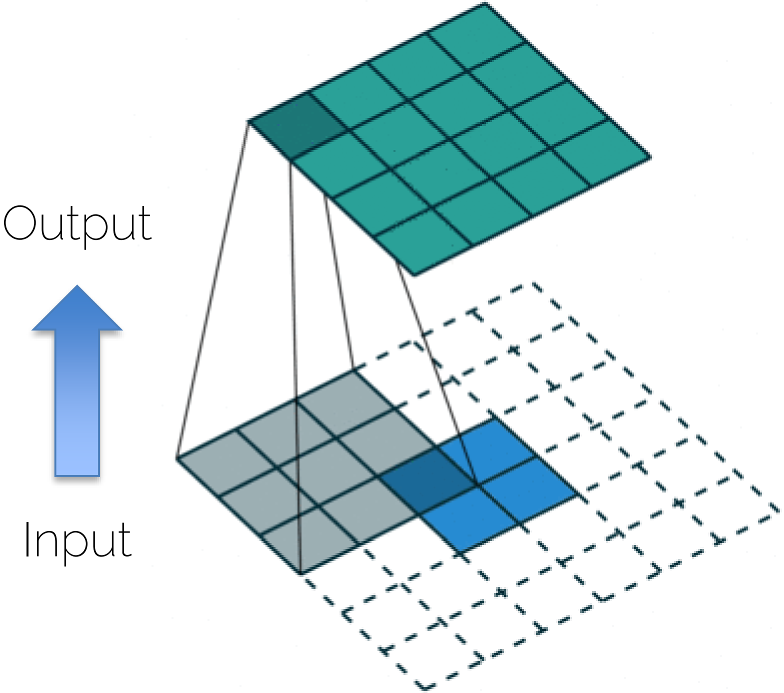


https://github.com/hindupuravinash/the-gan-zoo

Convolution and Deconvolution



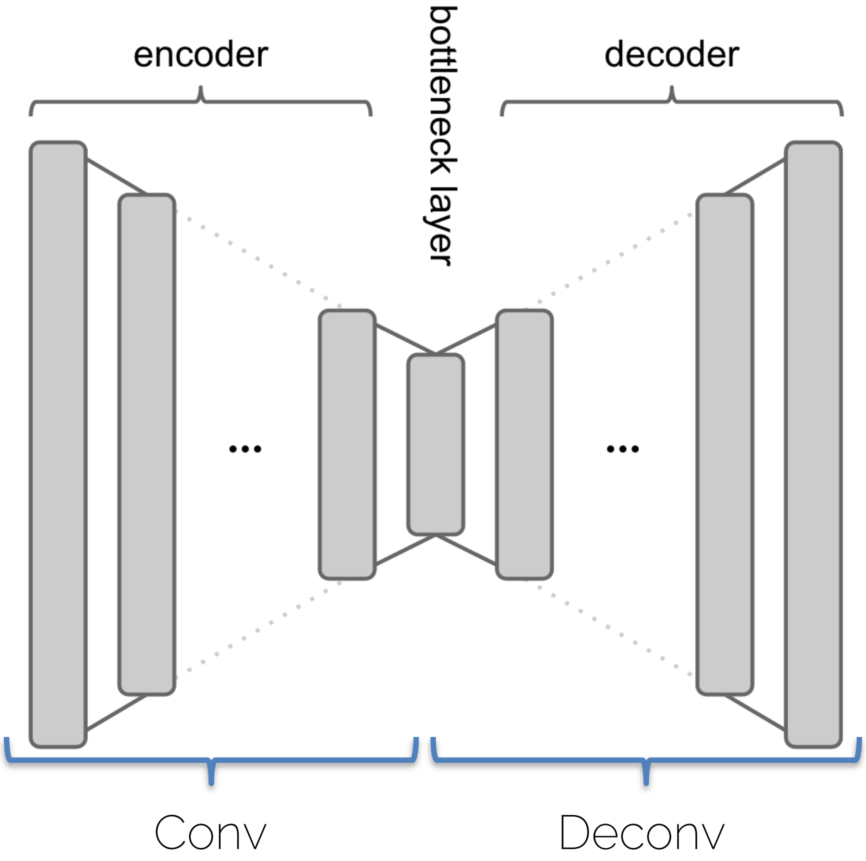
Convolution
no padding, no stride



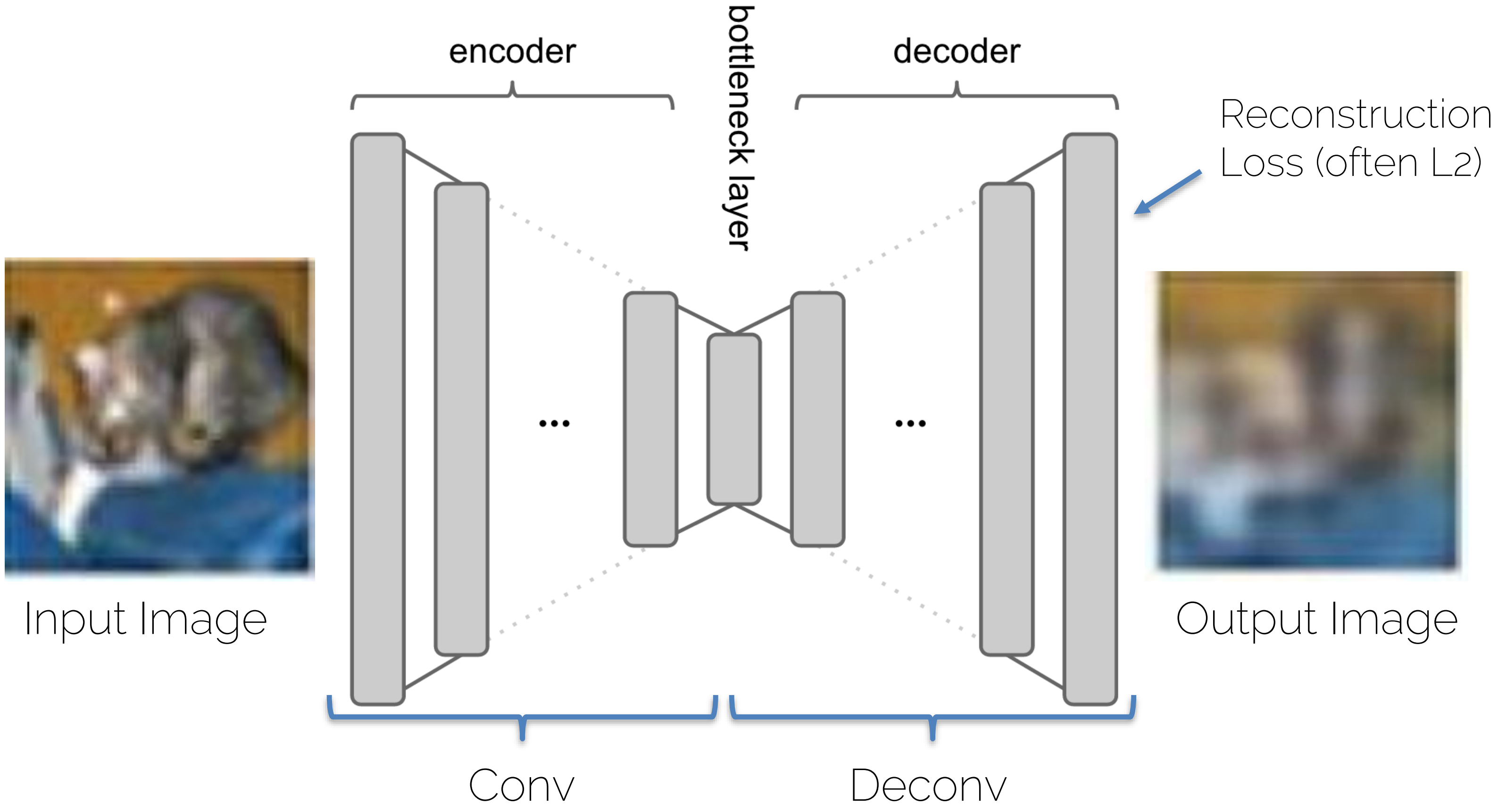
Transposed convolution
no padding, no stride

https://github.com/vdumoulin/conv_arithmetic

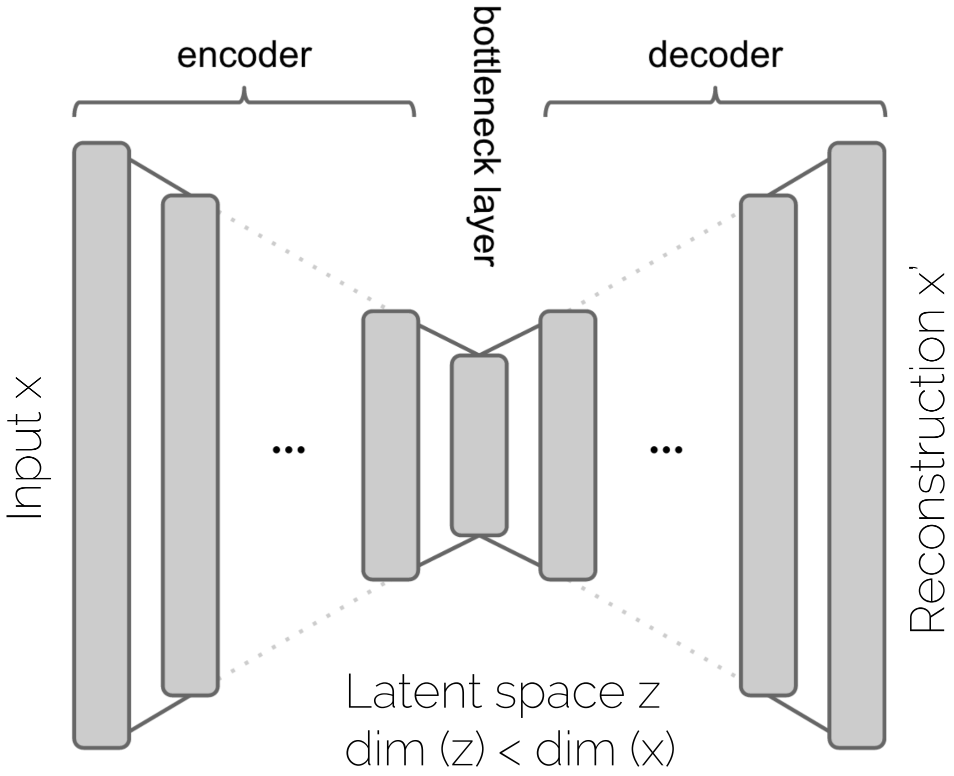
Autoencoder



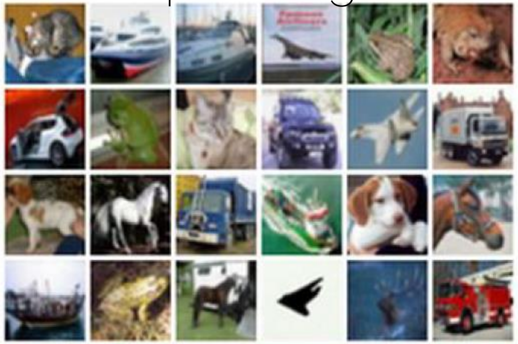
Reconstruction: Autoencoder



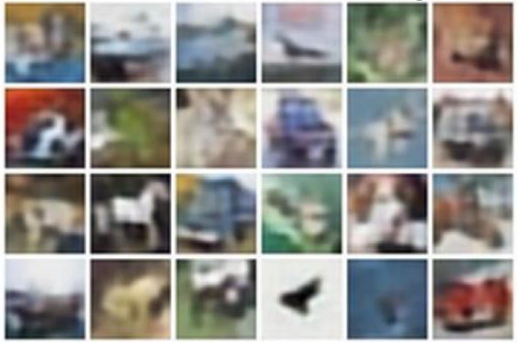
Training Autoencoders



Input images

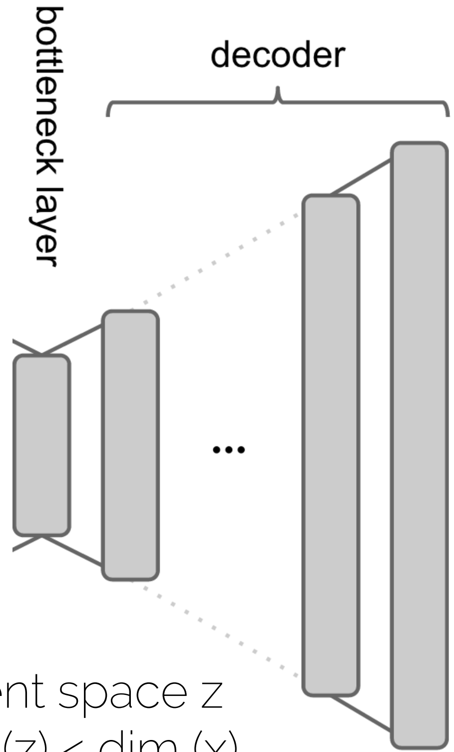


Reconstructed images



Decoder as Generative Model

"Test time":
-> reconstruction from
'random' vector

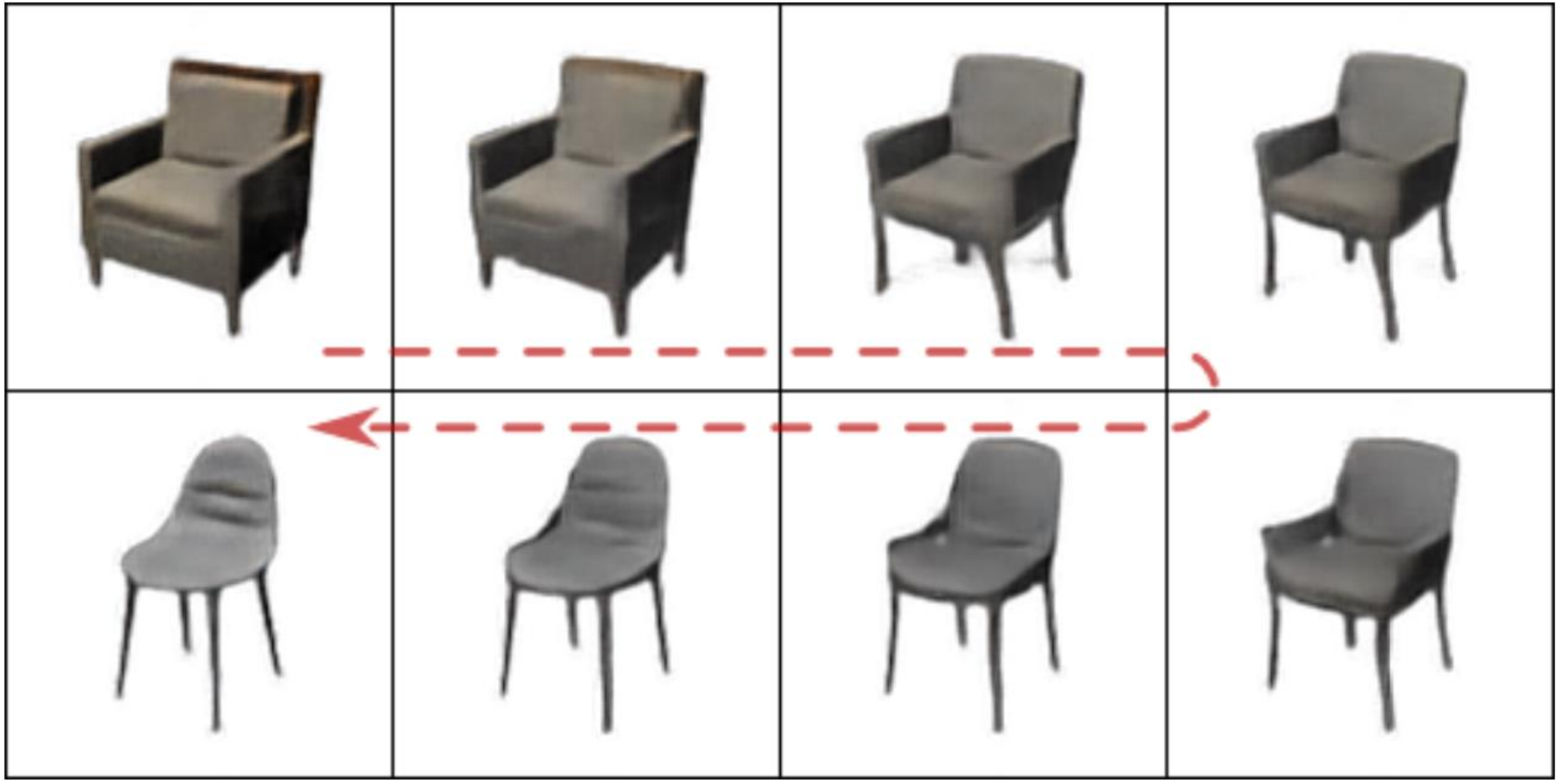


Latent space z
dim (z) < dim (x)

Reconstruction
Loss (often L2)

Output Image

Decoder as Generative Model



Interpolation between two chair models

[Dosovitsky et al. 14] Learning to Generate Chairs

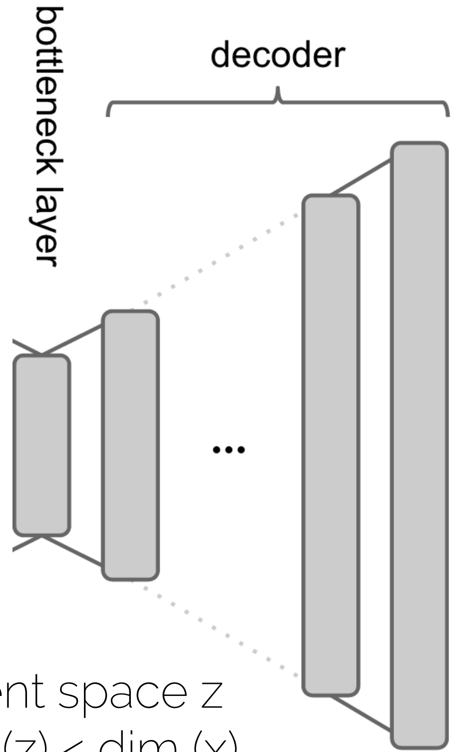
Decoder as Generative Model

Morphing between chair models

[Dosovitsky et al. 14] Learning to Generate Chairs

Decoder as Generative Model

"Test time":
-> reconstruction from
'random' vector



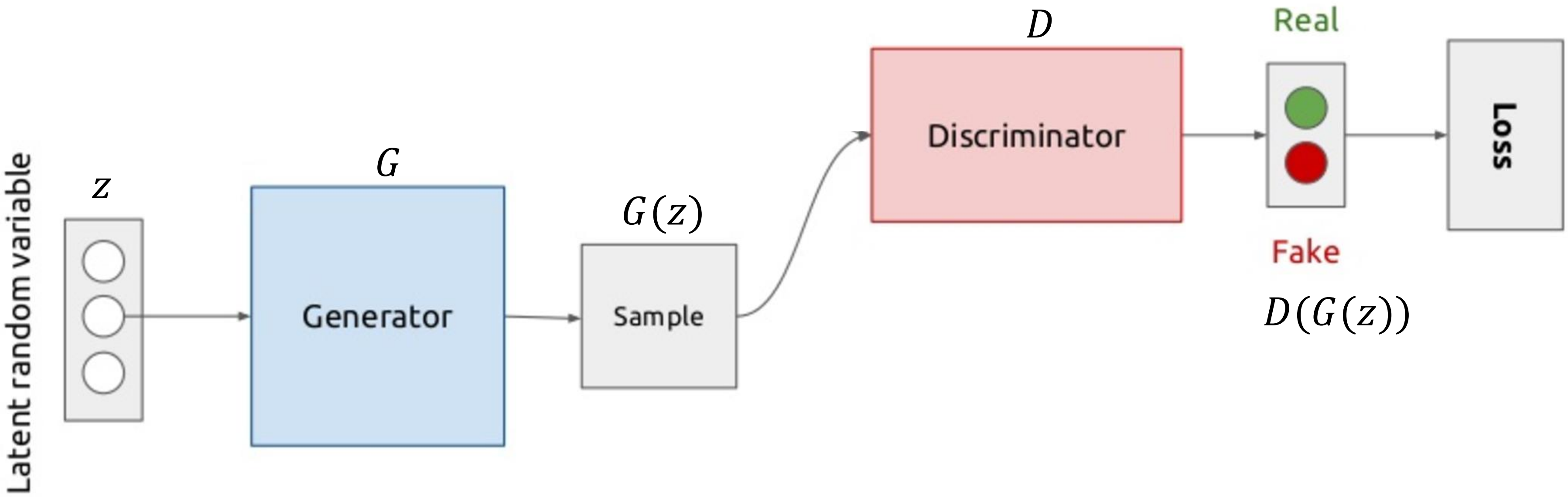
Latent space z
dim (z) < dim (x)

Reconstruction Loss
Often L2, i.e., sum of squared dist.
-> L2 distributes error equally

-> mean is opt.
-> res. Is blurry

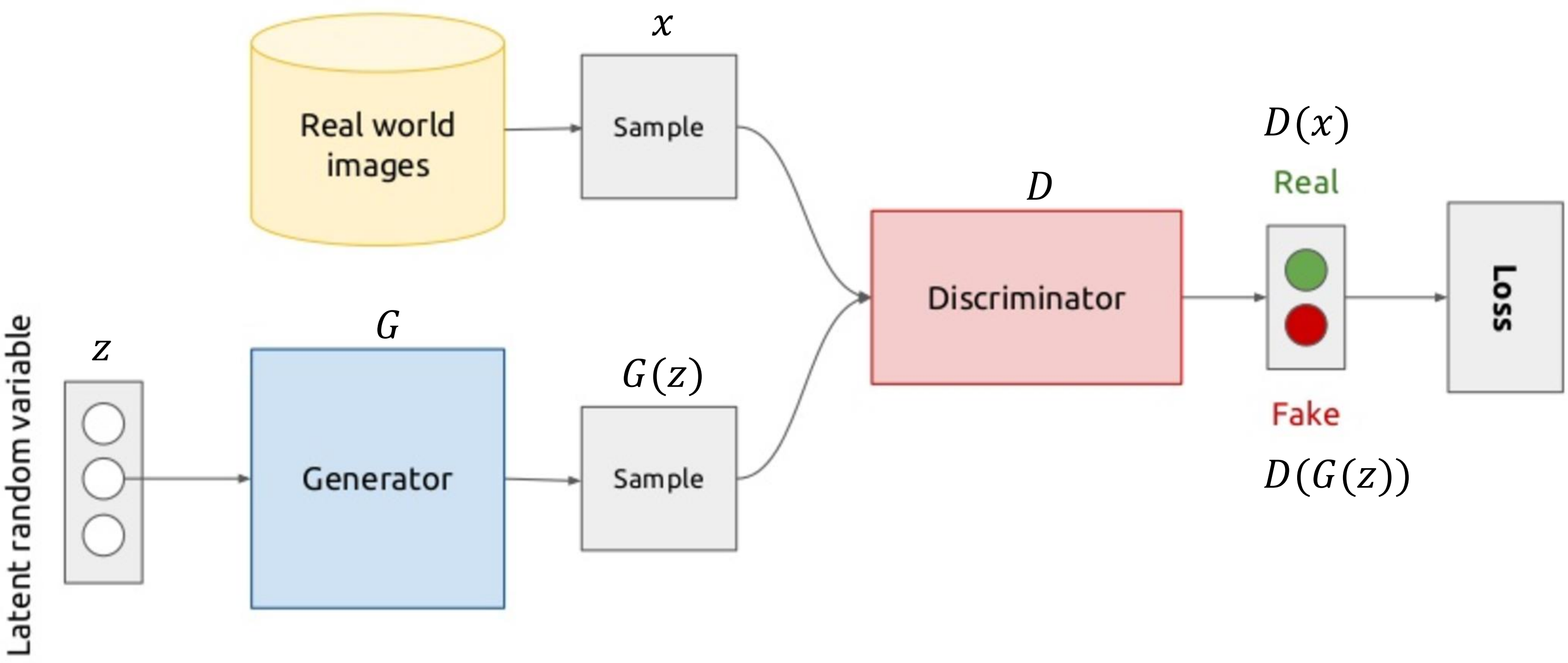
Instead of L2, can we "learn" a loss function?

Generative Adversarial Networks (GANs)



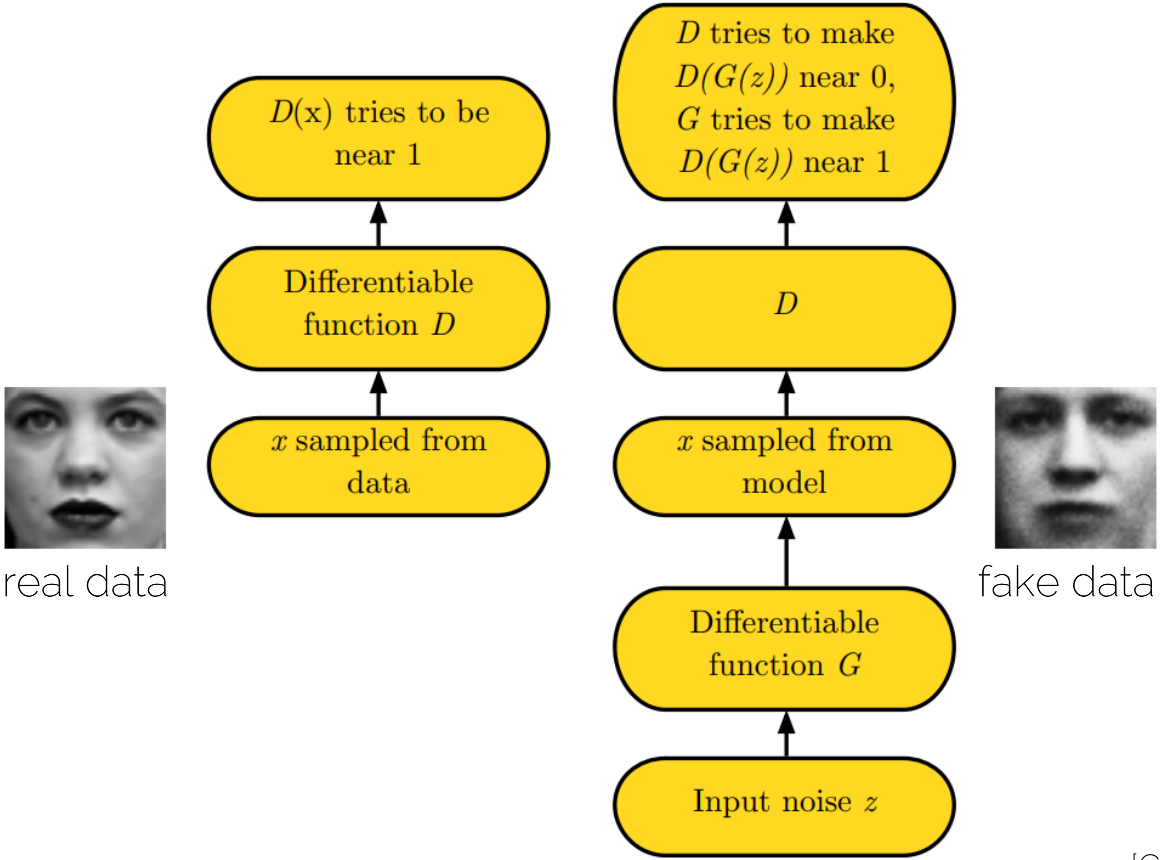
[Goodfellow et al. 14] GANs (slide McGuinness)

Generative Adversarial Networks (GANs)



[Goodfellow et al. 14] GANs (slide McGuinness)

Generative Adversarial Networks (GANs)



GANs: Loss Functions

Discriminator loss

$$J^{(D)} = \underbrace{-\frac{1}{2}\mathbb{E}_{\boldsymbol{x}\sim p_{\text{data}}} \log D(\boldsymbol{x}) - \frac{1}{2}\mathbb{E}_{\boldsymbol{z}} \log\left(1 - D\left(G(\boldsymbol{z})\right)\right)}_{\text{binary cross entropy}}$$

Generator loss

$$J^{(G)} = -J^{(D)}$$

- Minimax Game:
  - G minimizes probability that D is correct
  - Equilibrium is saddle point of discriminator loss

-> D provides supervision (i.e., gradients) for G

[Goodfellow et al. 14/16] GANs

GANs: Loss Functions

Discriminator loss

$$J^{(D)} = -\frac{1}{2}\mathbb{E}_{\boldsymbol{x}\sim p_{\text{data}}} \log D(\boldsymbol{x}) - \frac{1}{2}\mathbb{E}_{\boldsymbol{z}} \log\left(1 - D\left(G(\boldsymbol{z})\right)\right)$$

Generator loss

$$J^{(G)} = -\frac{1}{2}\mathbb{E}_{\boldsymbol{z}} \log D\left(G(\boldsymbol{z})\right)$$

- Heuristic Method (often used in practice)
  - G maximizes the log-probability of D being mistaken
  - G can still learn even when D rejects all generator samples

[Goodfellow et al. 14/16] GANs

Alternating Gradient Updates

- Step 1: Fix G, and perform gradient step to

$$J^{(D)} = -\frac{1}{2}\mathbb{E}_{\boldsymbol{x}\sim p_{\text{data}}} \log D(\boldsymbol{x}) - \frac{1}{2}\mathbb{E}_{\boldsymbol{z}} \log\left(1 - D\left(G(\boldsymbol{z})\right)\right)$$

- Step 2: Fix D, and perform gradient step to

$$J^{(G)} = -\frac{1}{2}\mathbb{E}_{\boldsymbol{z}} \log D\left(G(\boldsymbol{z})\right)$$

Vanilla GAN

for number of training iterations **do**

for k steps **do**

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

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

end for

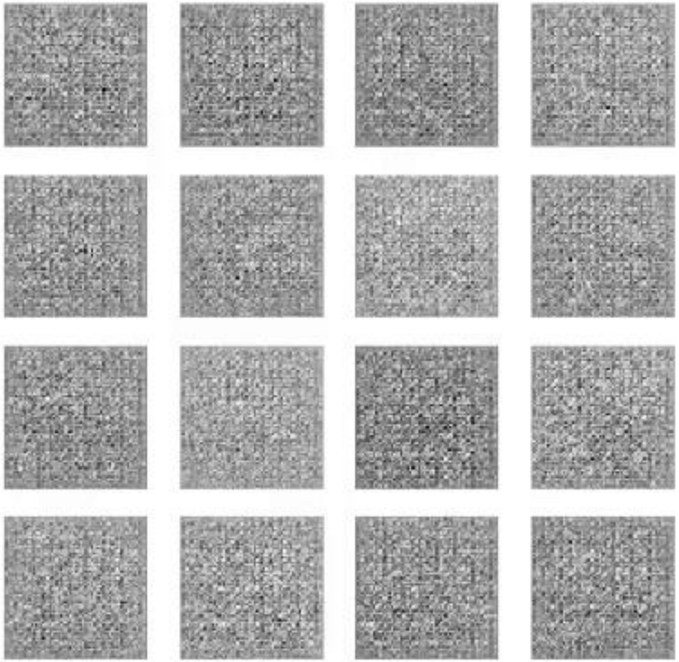
- Sample minibatch of m noise samples $\{\boldsymbol{z}^{(1)}, \ldots, \boldsymbol{z}^{(m)}\}$ from noise prior $p_g(\boldsymbol{z})$.
- Update the generator by descending its stochastic gradient:

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

end for

https://papers.nips.cc/paper/5423-generative-adversarial-nets

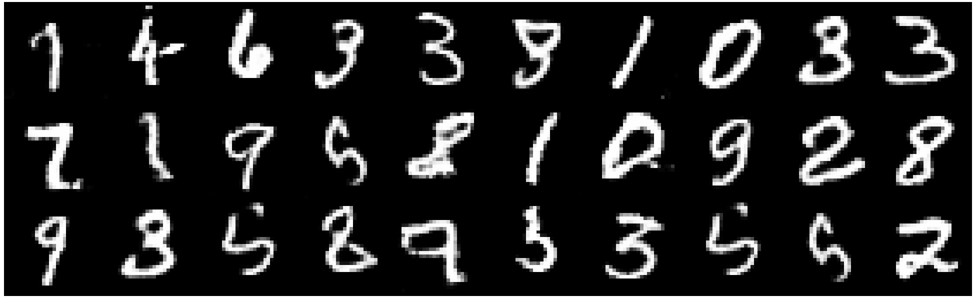
Training a GAN

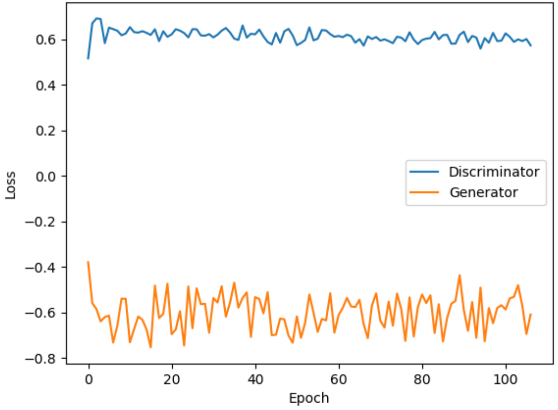


https://medium.com/ai-society/gans-from-scratch-1-a-deep-introduction-with-code-in-pytorch-and-tensorflow-cb03cdcdba0f

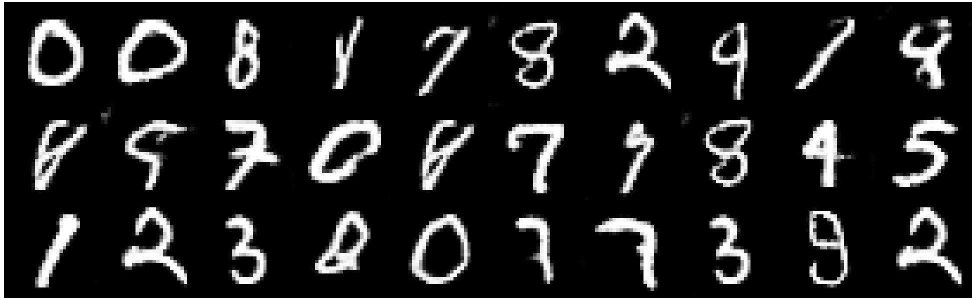
GANs: Loss Functions

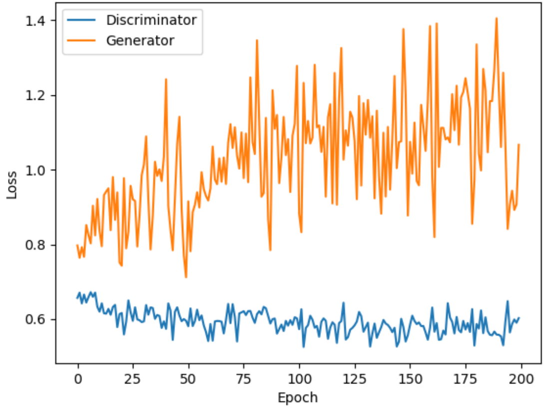
Minimax





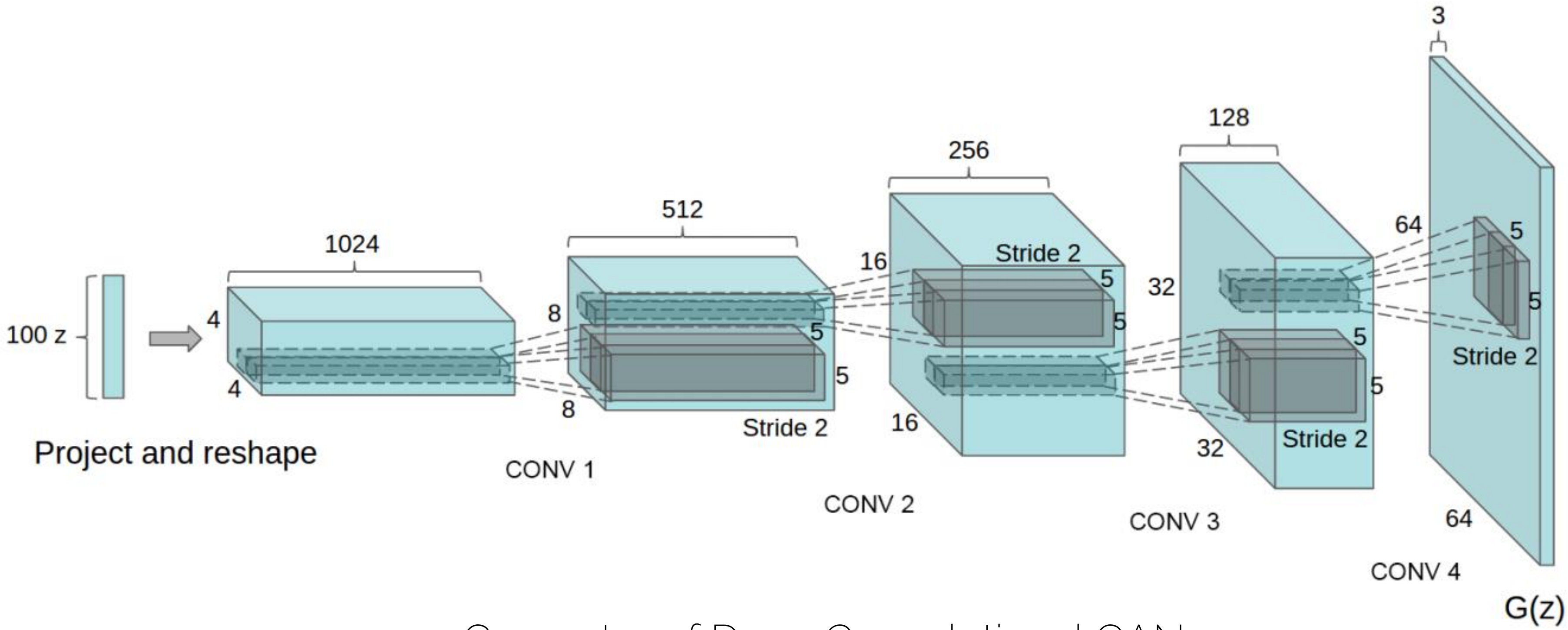
Heuristic





[Goodfellow et al. 14/16] GANs

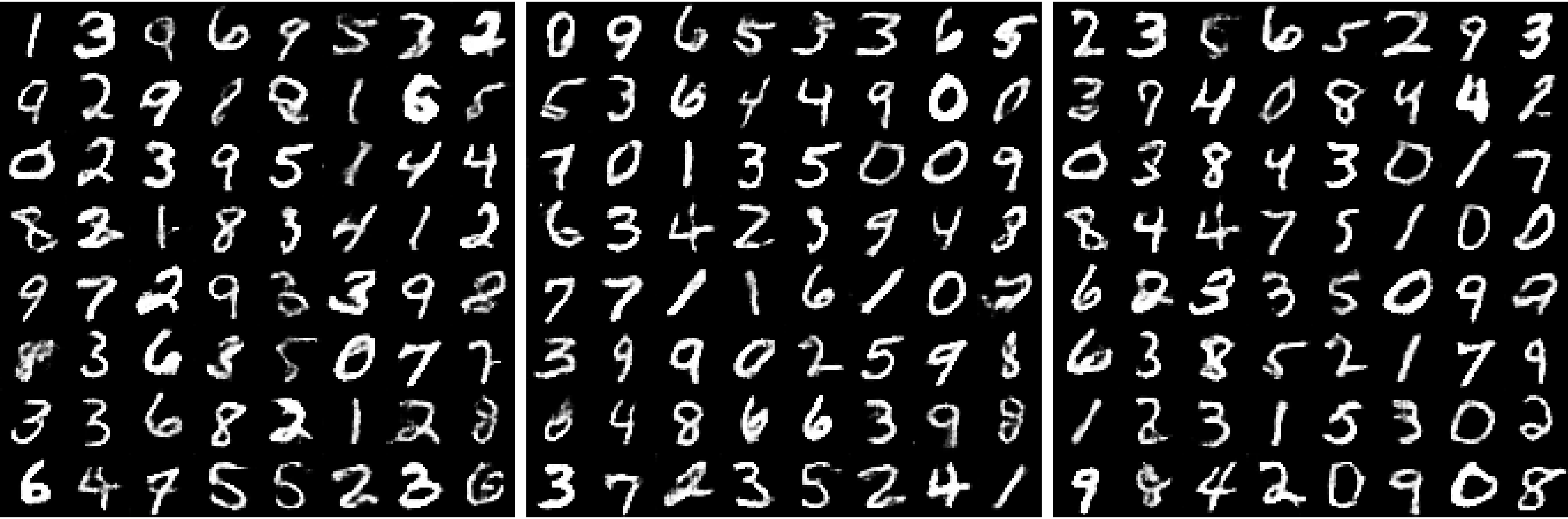
DCGAN: Generator



Generator of Deep Convolutional GANs

DCGAN: https://github.com/carpedm20/DCGAN-tensorflow

DCGAN: Results



Results on MNIST

DCGAN: https://github.com/carpedm20/DCGAN-tensorflow

DCGAN: Results

Results on CelebA (200k relatively well aligned portrait photos)

DCGAN: https://github.com/carpedm20/DCGAN-tensorflow

DCGAN: Results

Asian face dataset

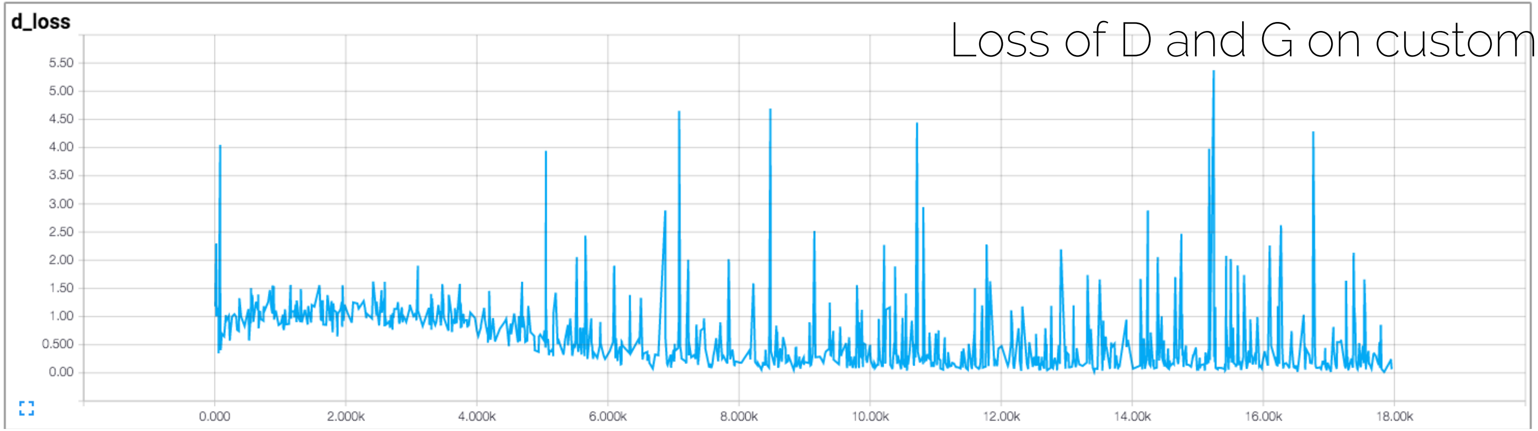
DCGAN: https://github.com/carpedm20/DCGAN-tensorflow

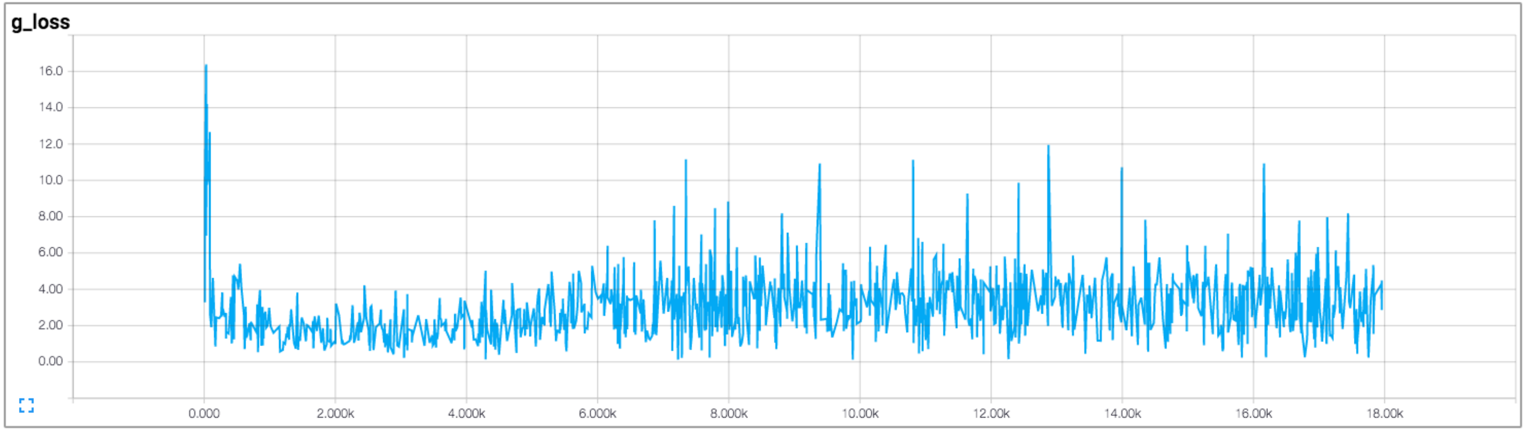
DCGAN: Results

DCGAN: https://github.com/carpedm20/DCGAN-tensorflow

DCGAN: Results

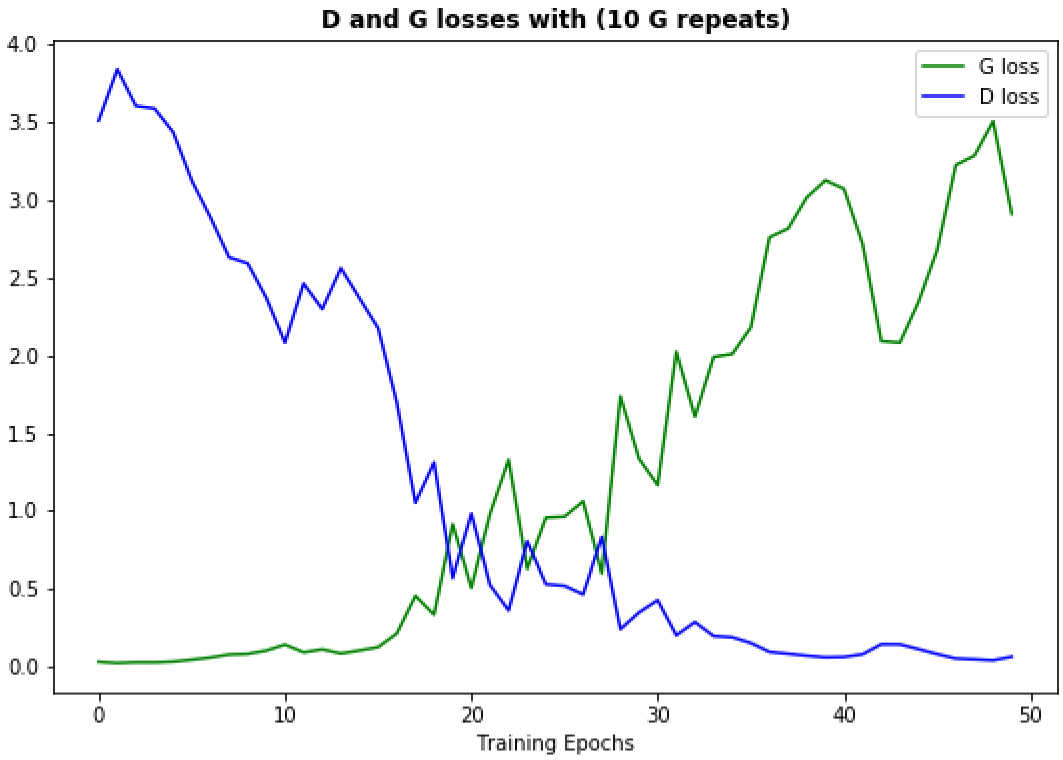
Loss of D and G on custom dataset





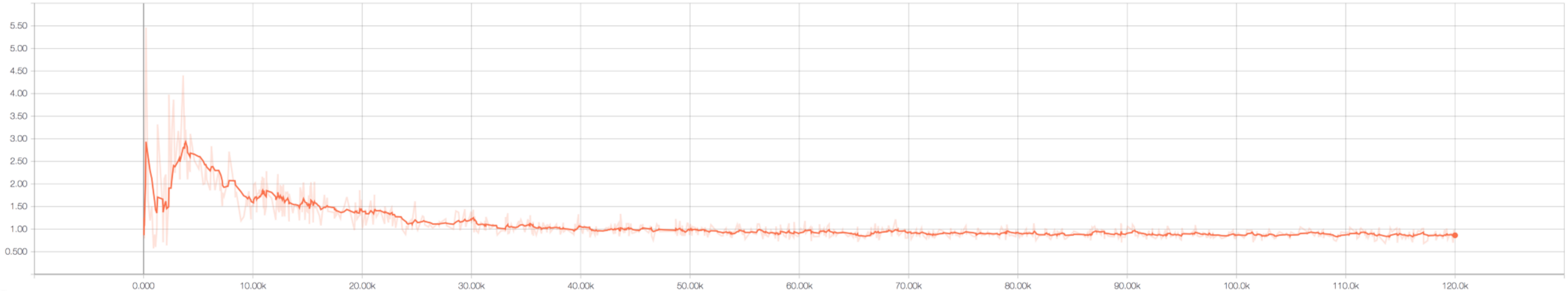
DCGAN: https://github.com/carpedm20/DCGAN-tensorflow

“Bad” Training Curves

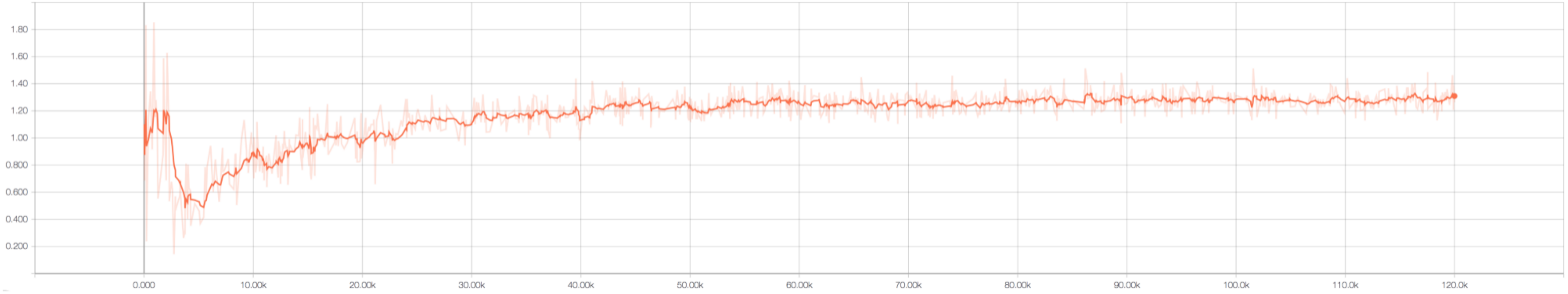


https://stackoverflow.com/questions/44313306/dcgans-discriminator-getting-too-strong-too-quickly-to-allow-generator-to-learn

“Good” Training Curves



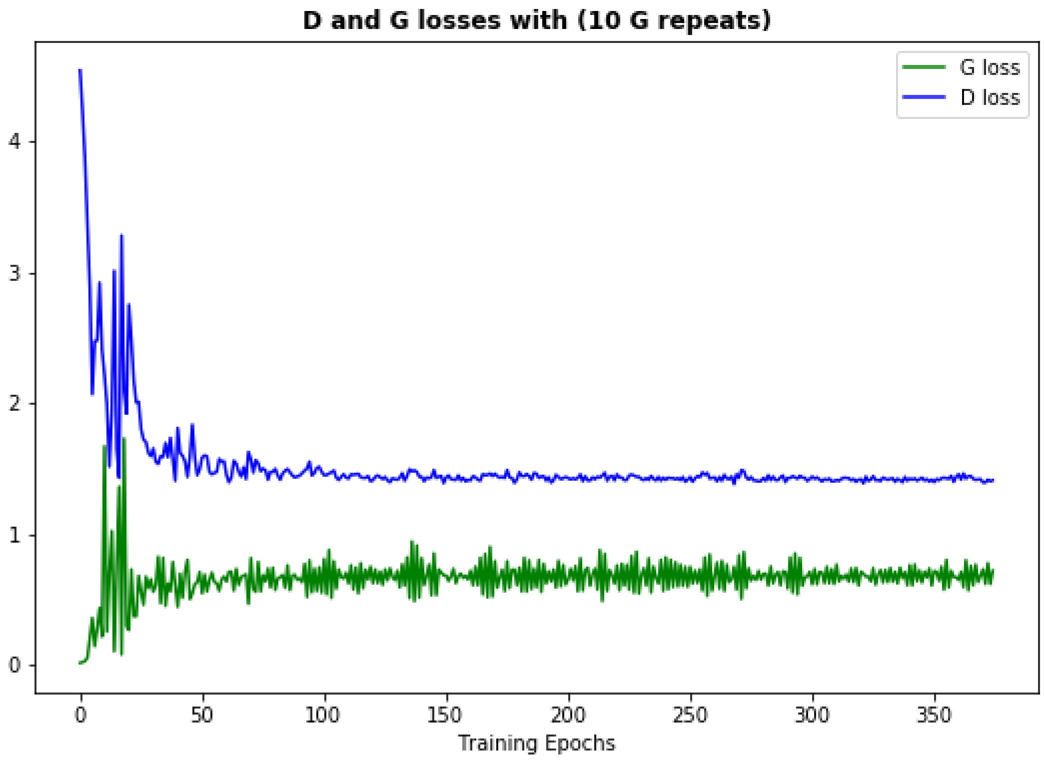
Generator’s Error through Time



Discriminator’s Error through Time

https://medium.com/ai-society/gans-from-scratch-1-a-deep-introduction-with-code-in-pytorch-and-tensorflow-cb03cdcdba0f

“Good” Training Curves



https://stackoverflow.com/questions/42690721/how-to-interpret-the-discriminators-loss-and-the-generators-loss-in-generative

Training Schedules

- Adaptive schedules

- For instance:

```
while loss_discriminator > t_d:
    train discriminator
while loss_generator > t_g:
    train generator
```

Weak vs Strong Discriminator

Need balance ☺

- Discriminator too weak?
  - No good gradients (cannot get better than teacher…)
- Generator too weak?
  - Discriminator will always be right

Mode Collapse

- $\min_G \max_D V(G,D) \neq \max_D \min_G V(G,D)$

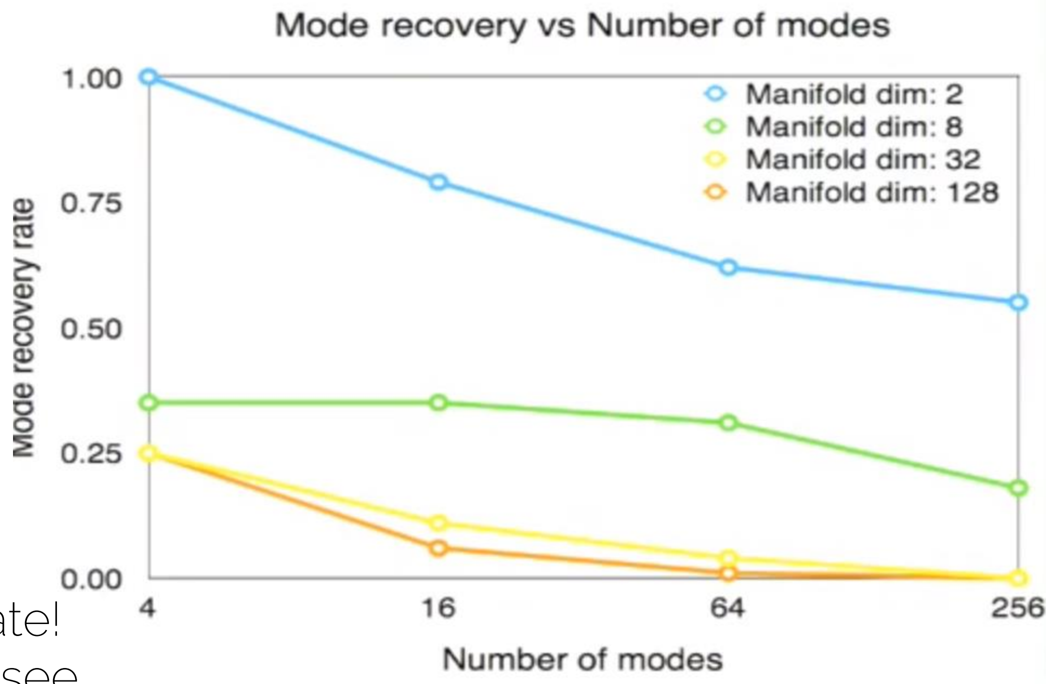
- D in inner loop -> convergence to correct dist.
- G in inner loop -> easy to convergence to one sample

[Metz et al. 16]

Mode Collapse

- Data dim. Fixed (512)

- Performance correlates with # of modes



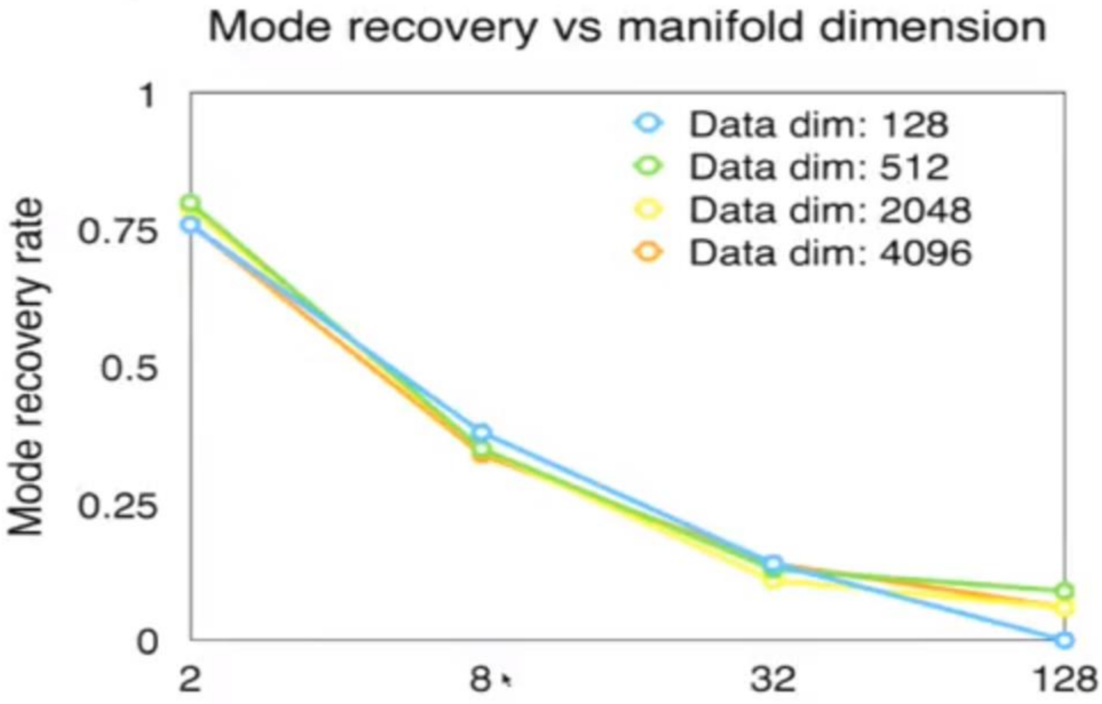
-> More modes, smaller recovery rate!
-> part of the reason, why we often see GAN-results on specific domains (e.g., faces)

Slide credit Ming-Yu Liu

Mode Collapse

- Performance correlates with dim of manifold

-> Larger latent space, more mode collapse

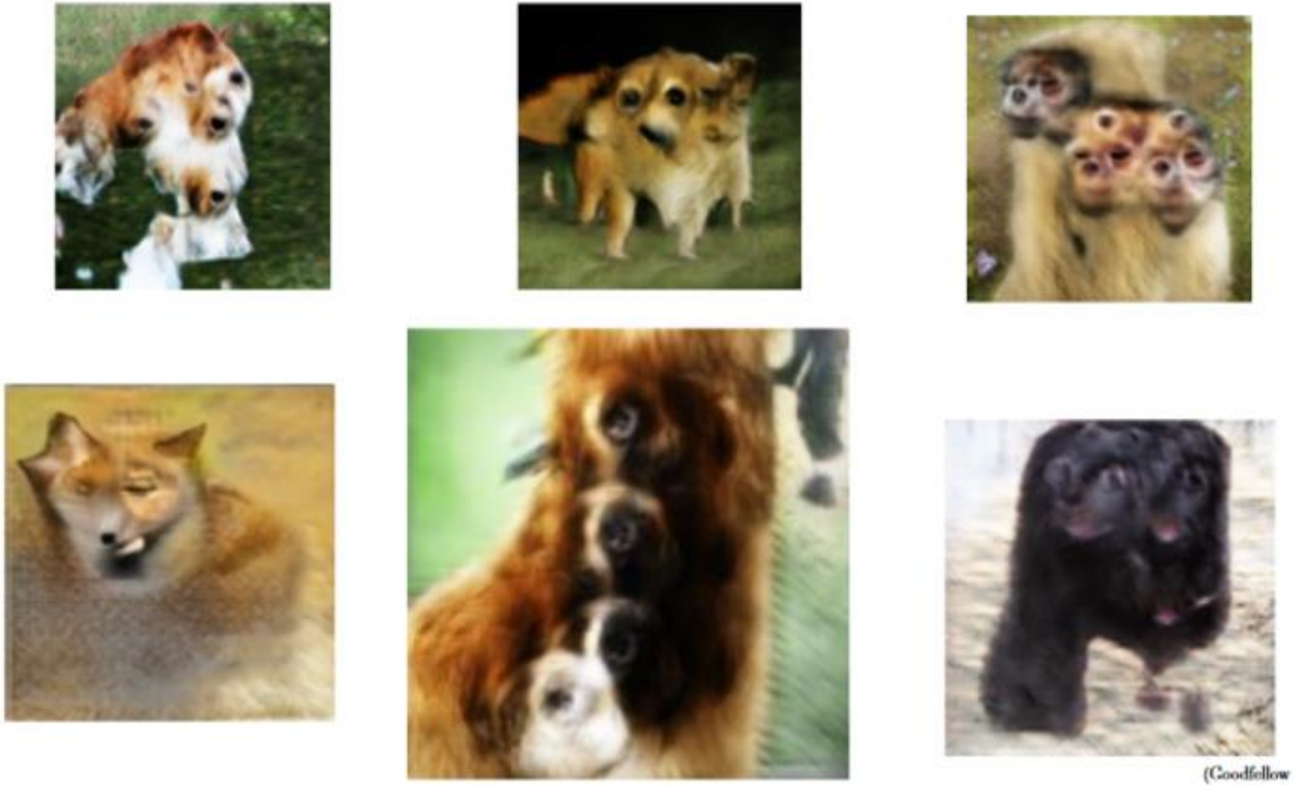


Slide credit Ming-Yu Liu

Problems with Global Structure

(Goodfellow 2016)

Problems with Counting



(Goodfellow 2016)

Evaluation of GAN Performance

Evaluation of GAN Performance

- Main difficulty of GANs: we don't know how good they are
- People cherry pick results in papers -> some of them will always look good, but how to quantify?
- Do we only memorize or do we generalize?
- GANs are difficult to evaluate! [This et al., ICLR 2016]

Evaluation of GAN Performance

Human evaluation:

- Every n updates, show a series of predictions
- Check train curves
- What does 'look good' mean at the beginning?
  - Need variety!
  - But don't have 'realistic' predictions yet…
- If it doesn't look good? Go back, try different hyperparameters…

Evaluation of GAN Performance

Inception Score (IS)

- Measures saliency and diversity

- Train an accurate classifier
- Train a image generation model (conditional)
- Check how accurate the classifier can recognize the generated images
- Makes some assumptions about data distributions…

Evaluation of GAN Performance

Inception Score (IS)

- Saliency: check whether the generated images can be classified with high confidence (i.e., high scores only on a single class)

- Diversity: check whether we obtain samples from all classes

<u>What if we only have one good image per class?</u>

Evaluation of GAN Performance

- Could also look at discriminator
  - If we end up with a strong discriminator, then generator must also be good
  - Use D features, for classification network
  - Only fine-tune last layer
  - If high class accuracy -> we have a good D and G

Caveat: not sure if people do this… Couldn't find paper

Next: Making GANs Work in Practice

- Training / Hyperparameters (most important)

- Choice of loss function

- Choice of architecture

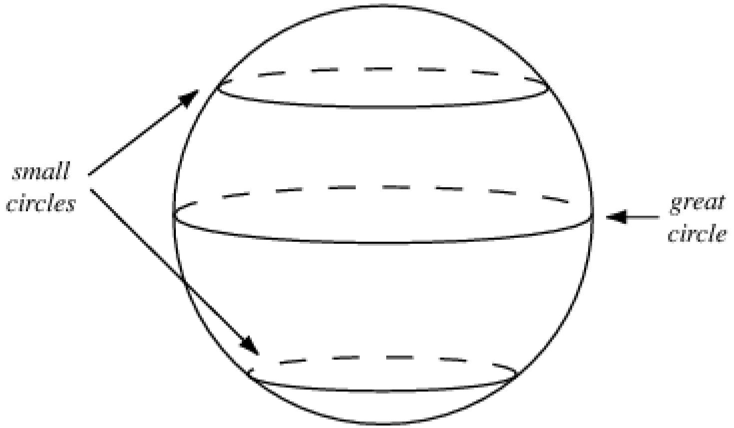
GAN Hacks: Normalize Inputs

- Normalize the inputs between -1 and 1
- Tanh as the last layer of the generator output
- No-brainer ☺

https://github.com/soumith/ganhacks

GAN Hacks: Sampling

- Use a spherical z
- Don't sample from a uniform distribution
- Sample from a Gaussian Distribution



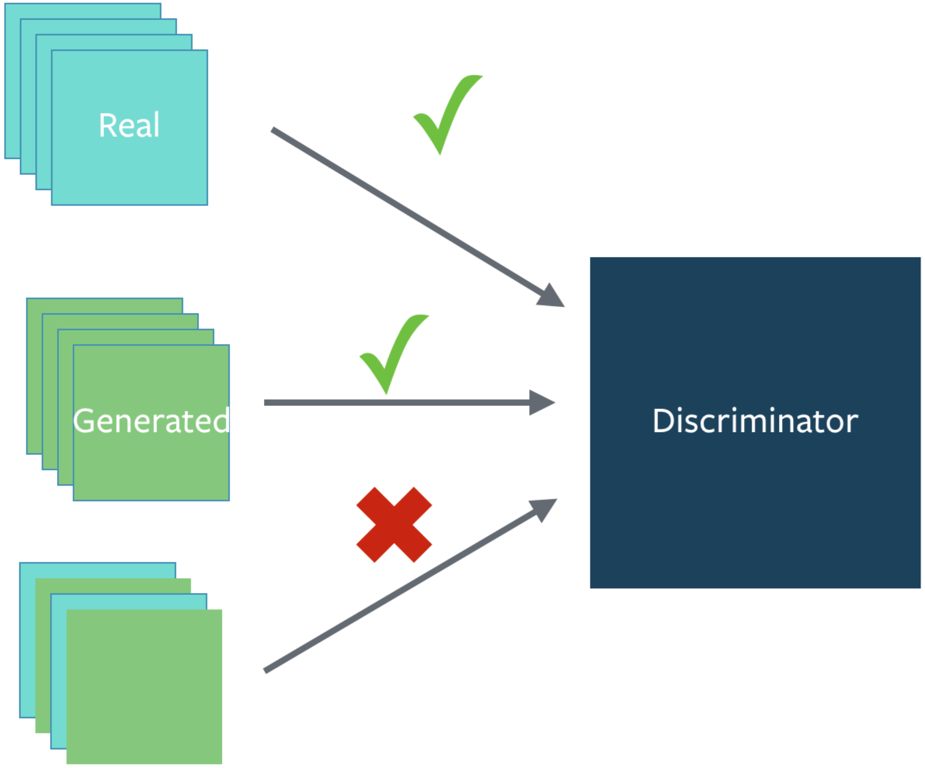
- When doing interpolations, do the interpolation via a great circle, rather than a straight line from point A to point B

- Tom White's [Sampling Generative Networks](https://github.com/dribnet/plat) ref code https://github.com/dribnet/plat has more details

GAN Hacks: BatchNorm

- Use Batch Norm

- Construct different mini-batches for real and fake, i.e. each mini-batch needs to contain only all real images or all generated images.



GAN Hacks: Use ADAM

- See Adam usage [Radford et al. 15]
- SGD for discriminator
- ADAM for generator

GAN Hacks: One-sided Label Smoothing

- Prevent discriminator from giving too large gradient signal to generator:

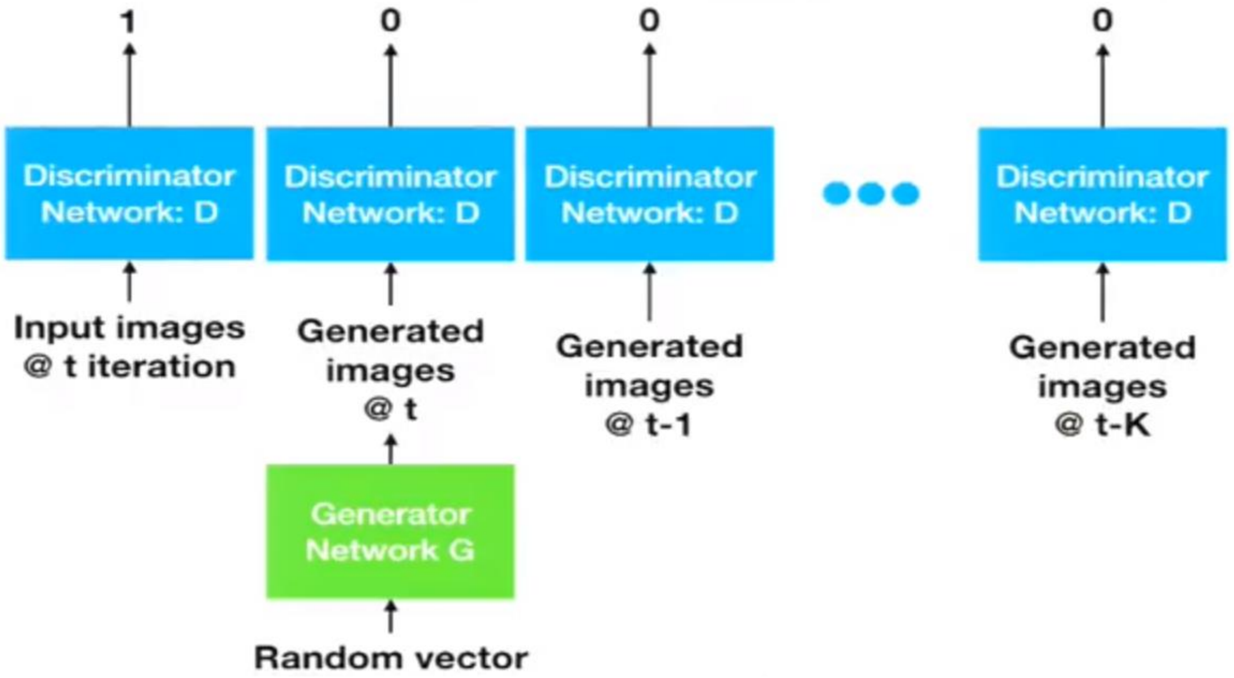
$$J^{(D)} = -\frac{1}{2}\mathbb{E}_{\boldsymbol{x}\sim p_{\text{data}}} \lambda \log D(\boldsymbol{x}) - \frac{1}{2}\mathbb{E}_{\boldsymbol{z}} \log\left(1 - D\left(G(\boldsymbol{z})\right)\right)$$

Some value smaller than 1; e.g.,0.9

-> reduces confidence; i.e., makes disc. 'weaker'
-> encourages 'extreme samples' (prevents extrapolating)

Salimans et al. 17 "Improved Techniques for Training GANs"

GAN Hacks: Historical Generator Batches

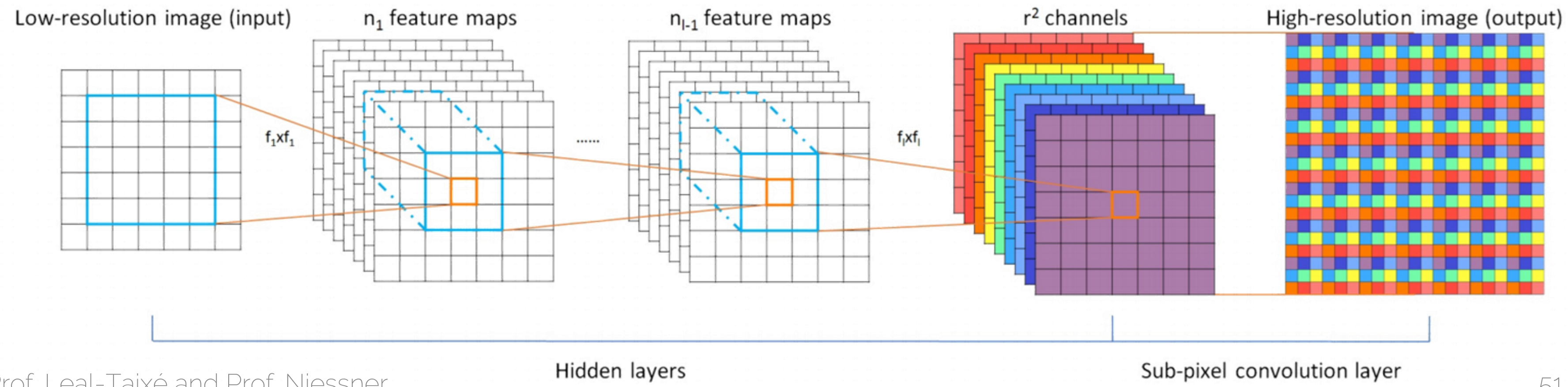


Help stabilize discriminator training in early stage

Srivastava et al. 17 “Learning from Simulated and Unsupervised Images through Adversarial Training”

GAN Hacks: Avoid Sparse Gradients

- Stability of GAN game suffers if gradients are sparse
- LeakyReLU -> good in both G and D
- Downsample -> use average pool, conv+stride
- Upsample -> deconv+stride, PixelShuffle



[Shi et al. 16] https://arxiv.org/pdf/1609.05158.pdf

Exponential Averaging of Weights

- Problem: discriminator is noisy due to SGD

- Rather than taking final result of a GAN, would be biased on last latest iterations (i.e., latest training samples),

  -> exponential average of weights

  -> keep second 'vector' of weights that are averaged
  -> almost no cost, average of weights from last n iters

New Objective Functions

New Objective Functions

"heuristic is standard…"

EBGAN: "Energy-based Generative Adversarial Networks"
BEGAN: "Boundary Equilibrium GAN"
WGAN: "Wasserstein Generative Adversarial Networks"
LSGAN: "Least Squares Generative Adversarial Networks"

….

The loss function alone will not make it suddenly work!

GAN Losses: EBGAN

- Discriminator is AE (Energy-based GAN)
- a good autoencoder: we want the reconstruction cost D(x) for real images to be low.
- a good critic: we want to penalize the discriminator if the reconstruction error for generated images drops below a value m.

$$\mathcal{L}_D(x, z) = D(x) + [m - D(G(z))]^+$$

$$\mathcal{L}_G(z) = D(G(z))$$

$$D(x) = ||Dec(Enc(x)) - x||$$

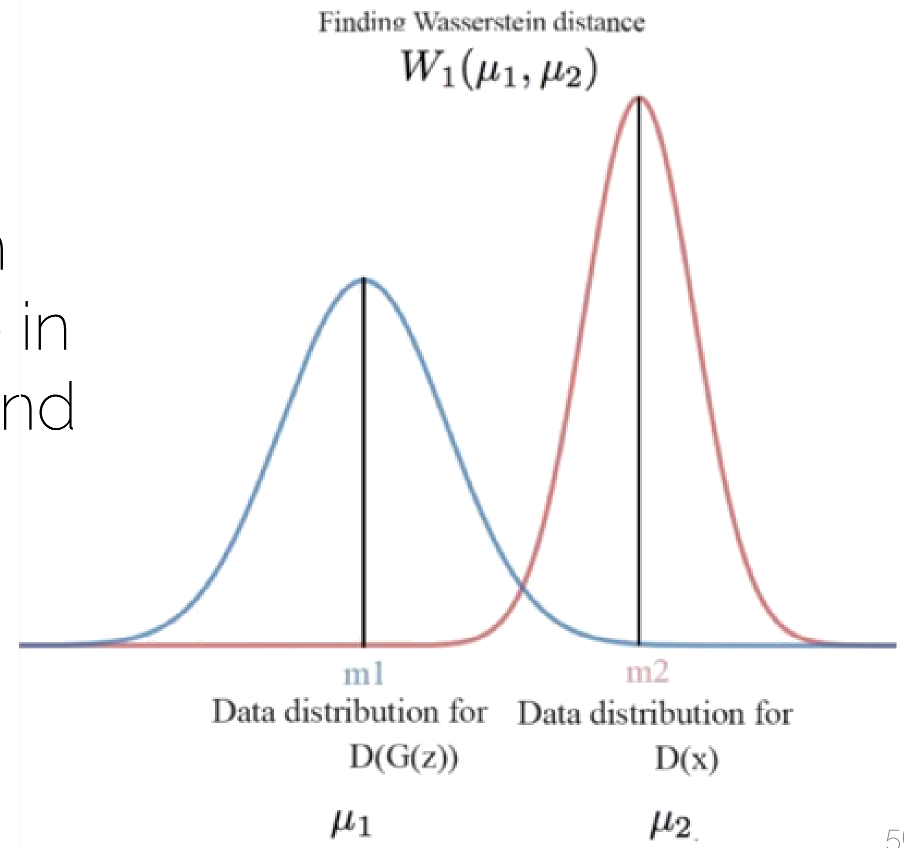
where $[\,u\,]^+ = max(0, u)$

https://medium.com/@jonathan_hui/gan-energy-based-gan-ebgan-boundary-equilibrium-gan-began-4662cceb7824

GAN Losses: BEGAN

- Similar to EBGAN

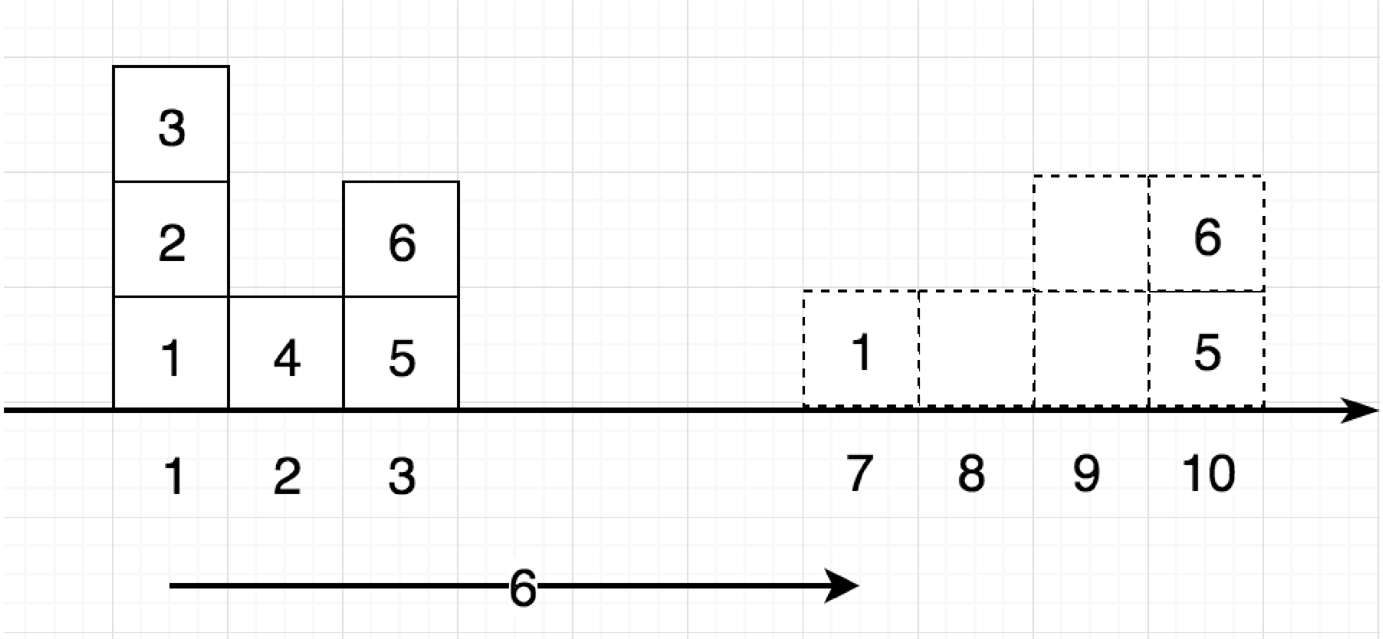
- Instead of reconstruction loss, measure difference in data distribution of real and generated images



https://medium.com/@jonathan_hui/gan-energy-based-gan-ebgan-boundary-equilibrium-gan-began-4662cceb7824

GAN Losses: WGAN

- Earth Mover Distance / Wasserstein Distance



Minimum amount of work to move earth from p(x) to q(x)

https://medium.com/@jonathan_hui/gan-wasserstein-gan-wgan-gp-6a1a2aa1b490

GAN Losses: WGAN

- Formulate EMD via it's dual:

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

$$|f(x_1) - f(x_2)| \leq |x_1 - x_2|.$$

1-Lipschitz function: upper bound between densities

https://medium.com/@jonathan_hui/gan-wasserstein-gan-wgan-gp-6a1a2aa1b490

GAN Losses: WGAN

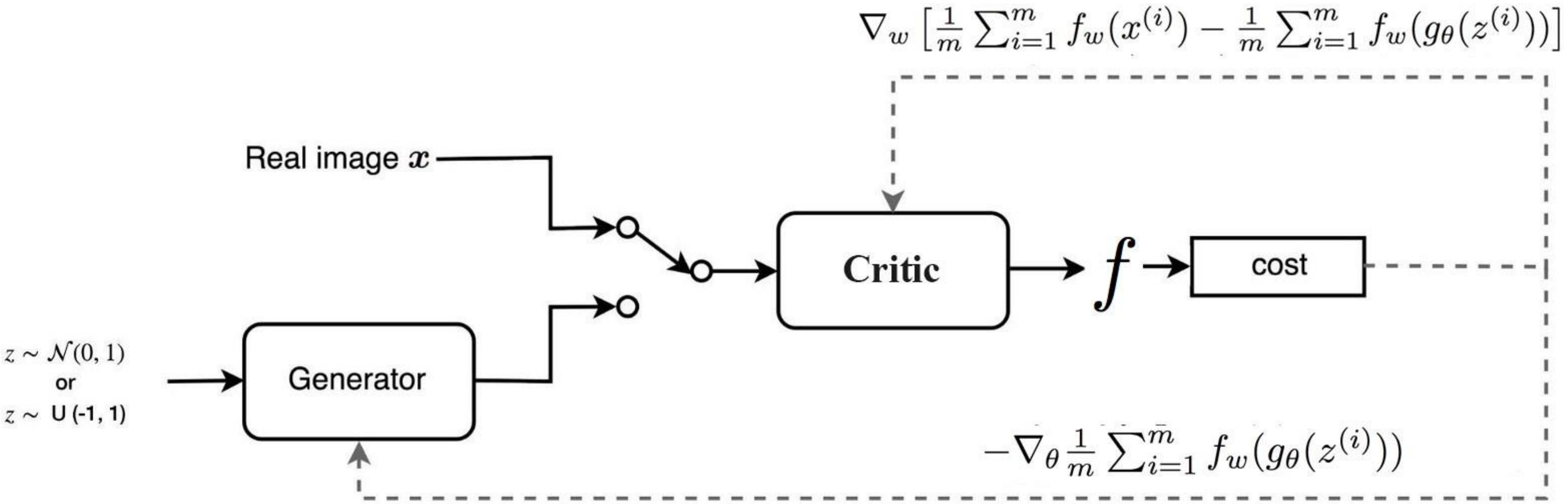
$$|f(x_1) - f(x_2)| \leq |x_1 - x_2|.$$

f is a critic function, defined by a neural network
-> f needs to be 1-Lipschitz; WGAN restricts max weight value in f; weights of the discriminator must be within a certain range controlled by hyperparameters c

$$w \leftarrow w + \alpha \cdot \text{RMSProp}(w, g_w)$$
$$w \leftarrow \text{clip}(w, -c, c)$$

https://medium.com/@jonathan_hui/gan-wasserstein-gan-wgan-gp-6a1a2aa1b490

GAN Losses: WGAN



https://medium.com/@jonathan_hui/gan-wasserstein-gan-wgan-gp-6a1a2aa1b490

GAN Losses: WGAN

	Discriminator/Critic	Generator
GAN	$\nabla_{\theta_d} \frac{1}{m} \sum_{i=1}^{m} \left[\log D\left(\boldsymbol{x}^{(i)}\right) + \log\left(1 - D\left(G\left(\boldsymbol{z}^{(i)}\right)\right)\right)\right]$	$\nabla_{\theta_g} \frac{1}{m} \sum_{i=1}^{m} -\log\left(D\left(G\left(\boldsymbol{z}^{(i)}\right)\right)\right)$
WGAN	$\nabla_w \frac{1}{m} \sum_{i=1}^{m} \left[f\left(x^{(i)}\right) - f\left(G\left(z^{(i)}\right)\right)\right]$	$\nabla_\theta \frac{1}{m} \sum_{i=1}^{m} -f\left(G\left(z^{(i)}\right)\right)$

https://medium.com/@jonathan_hui/gan-wasserstein-gan-wgan-gp-6a1a2aa1b490

GAN Losses: WGAN

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

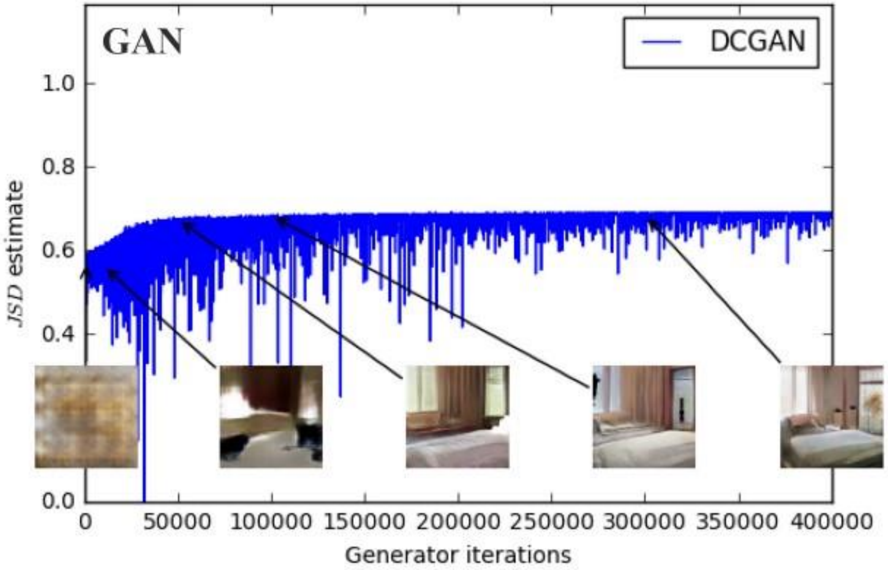
Require: : α, the learning rate. c, the clipping parameter. m, the batch size. n_{critic}, the number of iterations of the critic per generator iteration.

Require: : w_0, initial critic parameters. θ_0, initial generator's parameters.

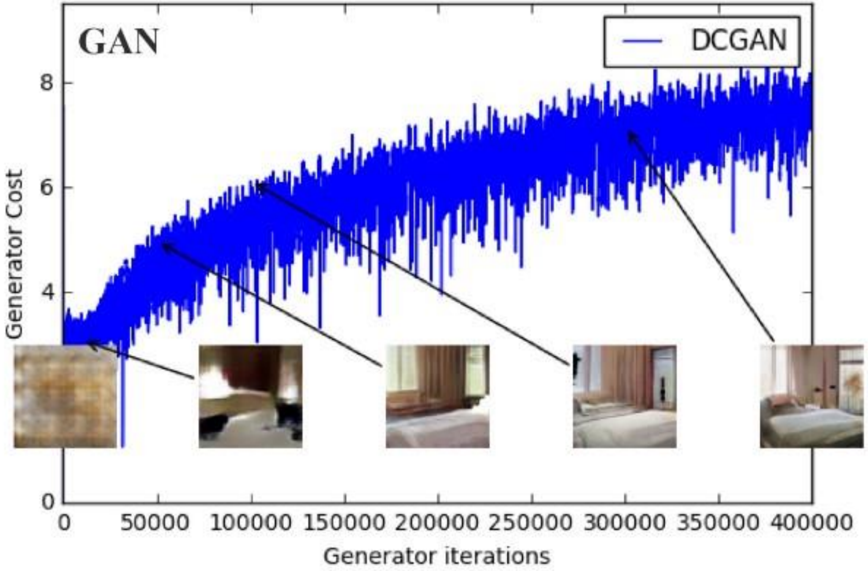
while θ has not converged **do**
  for $t = 0, ..., n_{\text{critic}}$ **do**
    Sample $\{x^{(i)}\}_{i=1}^m \sim \mathbb{P}_r$ a batch from the real data.
    Sample $\{z^{(i)}\}_{i=1}^m \sim p(z)$ a batch of prior samples.
    $g_w \leftarrow \nabla_w \left[\frac{1}{m}\sum_{i=1}^m f_w(x^{(i)}) - \frac{1}{m}\sum_{i=1}^m f_w(g_\theta(z^{(i)}))\right]$
    $w \leftarrow w + \alpha \cdot \text{RMSProp}(w, g_w)$
    $w \leftarrow \text{clip}(w, -c, c)$
  end for
  Sample $\{z^{(i)}\}_{i=1}^m \sim p(z)$ a batch of prior samples.
  $g_\theta \leftarrow -\nabla_\theta \frac{1}{m}\sum_{i=1}^m f_w(g_\theta(z^{(i)}))$
  $\theta \leftarrow \theta - \alpha \cdot \text{RMSProp}(\theta, g_\theta)$
end while

https://medium.com/@jonathan_hui/gan-wasserstein-gan-wgan-gp-6a1a2aa1b490

GAN Losses: WGAN



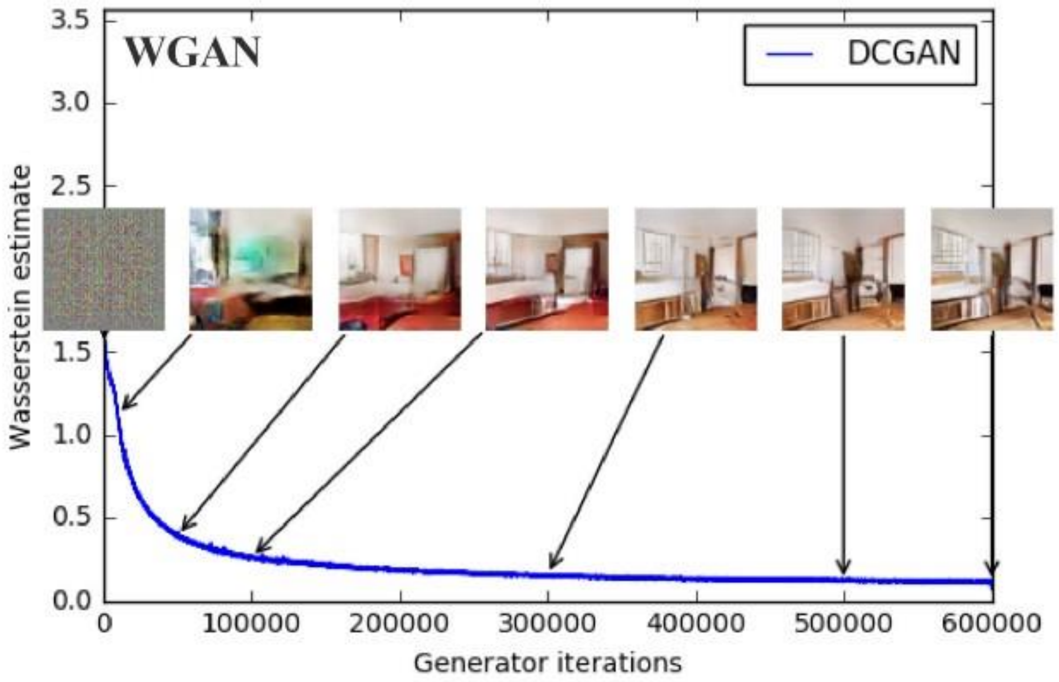
$$\frac{1}{m}\sum_{i=1}^{m}\log\left(1-D\left(G\left(\boldsymbol{z}^{(i)}\right)\right)\right)$$



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

https://medium.com/@jonathan_hui/gan-wasserstein-gan-wgan-gp-6a1a2aa1b490

GAN Losses: WGAN



$$\frac{1}{m}\sum_{i=1}^{m} f_w(x^{(i)}) - \frac{1}{m}\sum_{i=1}^{m} f_w(g_\theta(z^{(i)}))$$

https://medium.com/@jonathan_hui/gan-wasserstein-gan-wgan-gp-6a1a2aa1b490

GAN Losses: WGAN

+ mitigates mode collapse
+ generator still learns when critic performs well
+ actual convergence

- Enforcing Lipschitz constraint is difficult
- Weight clipping is “terrible”
    -> too high: takes long time to reach limit; slow training
    -> too small: vanishing gradients when layers are big

GAN Losses

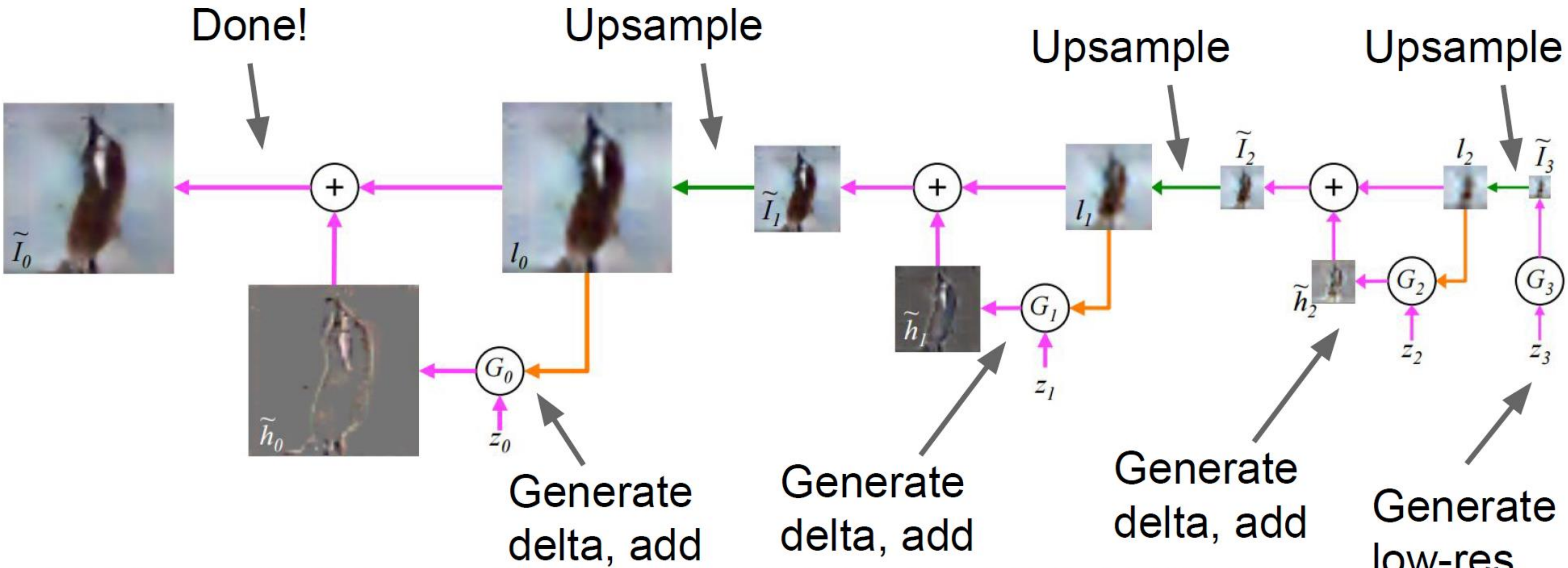
- Many more variations!!!

- High-level understanding: "loss" is a meta loss to train the actual loss (i.e., D) to provide gradients for G

- Always start simple: if things don't converge, don't randomly shuffle loss around; always try easy things first (AE, VAE, 'simple heuristic' GAN)

GAN Architectures

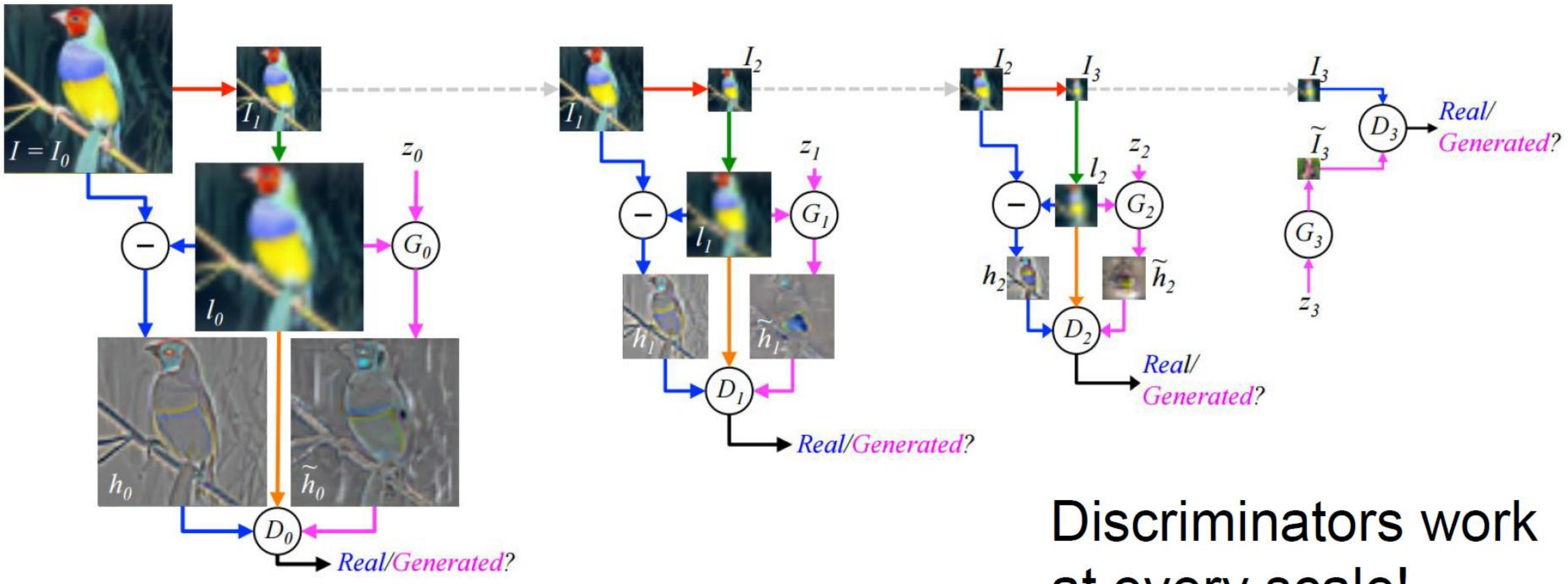
Multiscale GANs



Denton et al, "Deep generative image models using a Laplacian pyramid of adversarial networks", NIPS 2015

Credit: Li/Karpathy/Johnson

Multiscale GANs

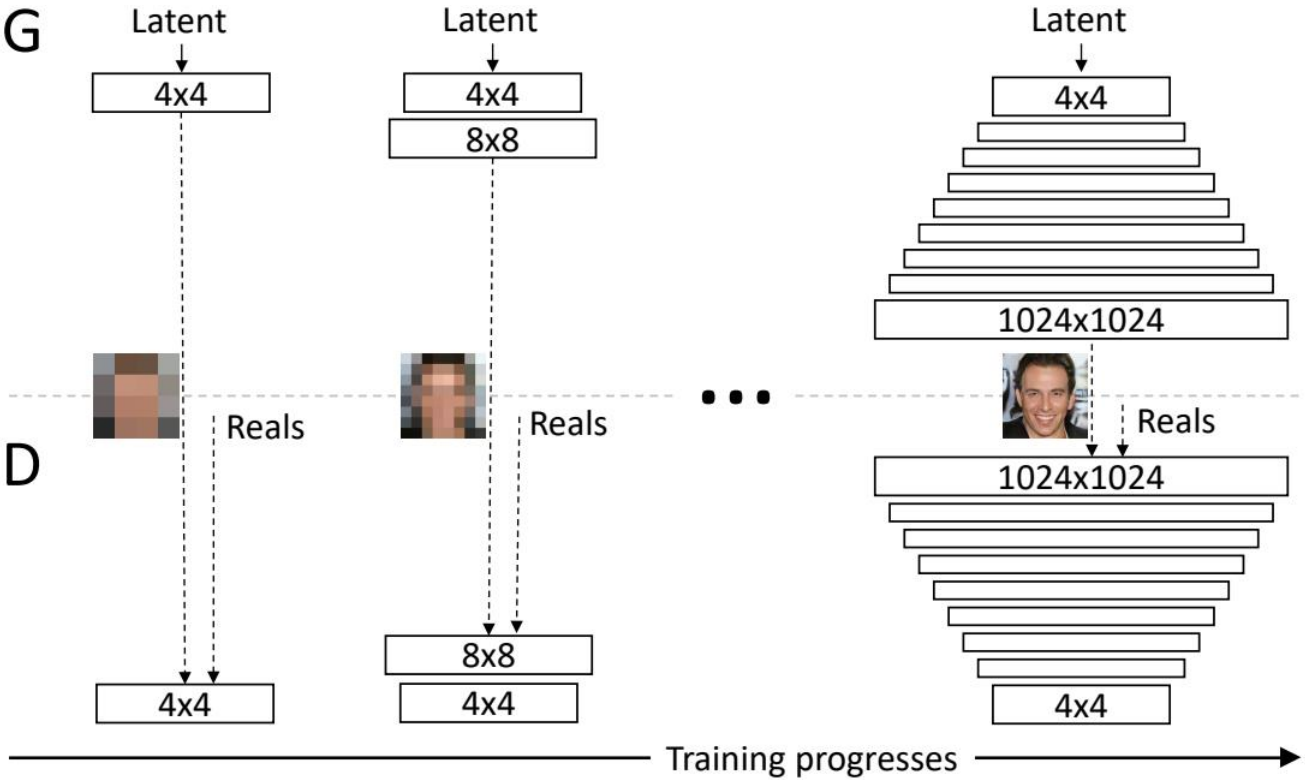


Discriminators work at every scale!

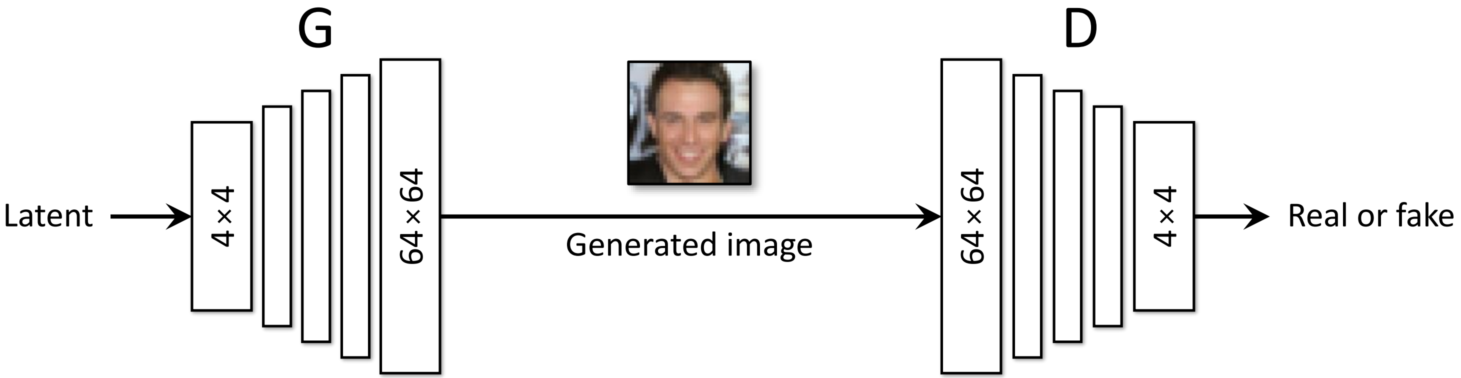
Denton et al, NIPS 2015

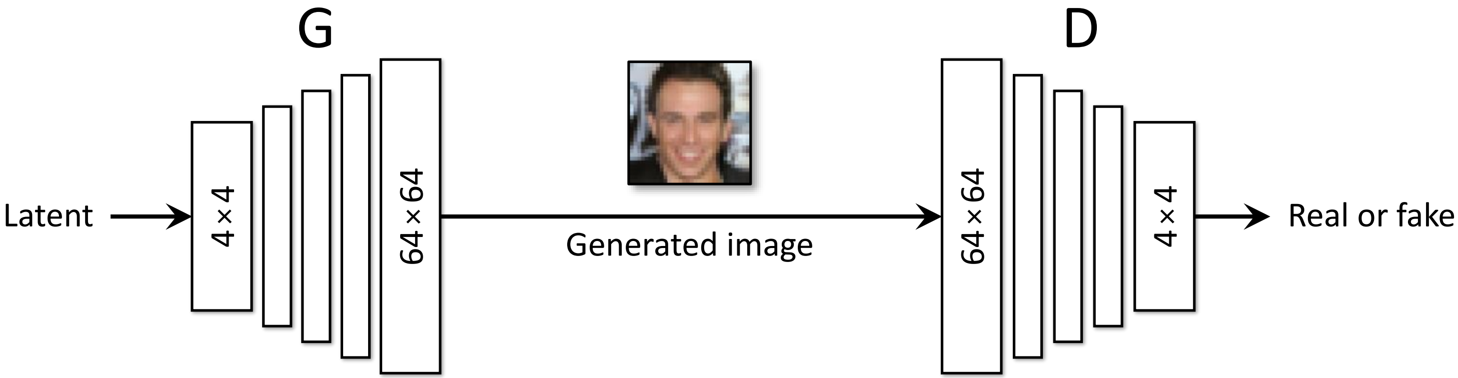
Credit: Li/Karpathy/Johnson

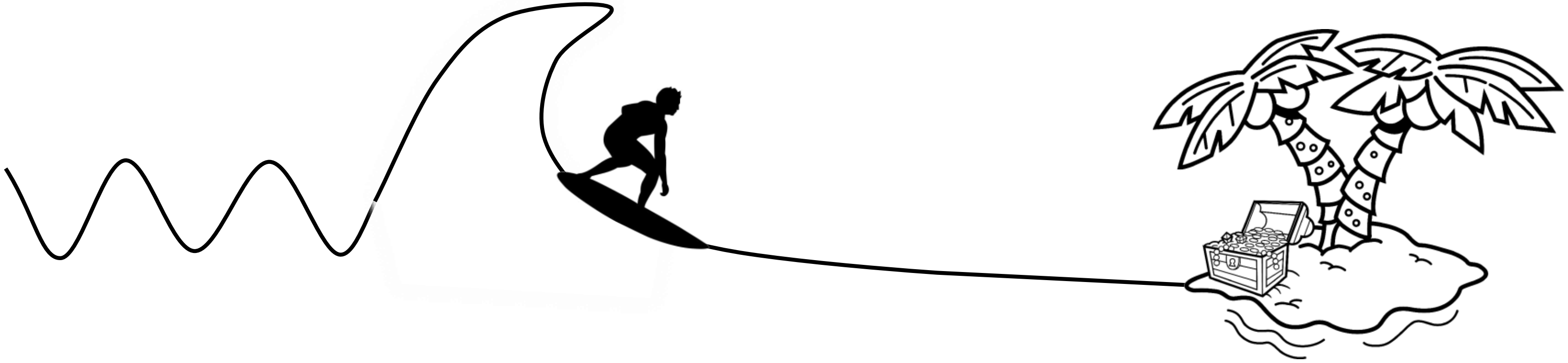
Progressive Growing GANs

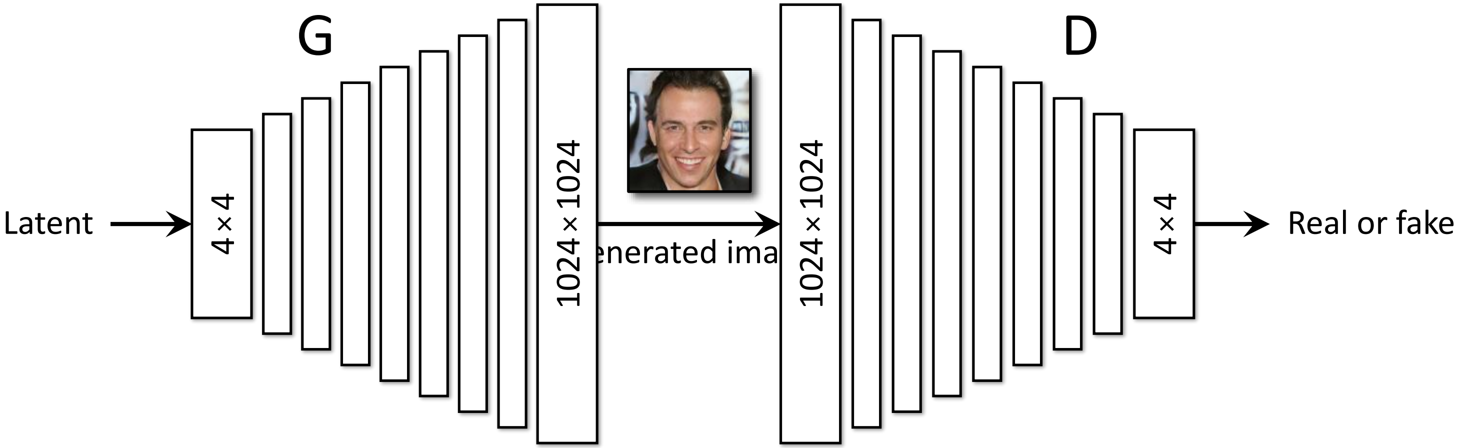


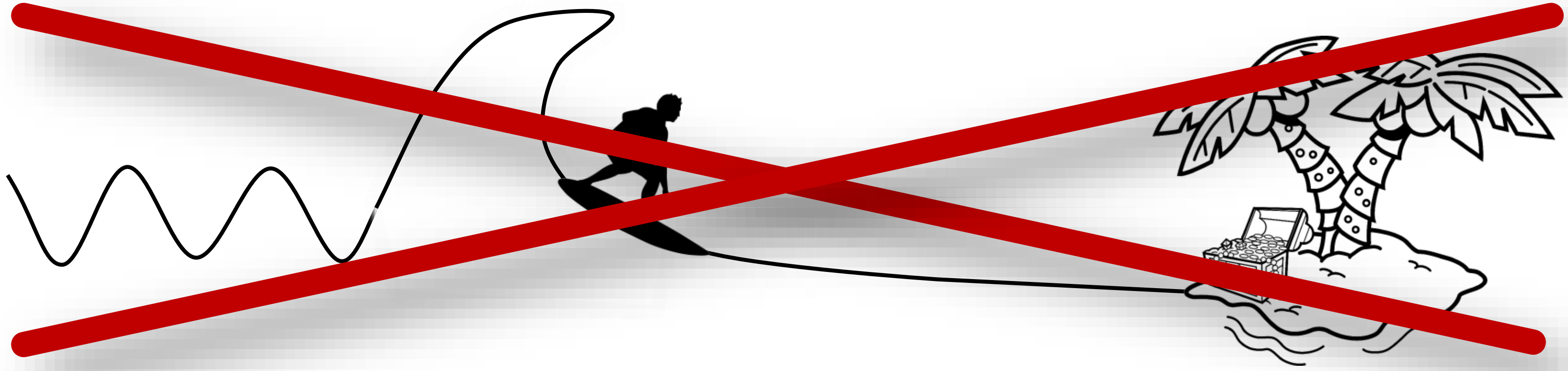
https://github.com/tkarras/progressive_growing_of_gans [Karras et al. 17]

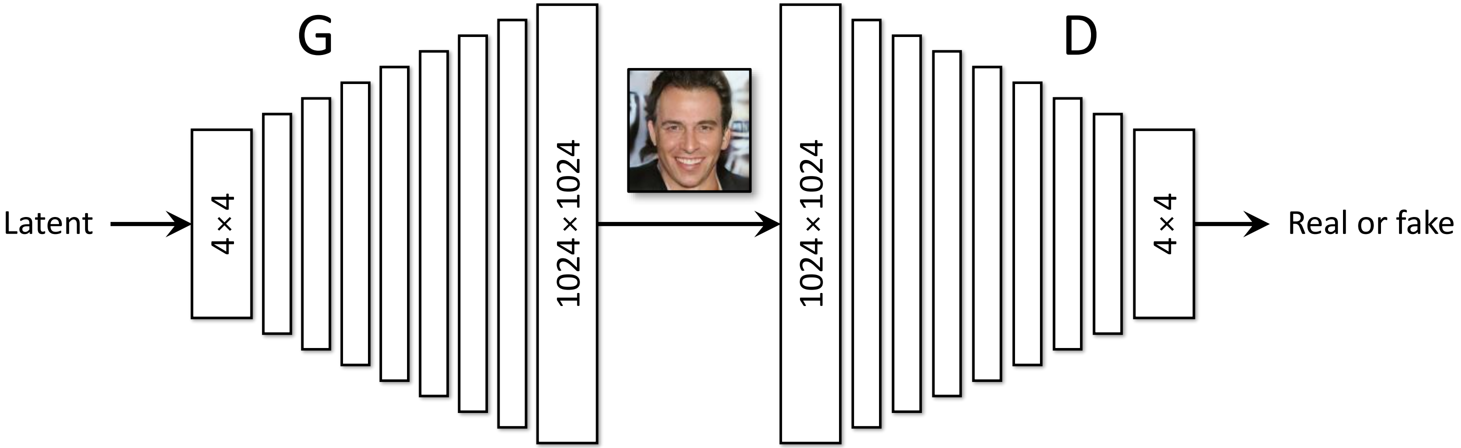

G
D
Latent
4×4
64×64
Generated image
64×64
4×4
Real or fake

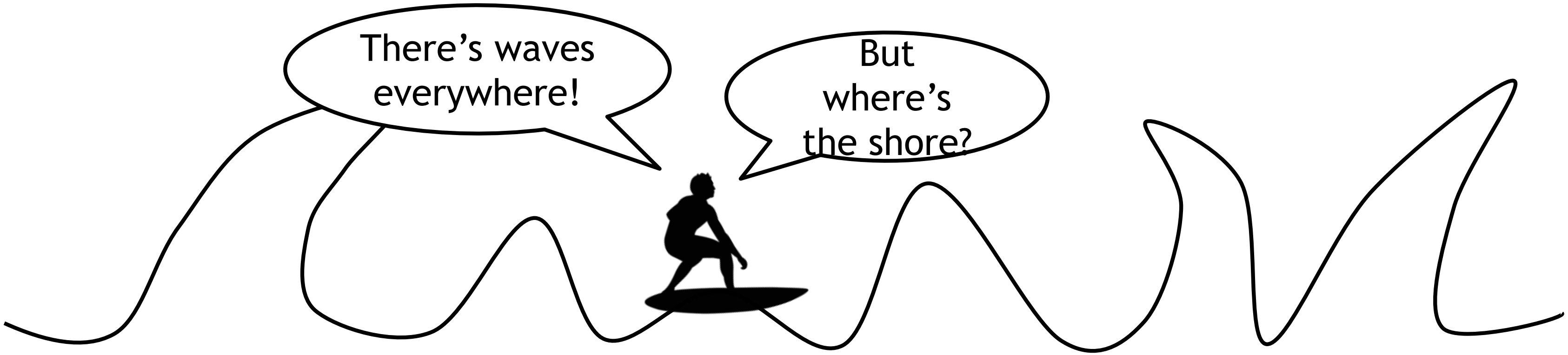

G
D
Latent
4×4
64×64
Generated image
64×64
4×4
Real or fake

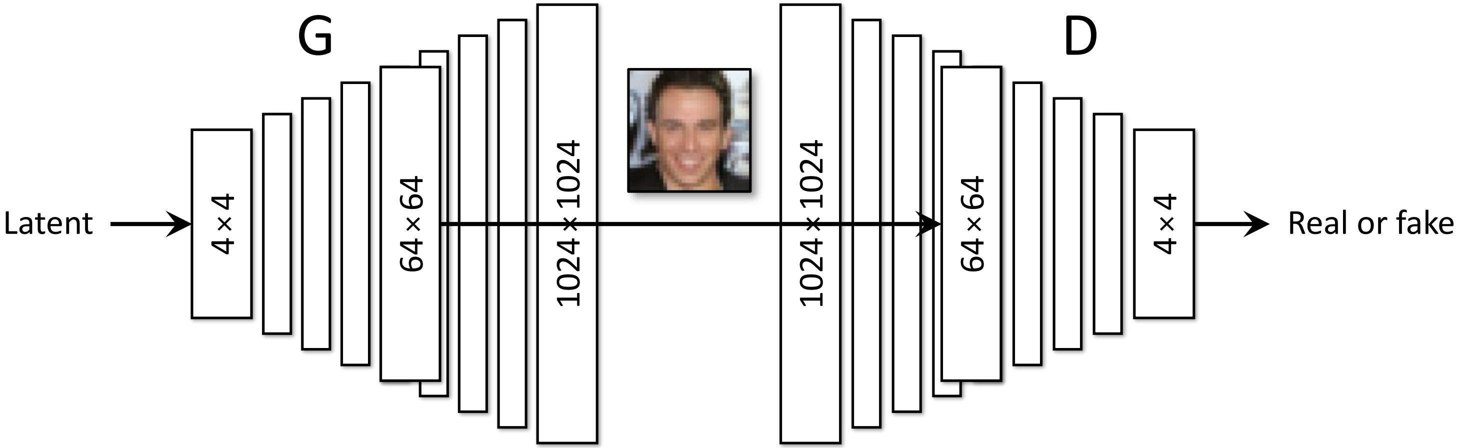


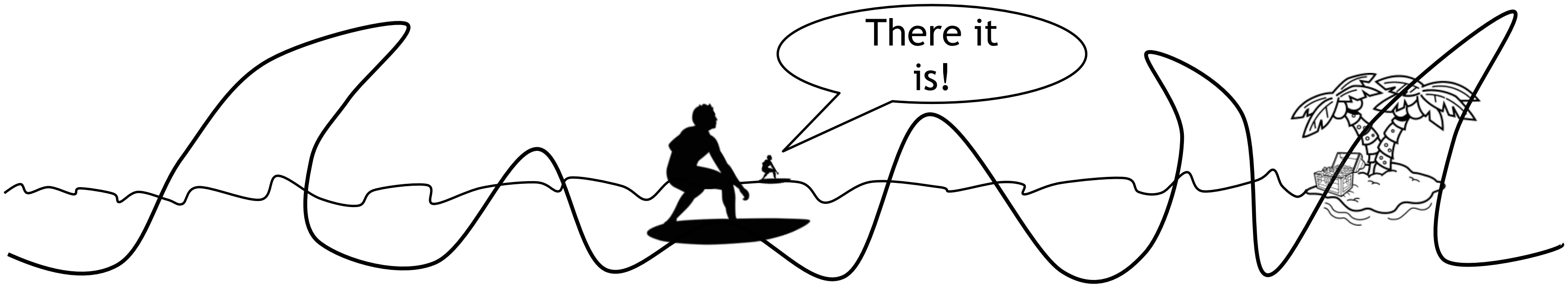

G
D
Latent
4 × 4
1024 × 1024
enerated ima
1024 × 1024
4 × 4
Real or fake

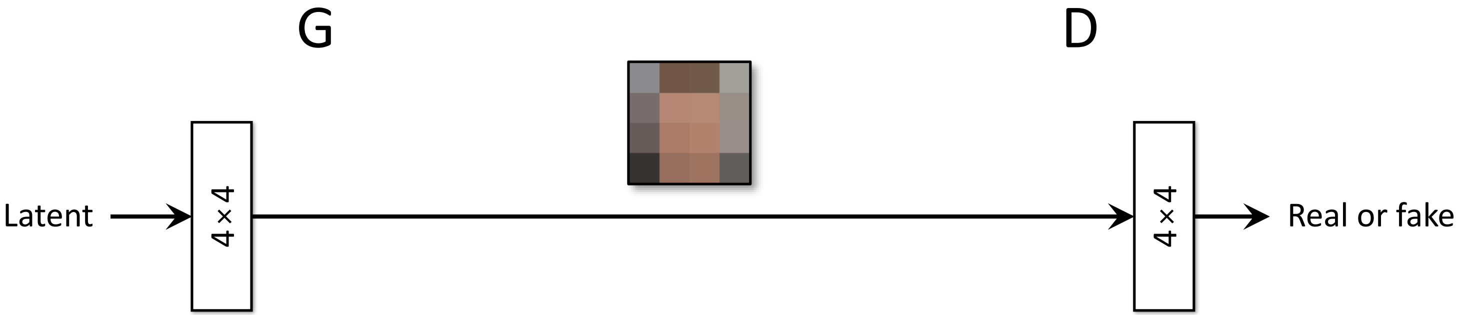



G
D
Latent
4 × 4
1024 × 1024
1024 × 1024
4 × 4
Real or fake

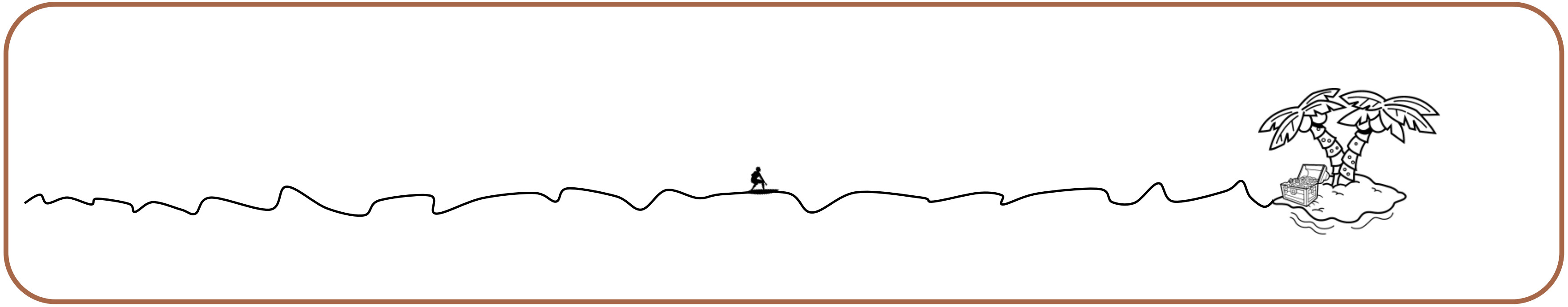

There's waves everywhere!
But where's the shore?

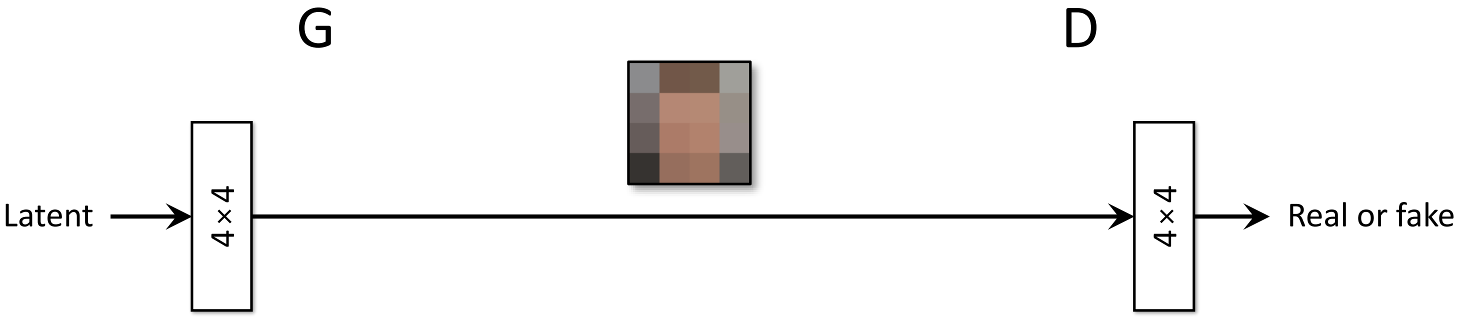

G
D
Latent
4×4
64×64
1024×1024
1024×1024
64×64
4×4
Real or fake

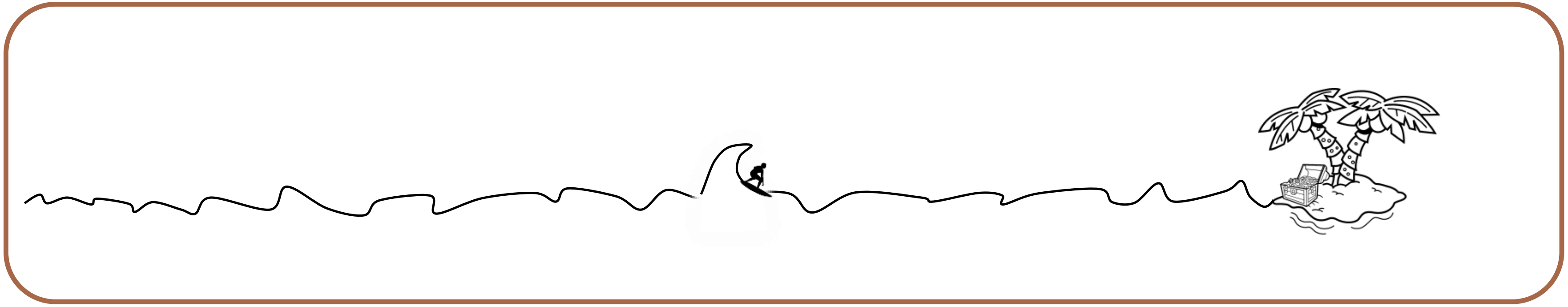

There it is!

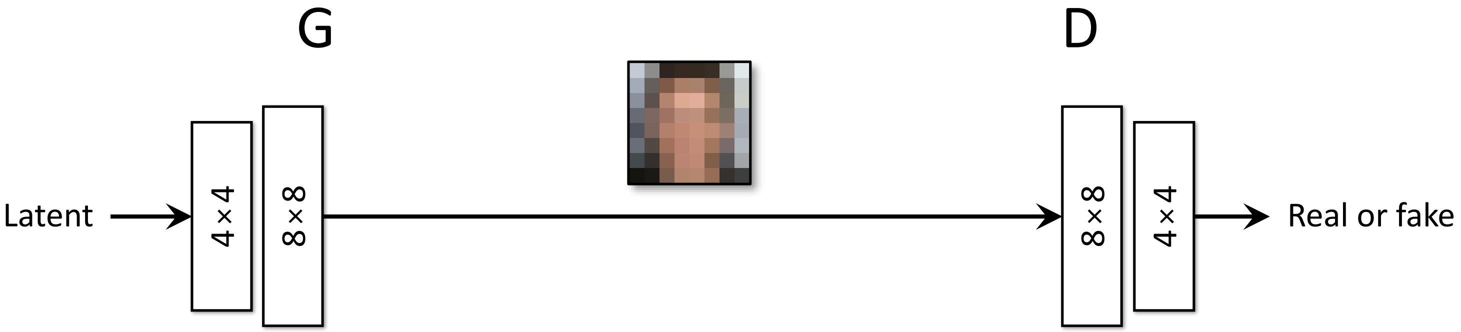


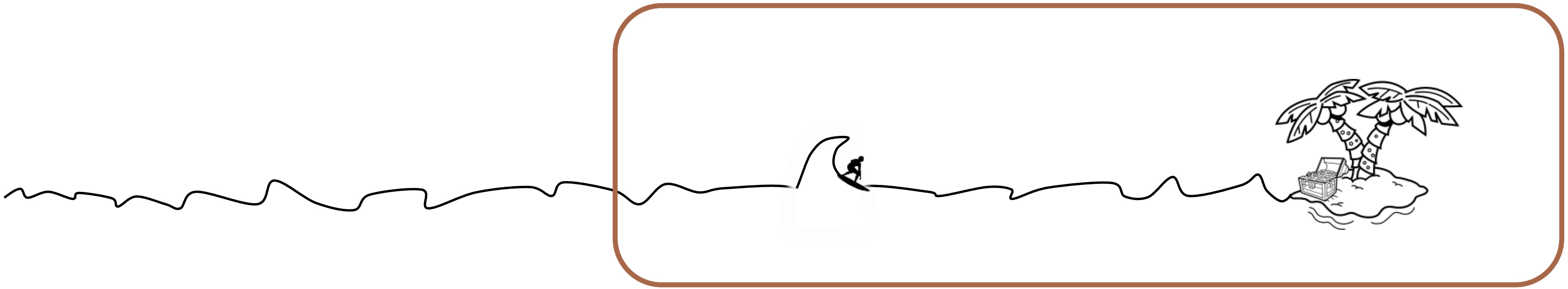
G
D
Latent
4×4
4×4
Real or fake

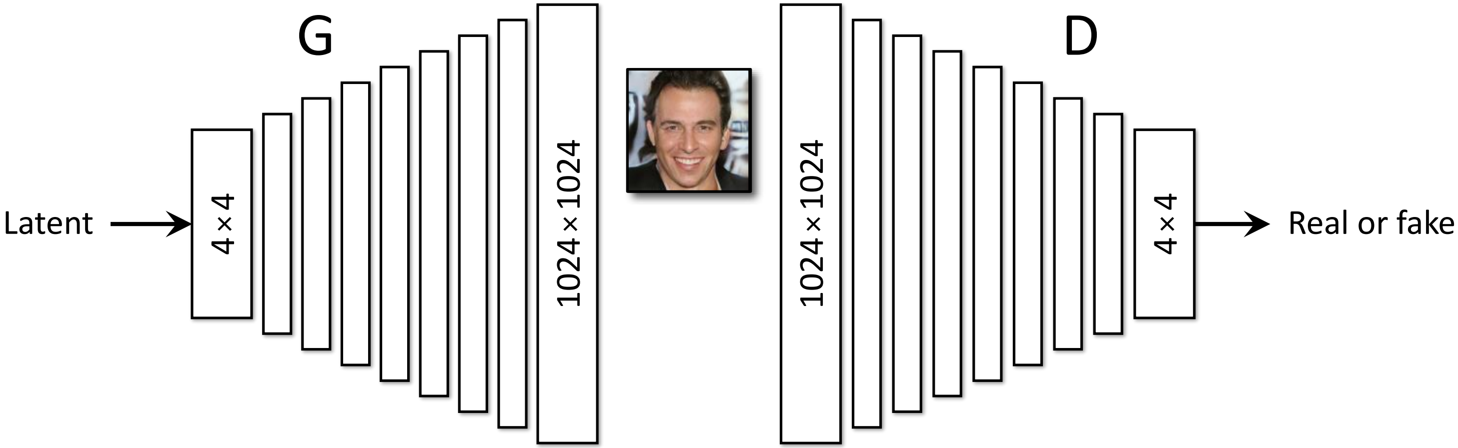


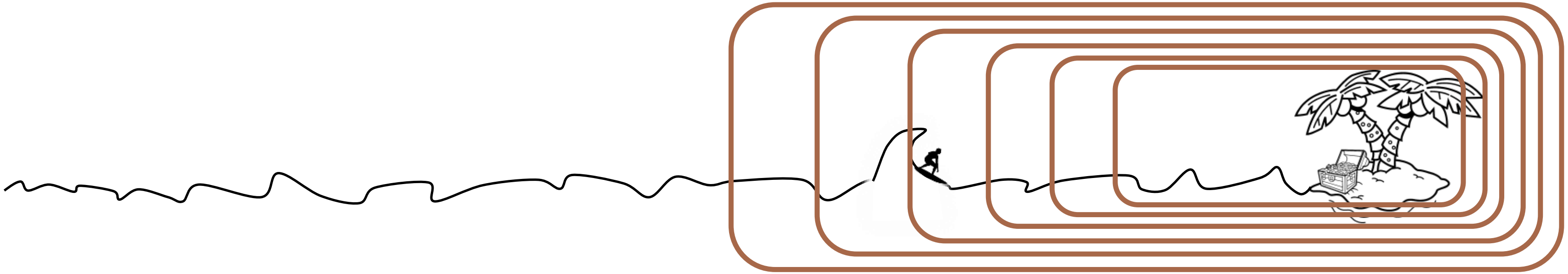

G
D
Latent
4×4
4×4
Real or fake

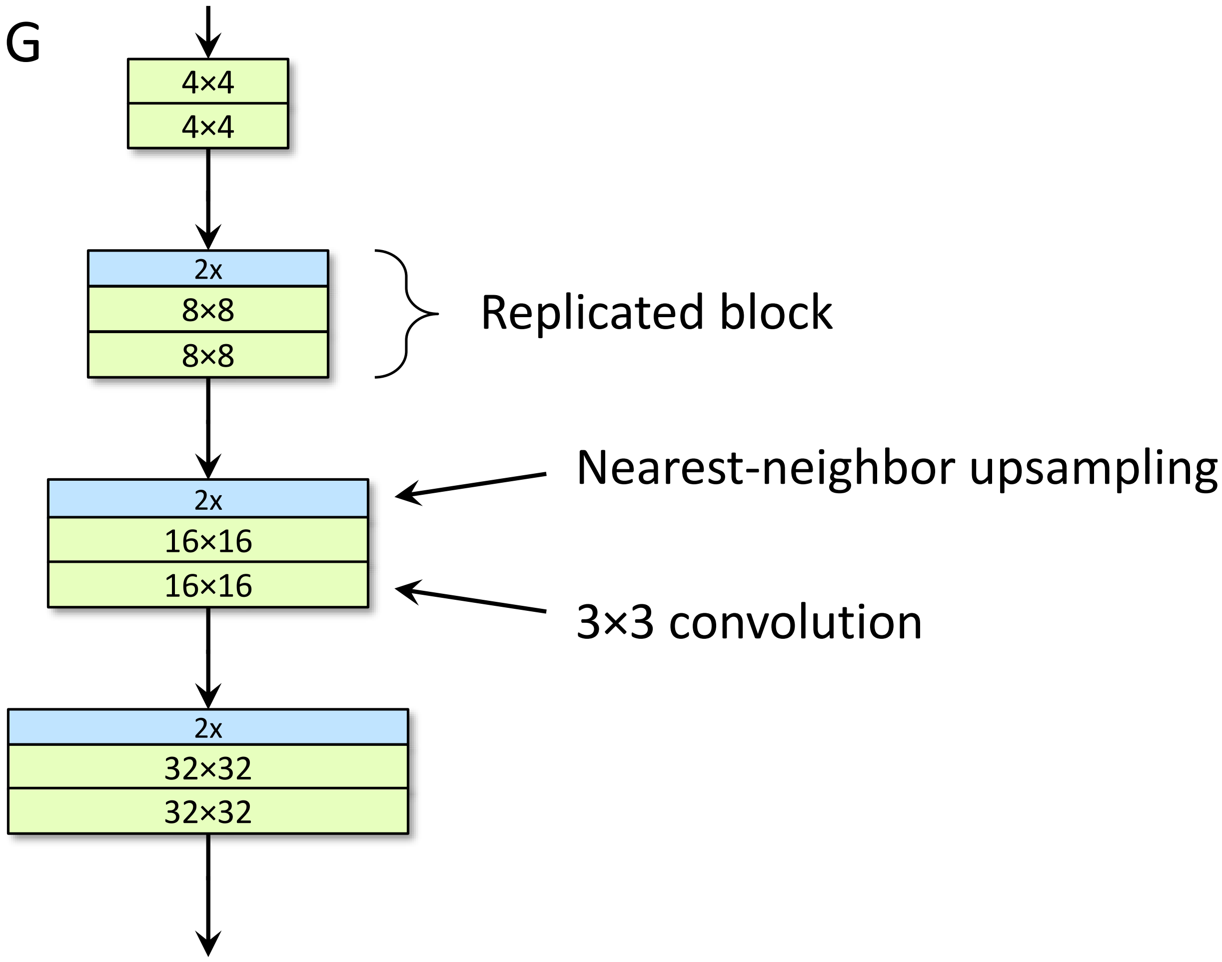


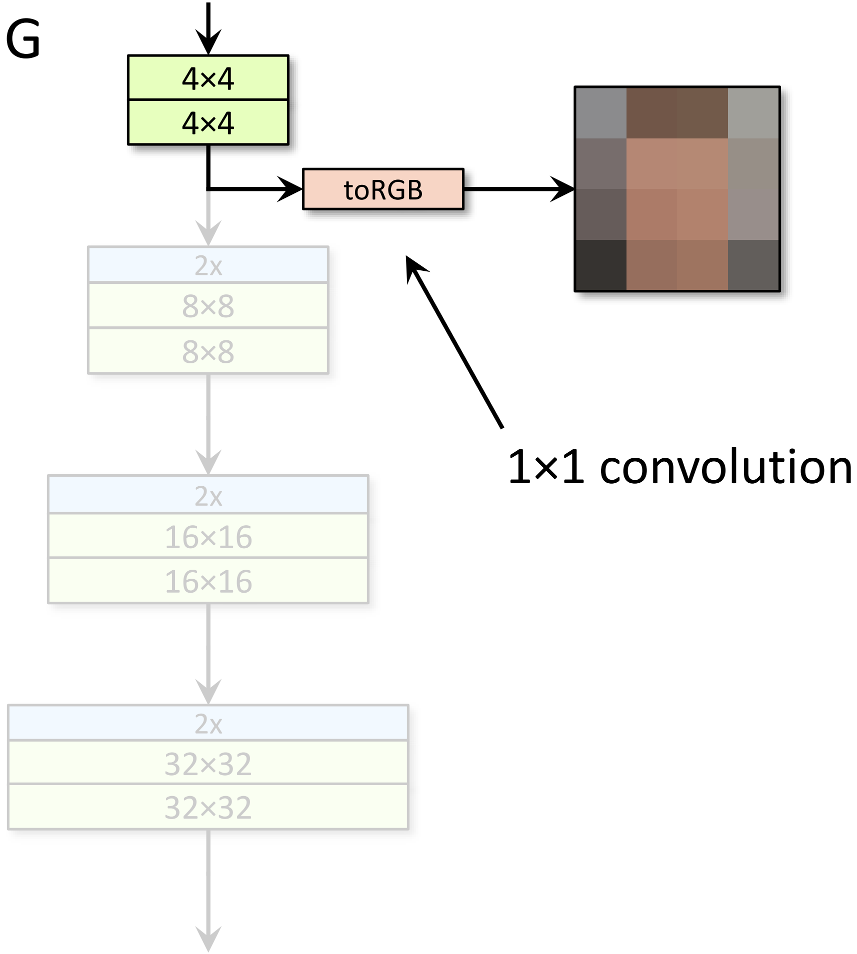

G
D
Latent
4×4
8×8
8×8
4×4
Real or fake

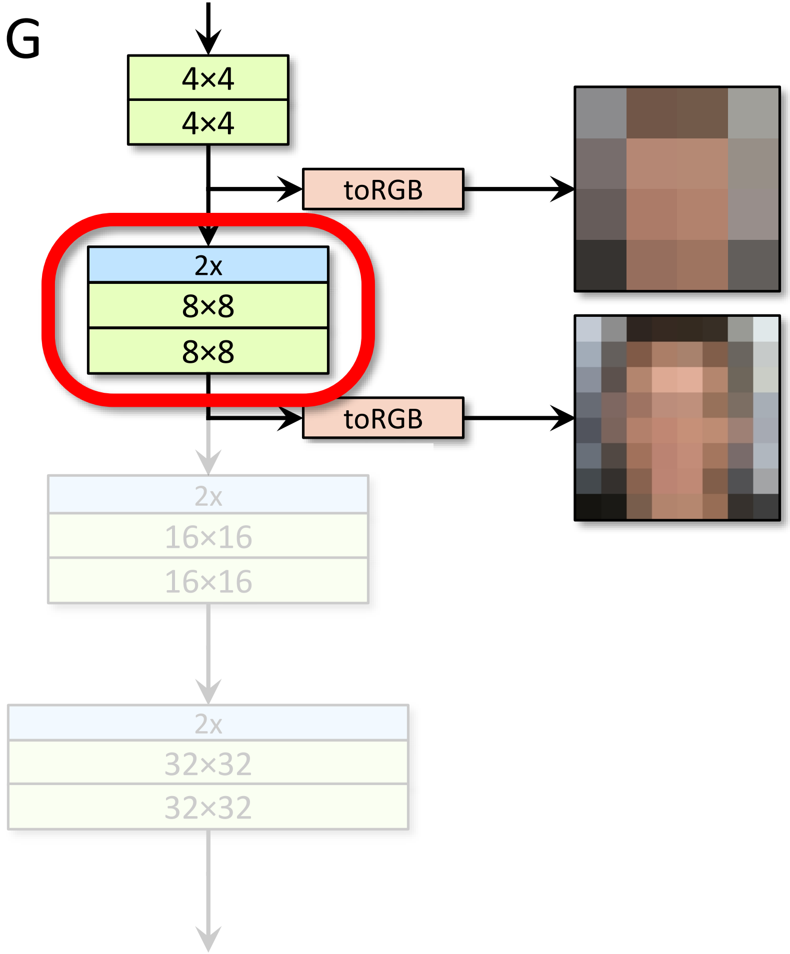


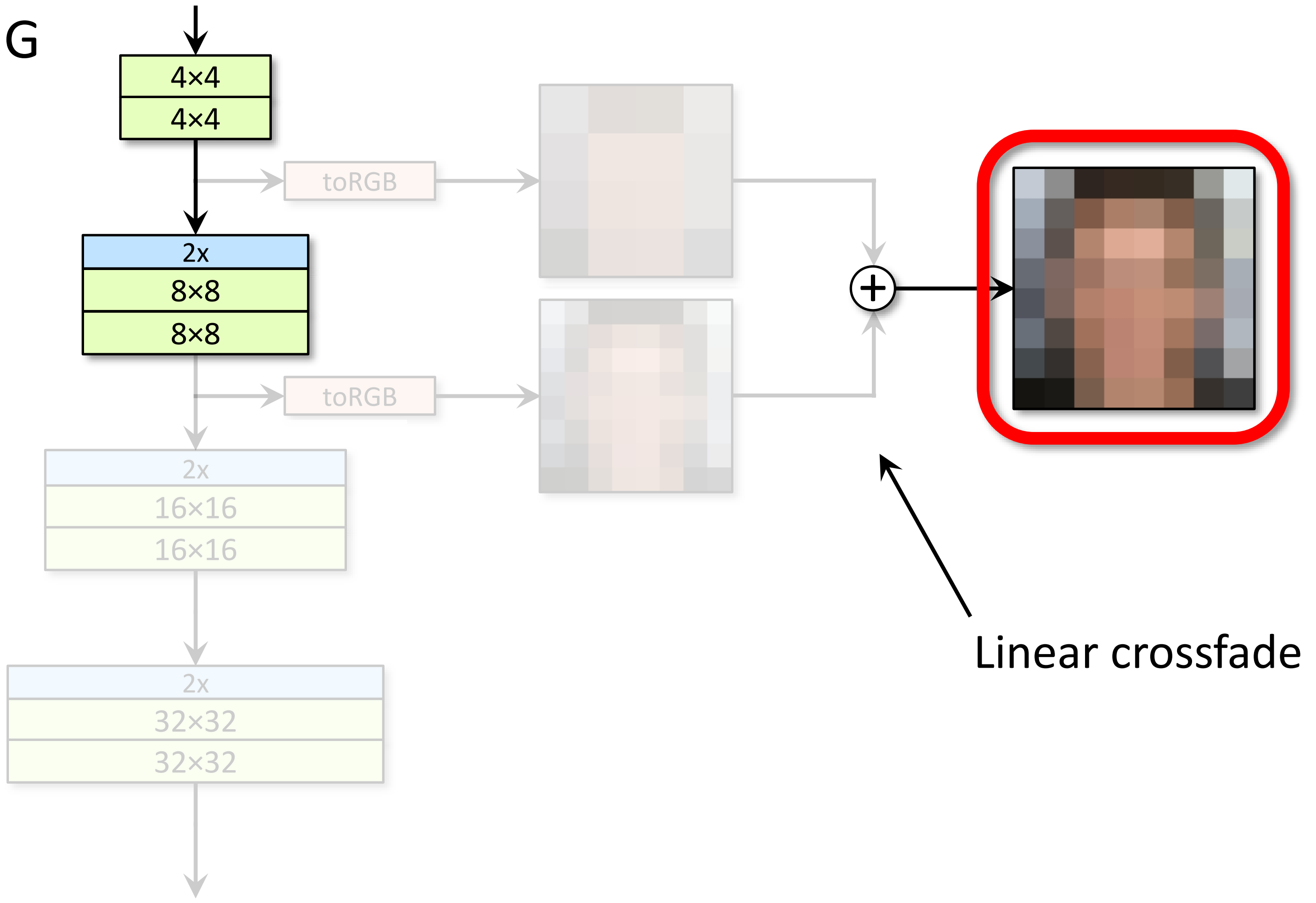

G
D
Latent
4 × 4
1024 × 1024
1024 × 1024
4 × 4
Real or fake



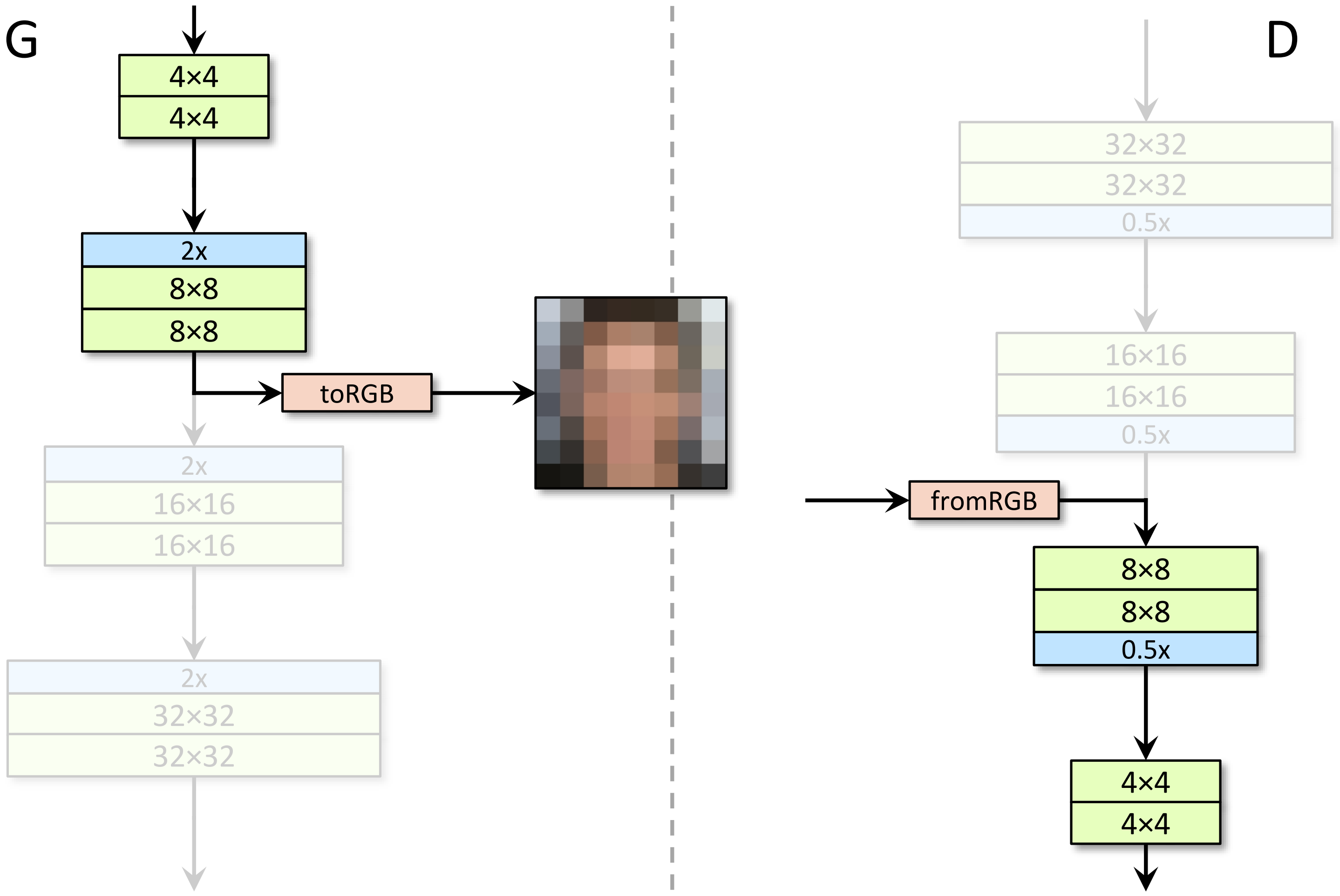

G
4×4
4×4
2x
8×8
8×8
Replicated block
2x
16×16
16×16
Nearest-neighbor upsampling
3×3 convolution
2x
32×32
32×32


G
4×4
4×4
toRGB
2x
8×8
8×8
2x
16×16
16×16
2x
32×32
32×32
1×1 convolution


G
4×4
4×4
toRGB
2x
8×8
8×8
toRGB
2x
16×16
16×16
2x
32×32
32×32

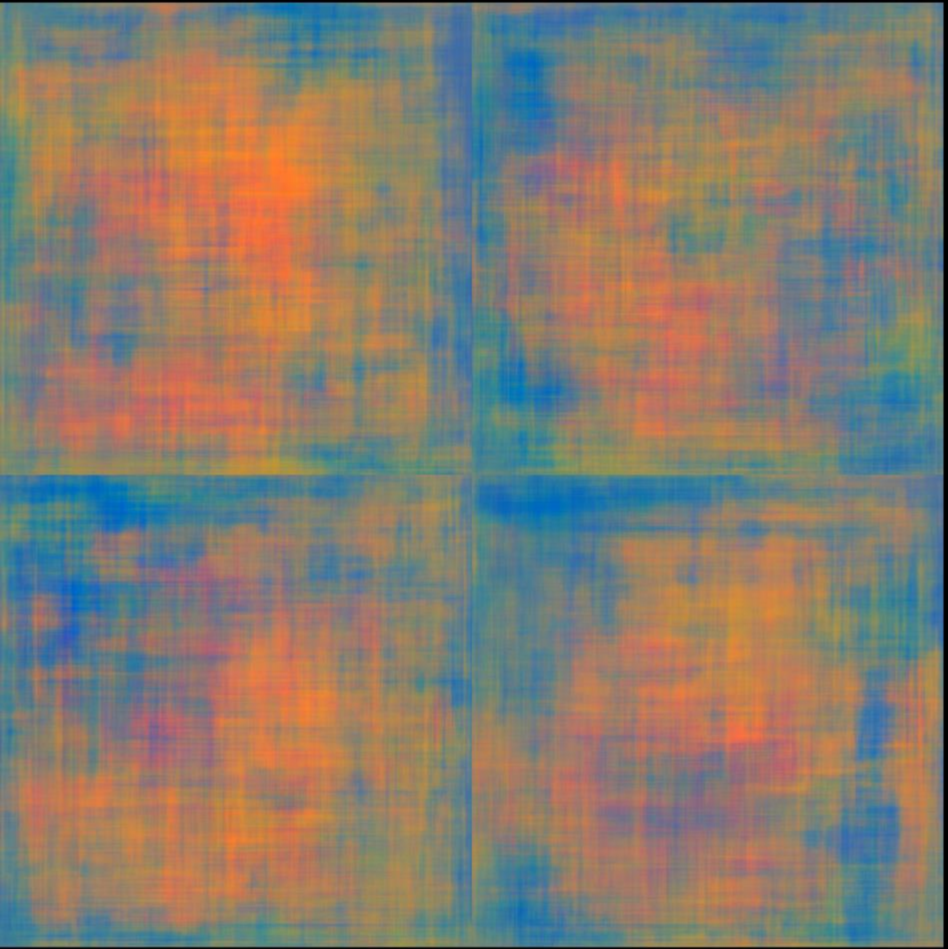


G
4×4
4×4
toRGB
2x
8×8
8×8
toRGB
2x
16×16
16×16
2x
32×32
32×32
Linear crossfade

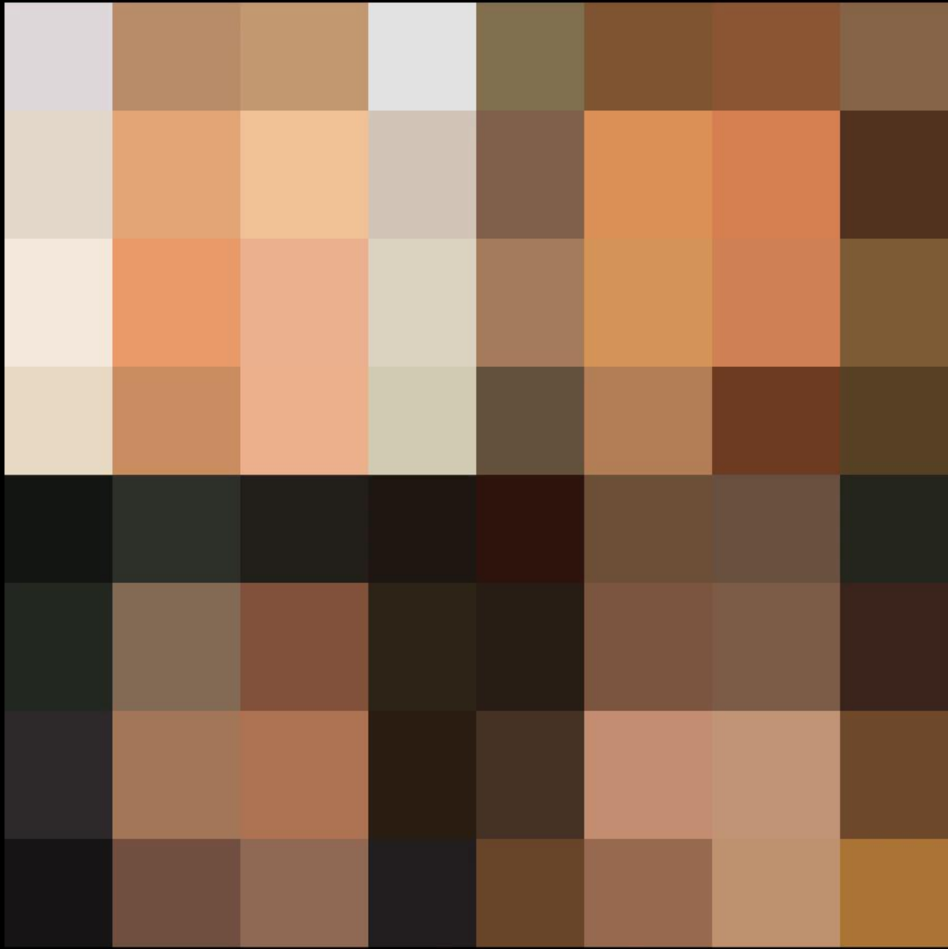


G
4×4
4×4
2x
8×8
8×8
toRGB
2x
16×16
16×16
2x
32×32
32×32
D
32×32
32×32
0.5x
16×16
16×16
0.5x
fromRGB
8×8
8×8
0.5x
4×4
4×4

5 min 00 sec

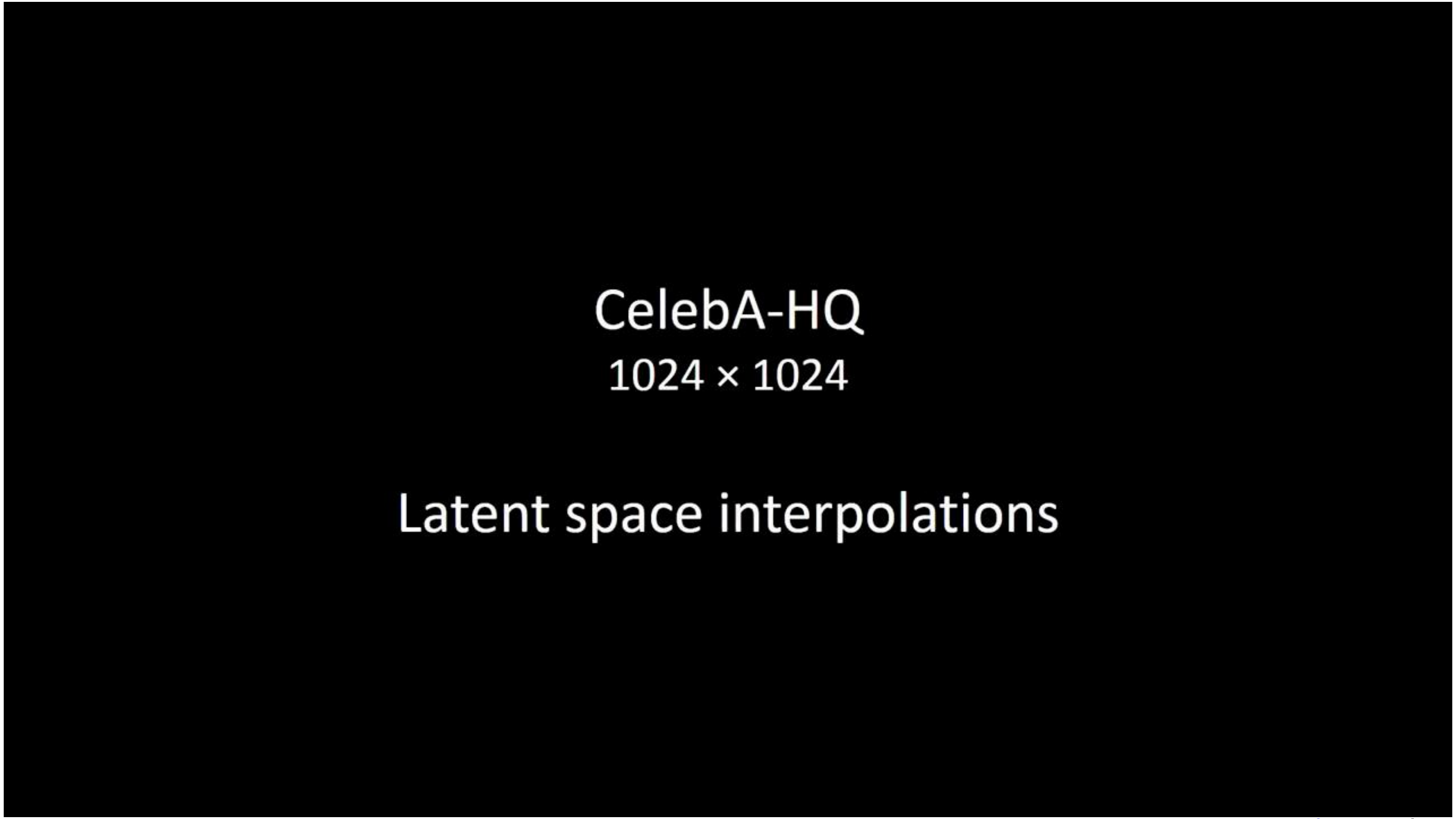


Fixed resolution



Progressive growing

Progressive Growing GANs



https://github.com/tkarras/progressive_growing_of_gans [Karras et al. 17]

Lots of GAN Variations

- Hundreds of GAN papers in the last two years
  - > Mostly with different losses
  - > Extremely hard to train and evaluate

Are GANs Created Equal? A Large-Scale Study

Mario Lucic* Karol Kurach* Marcin Michalski Sylvain Gelly Olivier Bousquet
Google Brain

Abstract

Generative adversarial networks (GAN) are a powerful subclass of generative models. Despite a very rich research

GAN algorithm(s) perform objectively better than the others. That's partially due to the lack of robust and consistent metric, as well as limited comparisons which put all algorithms on equal footage, including the computational

Next lectures

- Next Monday 16^{th}, more on Generative models
  - Conditional GANs (cGANs)!
- Keep working on the projects!

Thanks ☺