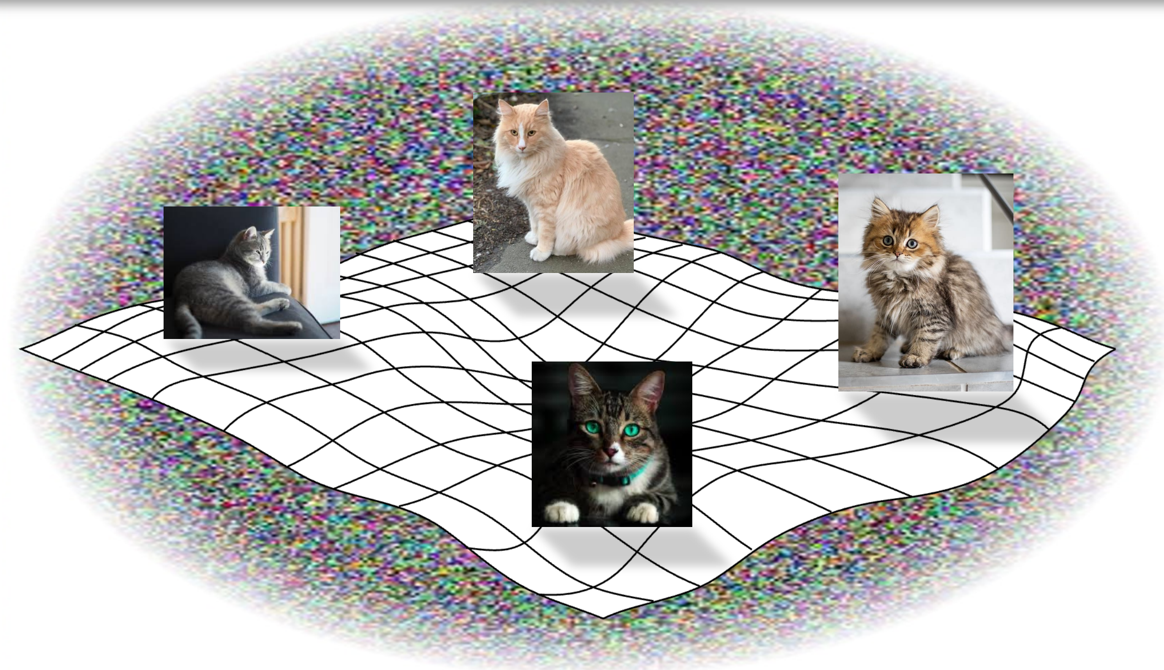
CS5670: Computer Vision

Image Manifolds & Image Generation



Some slides adapted from content by Abe Davis, Jin Sun, and Phillip Isola

Announcements

- Project 5 (Neural Radiance Fields) due tomorrow by 8:00 pm
- In class final next Tuesday, May 7
  - 2 sheets of notes (front and back) allowed
- Course evaluations are open
  - We would love your feedback!
  - Small amount of extra credit for filling out
    - What you write is still anonymous; instructors only see if students filled it out
  - https://apps.engineering.cornell.edu/CourseEval/

Readings

- Szeliski 2nd Edition Chapter 5.5.4
- 5-Minute Graphics from Steve Seitz:
  - Large Language Models from scratch
  - Large Language Models: Part 2
  - Text to Image in 5 minutes: Parti, Dall-E 2, Imagen
  - Text to Image: Part 2 -- how image diffusion works in 5 minutes

Agenda

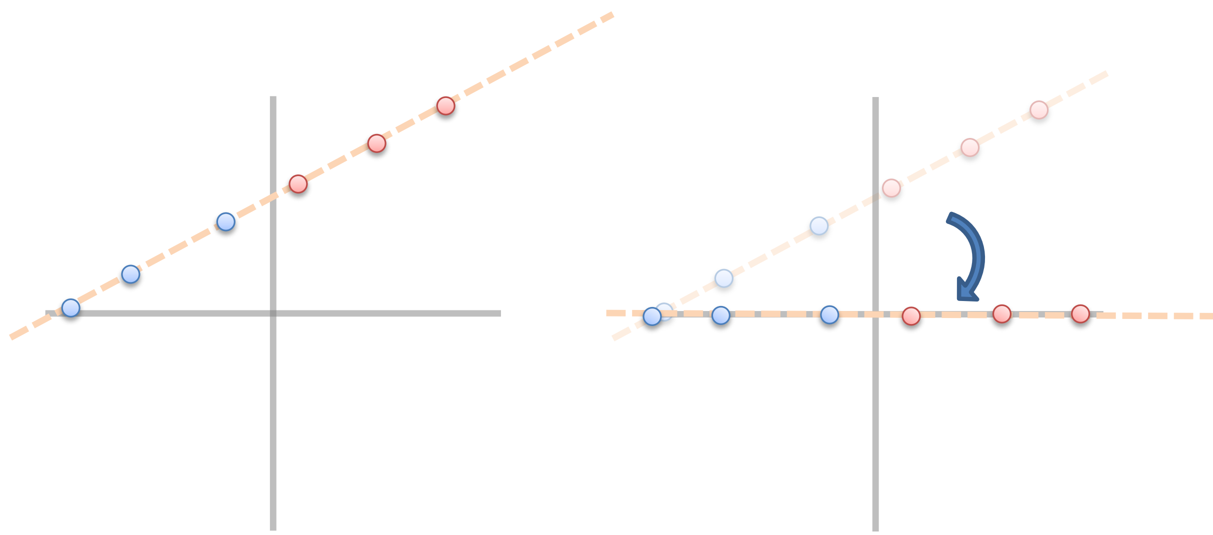
- The manifold of natural images
- Image-to-image methods and GANs
- Image synthesis methods
- Next time: diffusion models

By Abe Davis

DIMENSIONALITY REDUCTION

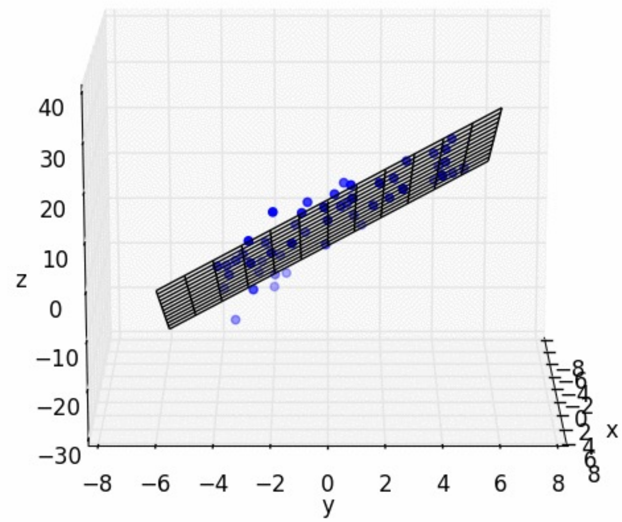
Linear Dimensionality Reduction: 2D->1D

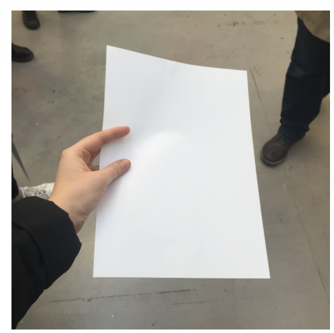
- Consider a bunch of data points in 2D
- Let’s say these points lie along a line
- If so, we can translate and rotate our data so that it is 1D



Linear Dimensionality Reduction: 3D->2D

- Similar to 1D case, we can fit a plane to the data, and transform our coordinate system so that plane becomes the x-y plane
- "Plane fitting"
- Now we only need to store two numbers for each point (and the plane parameters)
- More generally: look for the 2D subspace that best fits the data, and ignore the remaining dimensions

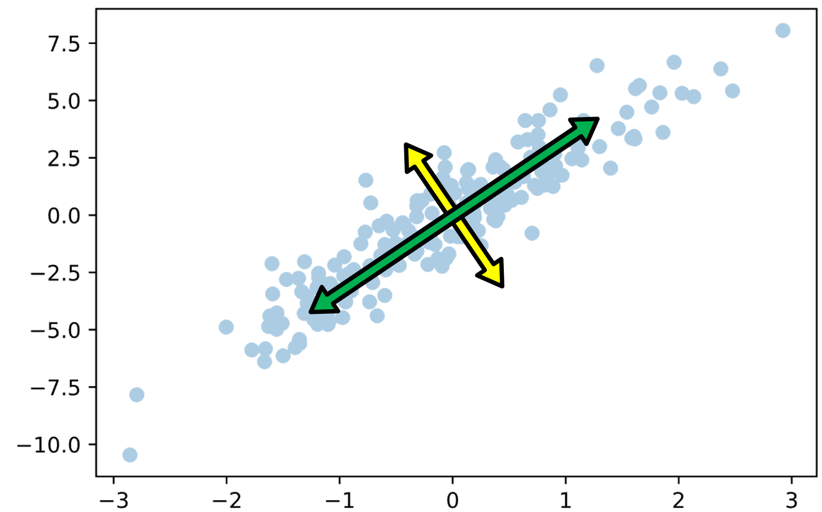




Think of this as data that sits on a flat sheet of paper, suspended in 3D space. We will come back to this analogy in a couple slides…

Generalizing Linear Dimensionality Reduction

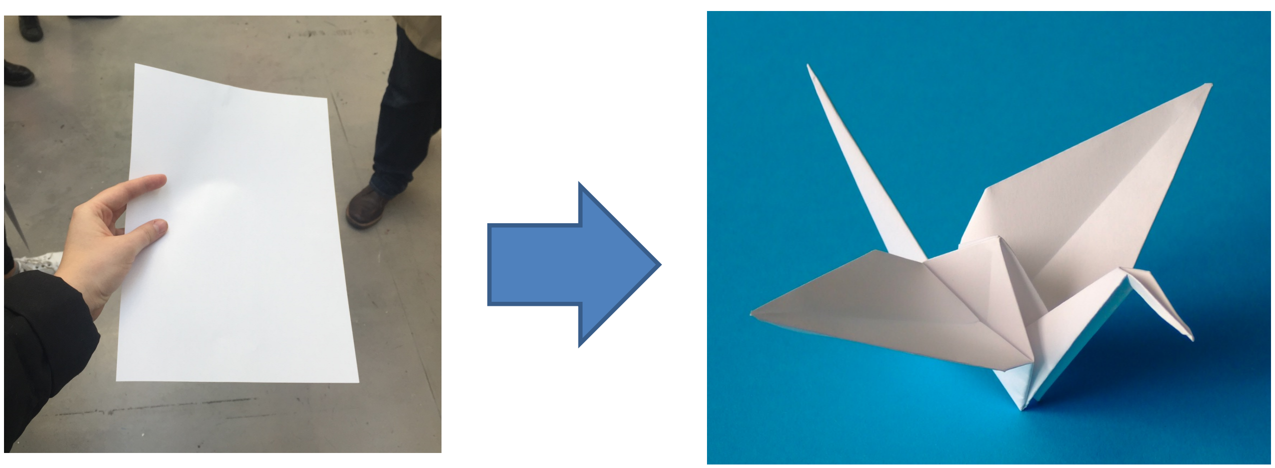
- ***Principal Components Analysis (PCA)***: find and order orthogonal axes by how much the data varies along each axis.
- The axes we find (ordered by variance of our data) are called ***principal components***.
- Dimensionality reduction can be done by using only the first *k* principal components



Side Note: principal components are closely related to the eigenvectors of the covariance matrix for our data

Manifolds

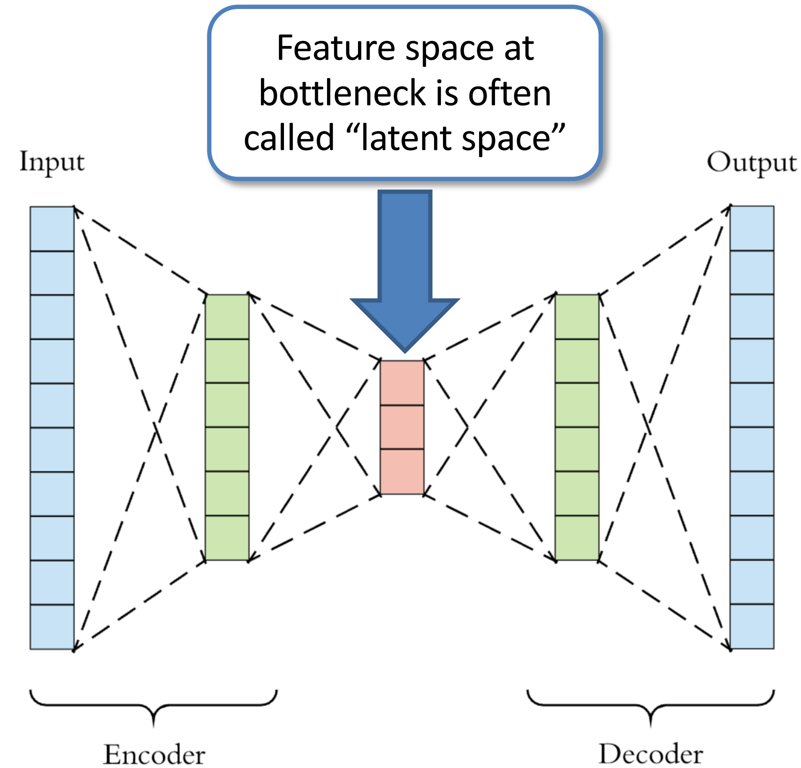
- Think of a piece of paper as a 2D subspace
- If we bend & fold it, it's still locally a 2D subspace…
- A "manifold" is the generalization of this concept to higher dimensions…



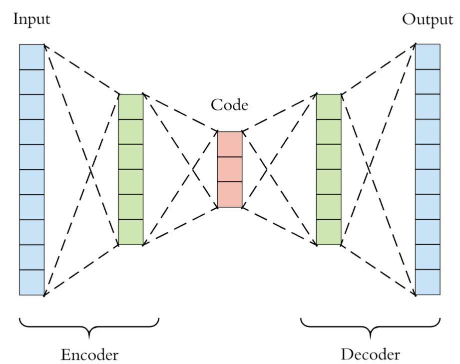
Autoencoders: Dimensionality Reduction for Manifolds

- Learn a non-linear (deep network) transformation into some lower-dimensional space (encoder)
- Learn a transformation from lower-dimensional space back to original content (decoder)
- Loss function measures difference between input & output

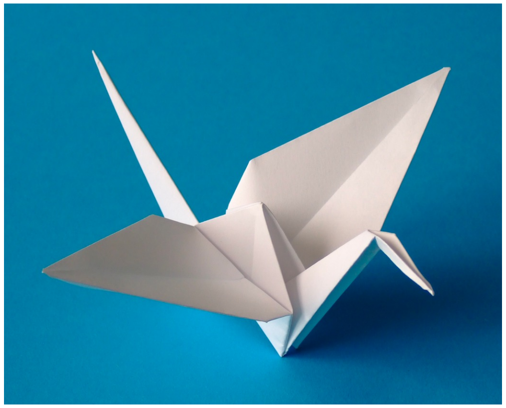
- **Unsupervised**
  – No labels required! Signal is just from learning to compress data



Autoencoders: Dimensionality Reduction for Manifolds



- Transformations that reduce dimensionality **cannot be invertible** in general



- An autoencoder tries to learn a transformation that is **invertible for points on some manifold**

By Abe Davis

IMAGE MANIFOLDS

The Space of All Images

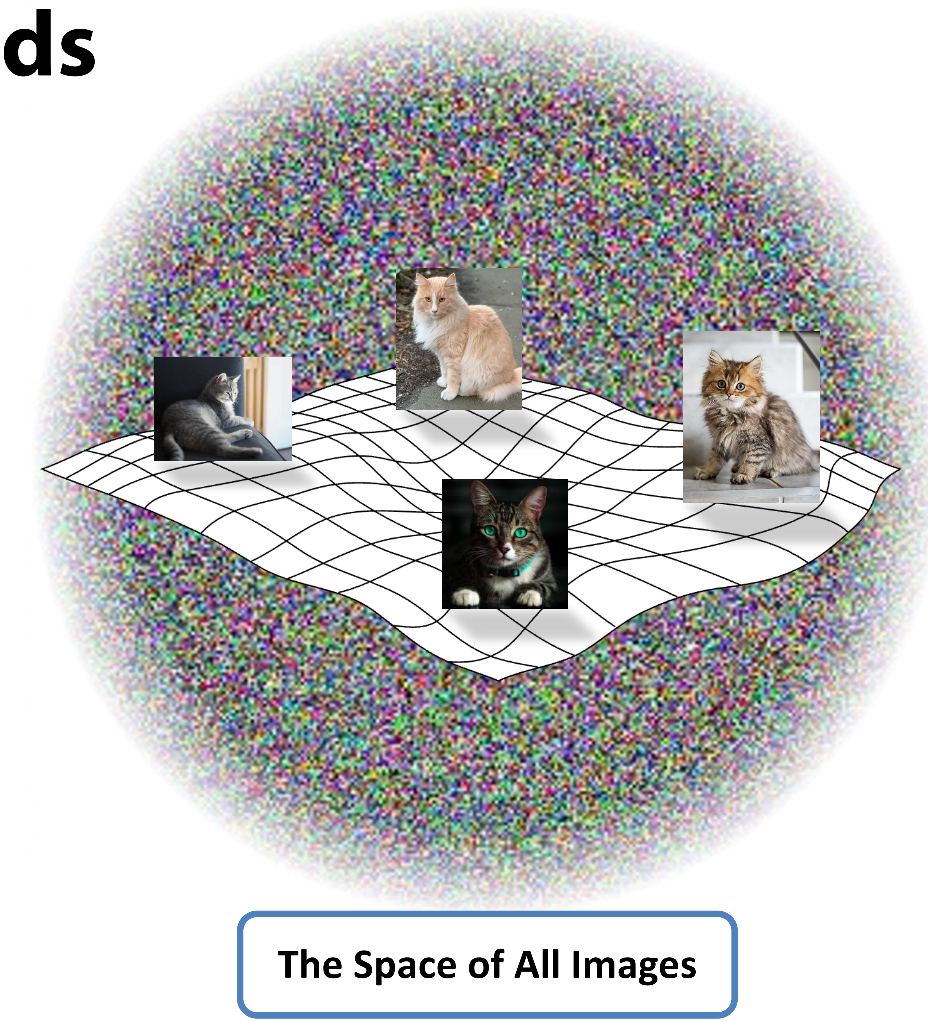
- Lets consider the space of all 100x100 images
- Now lets randomly sample that space…
- Conclusion: Most images are noise

Question:
What do we expect a random uniform sample of all images to look like?

```
pixels = np.random.rand(100,100,3)
```

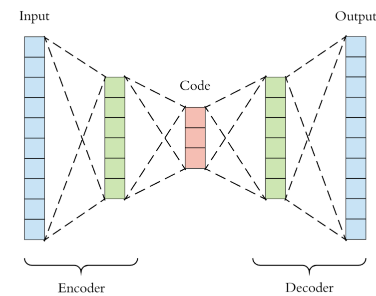
Natural Image Manifolds

- Most images are “noise”
- “Meaningful” images tend to form some manifold within the space of all images
- Images of a particular class fall on manifolds within that manifold…



Denoising & the “Nullspace” of Autoencoders

- The autoencoder tries to learn a dimensionality reduction that is invertible for our data (data on some manifold)
- Most noise will be in the non-invertible part of image space (off the manifold)
- If we feed noisy data in, we will often get denoised data out

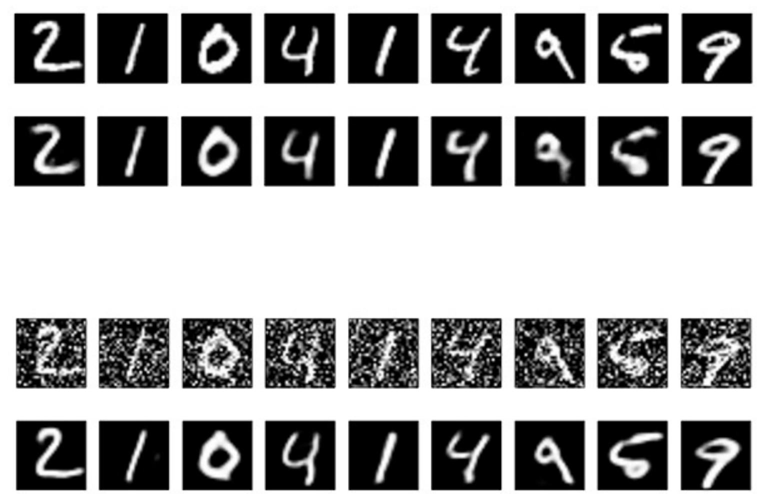


Input

Output

Noisy Input

Output



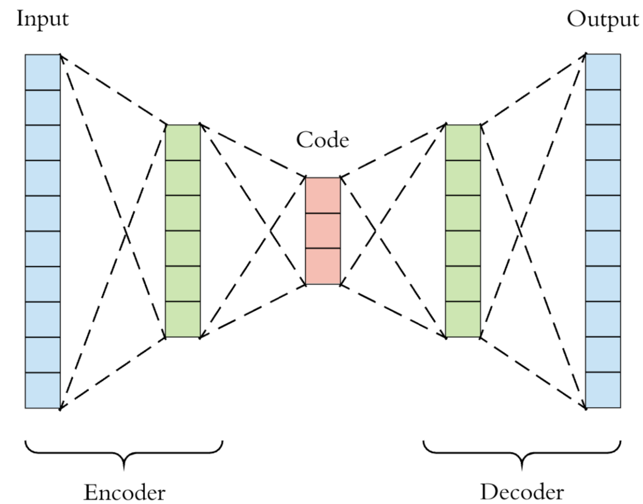
Examples from: https://blog.keras.io/building-autoencoders-in-keras.html

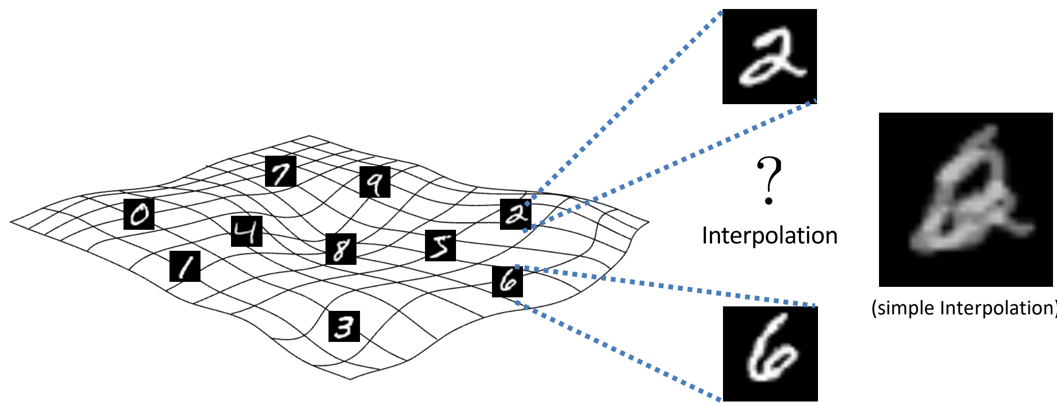
Problem

- Autoencoders can compress because data sits on a manifold

- This doesn't mean that every point in the latent space will be on the manifold…

- GANs (later this lecture) will learn a loss function that helps with this…





Abe Davis, with slides from Jin Sun, Phillip Isola, and Richard Zhang

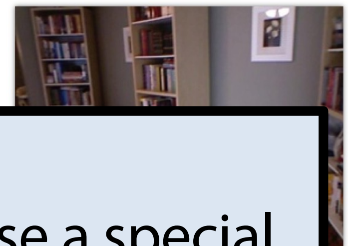
IMAGE-TO-IMAGE APPLICATIONS

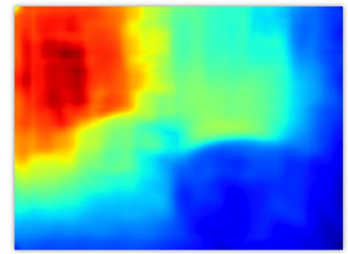
Image prediction (“structured prediction”)

Object labeling

[Long et al. 201

Depth prediction





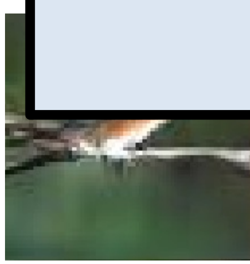
Depth Map

igen et al. 2014, …]

Recall: we often use a special CNN architecture like a U-Net for such image-to-image mappings

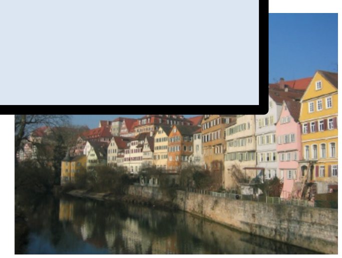
Text-to-ph

“this small bird has a pink breast and crown…”



[Reed et al. 2016, …]

yle transfer



[Gatys et al. 2016, …]

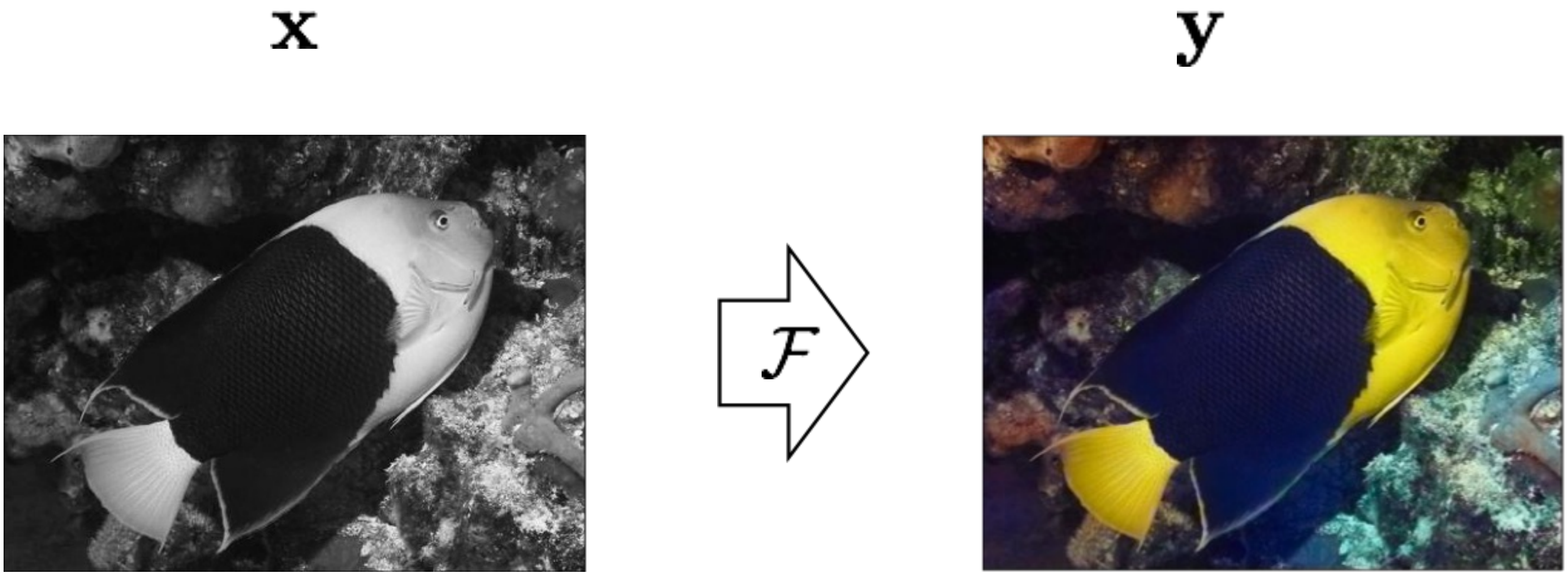
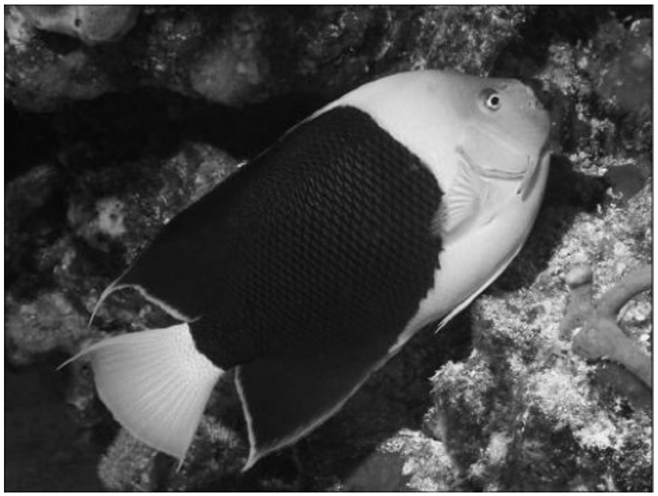
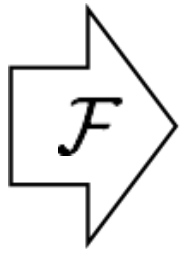


Image Colorization

from Jin Sun, Richard Zhang, Phillip Isola

$\mathbf{x}$



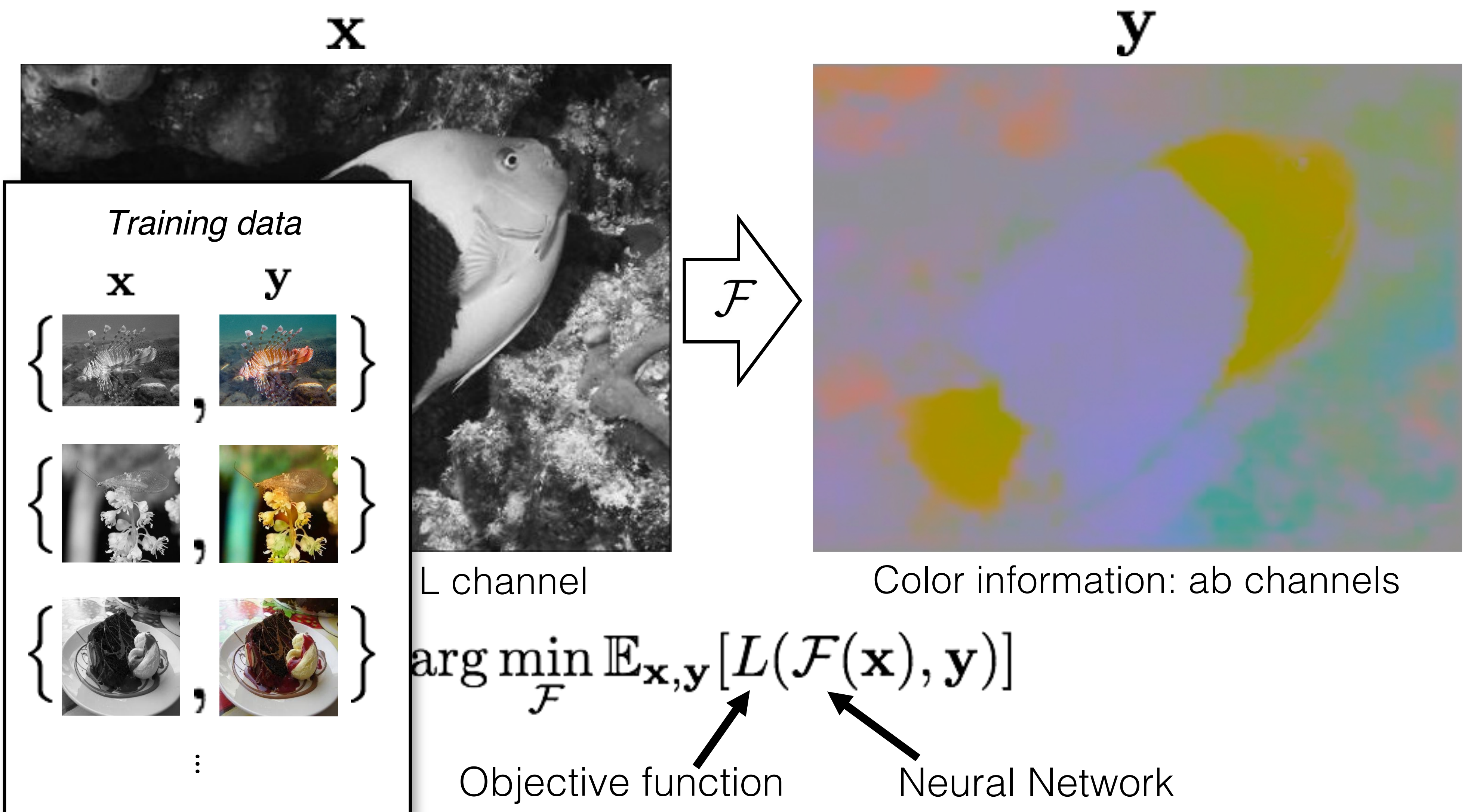


$\mathbf{y}$

$$\arg\min_{\mathcal{F}} \mathbb{E}_{\mathbf{x},\mathbf{y}}[L(\mathcal{F}(\mathbf{x}), \mathbf{y})]$$

"**What** should I do"   "**How** should I do it?"

from Jin Sun, Richard Zhang, Phillip Isola

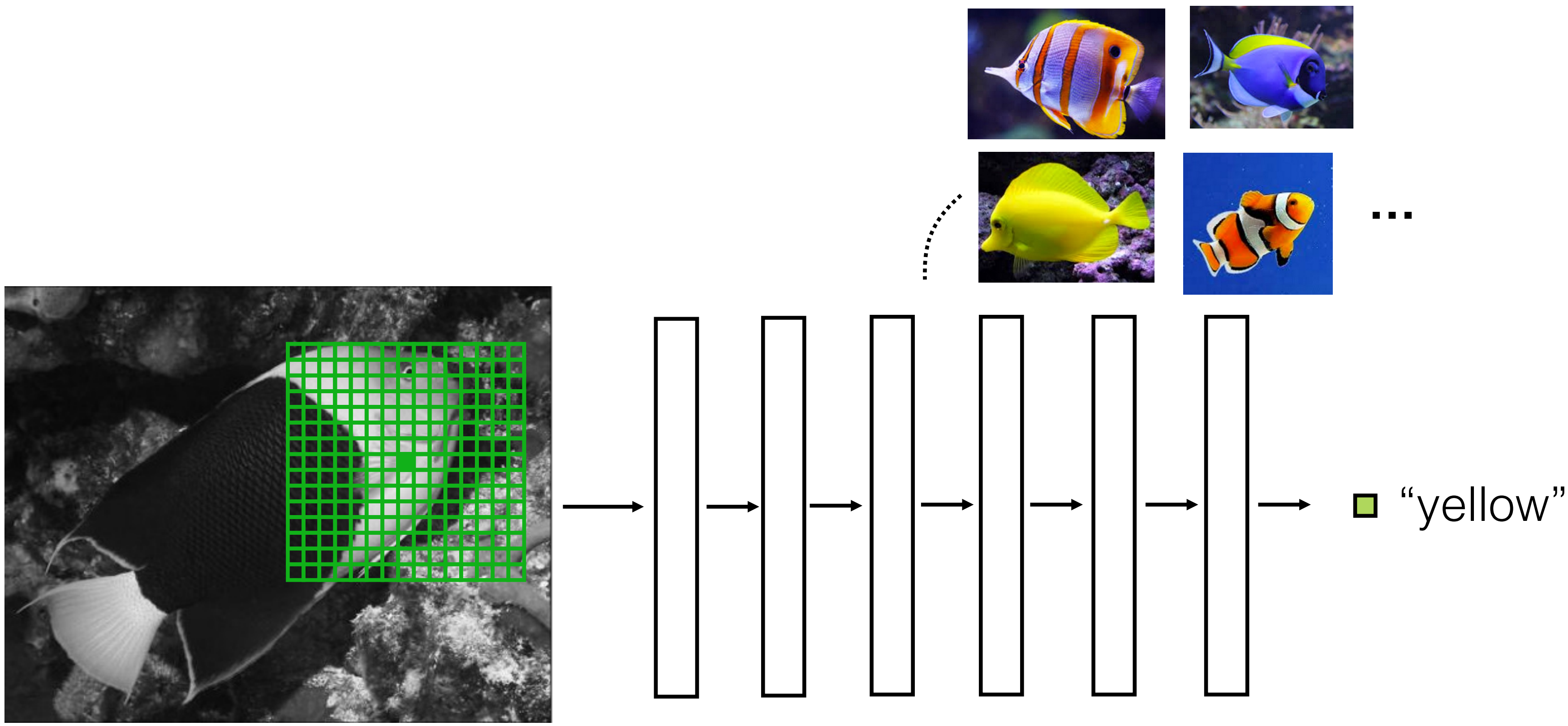


$$\arg\min_{\mathcal{F}} \mathbb{E}_{\mathbf{x},\mathbf{y}}[L(\mathcal{F}(\mathbf{x}), \mathbf{y})]$$

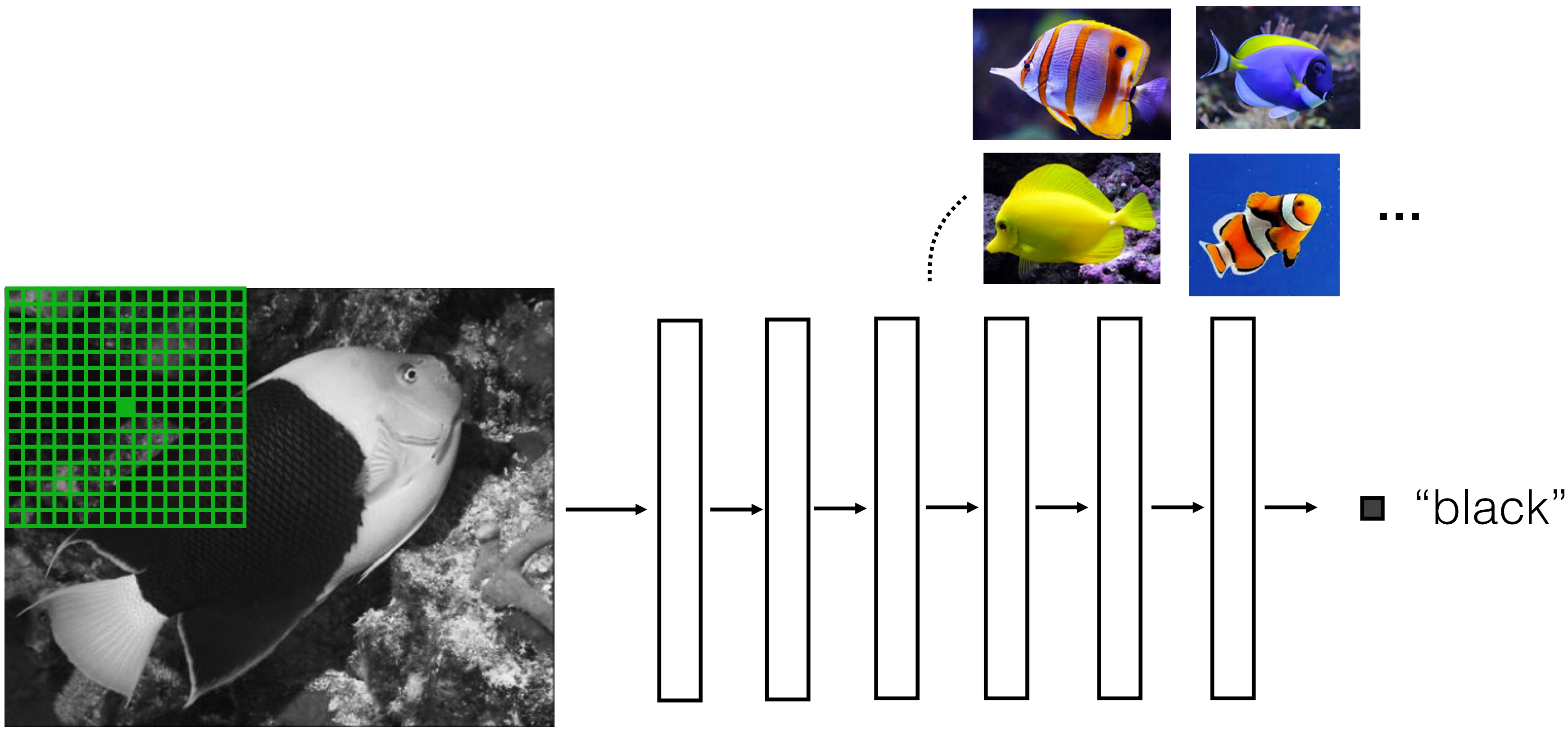
Objective function (loss)

Neural Network

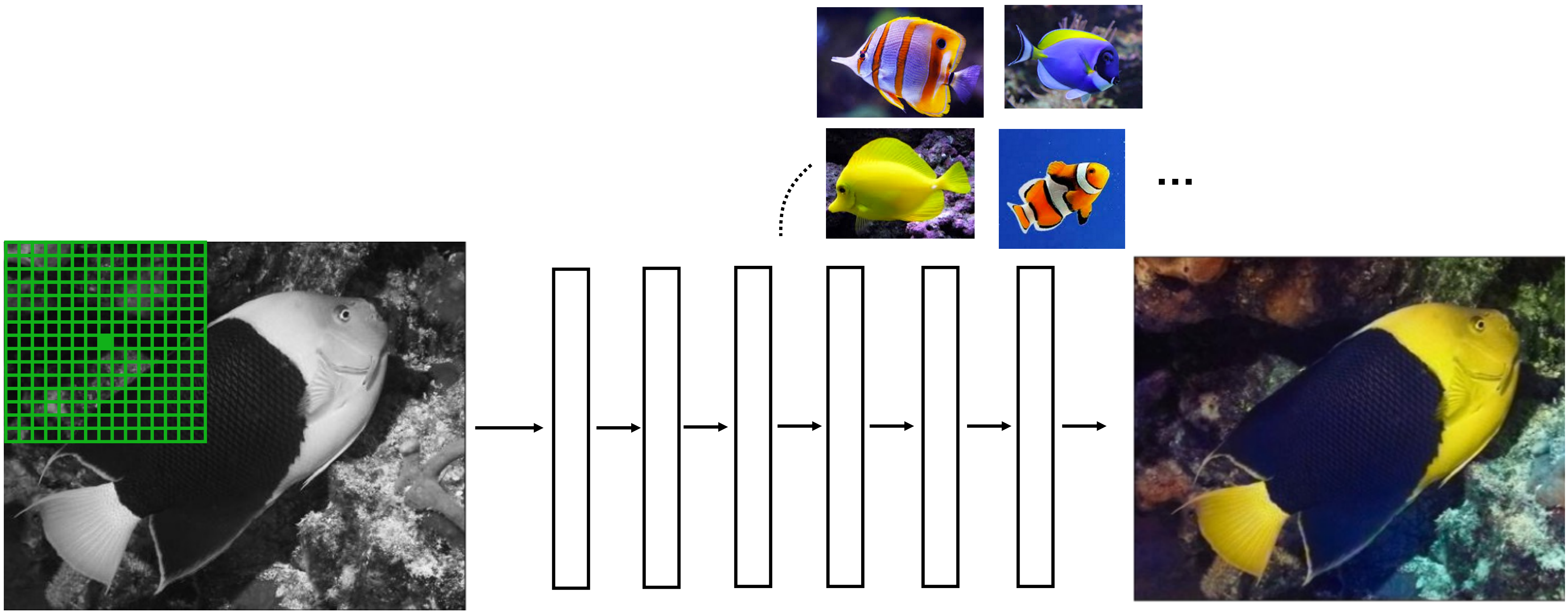
from Jin Sun, Richard Zhang, Phillip Isola



from Jin Sun, Richard Zhang, Phillip Isola



from Jin Sun, Richard Zhang, Phillip Isola



from Jin Sun, Richard Zhang, Phillip Isola

Recap: basic loss functions

Prediction: $\hat{\mathbf{y}} = \mathcal{F}(\mathbf{x})$

Truth: $\mathbf{y}$

Classification (cross-entropy):

$$L(\hat{\mathbf{y}}, \mathbf{y}) = -\sum_i \hat{\mathbf{y}}_i \log \mathbf{y}_i$$

How many extra bits it takes to correct the predictions

from Jin Sun, Richard Zhang, Phillip Isola

Recap: basic loss functions

Prediction: $\hat{\mathbf{y}} = \mathcal{F}(\mathbf{x})$

Truth: $\mathbf{y}$

Classification (cross-entropy):

$$L(\hat{\mathbf{y}}, \mathbf{y}) = -\sum_i \hat{\mathbf{y}}_i \log \mathbf{y}_i$$

← How many extra bits it takes to correct the predictions

Least-squares regression:

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

← How far off we are in Euclidean distance

from Jin Sun, Richard Zhang, Phillip Isola

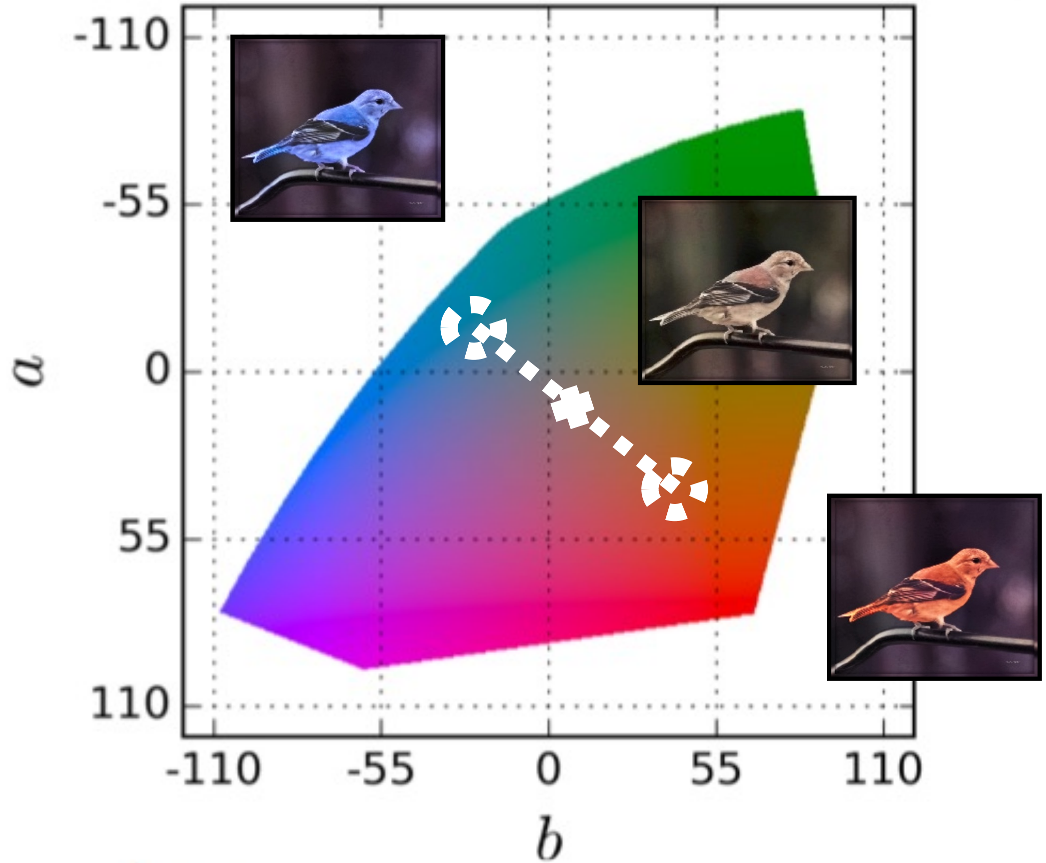
Designing loss functions

Input

Output (with L2 loss)

Ground truth

$$\mathrm{L}_2(\widehat{\mathbf{Y}}, \mathbf{Y}) = \frac{1}{2} \sum_{h,w} \|\mathbf{Y}_{h,w} - \widehat{\mathbf{Y}}_{h,w}\|_2^2$$ (L2 loss)



With L2 loss, predictions “regress to the mean”, and lack vivid colors

$$\mathrm{L}_2(\widehat{\mathbf{Y}}, \mathbf{Y}) = \frac{1}{2}\sum_{h,w}\|\mathbf{Y}_{h,w} - \widehat{\mathbf{Y}}_{h,w}\|_2^2$$

Designing loss functions

Input

Zhang et al. 2016

Ground truth

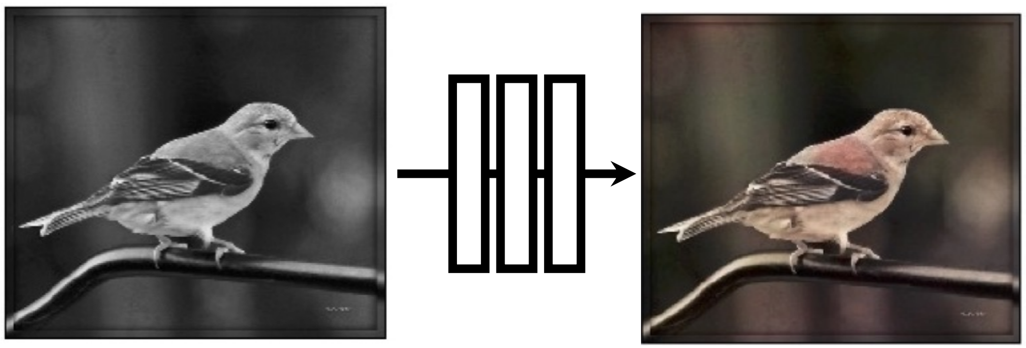
Color distribution cross-entropy loss with colorfulness enhancing term.

[Zhang, Isola, Efros, ECCV 2016]


DADS

Designing loss functions

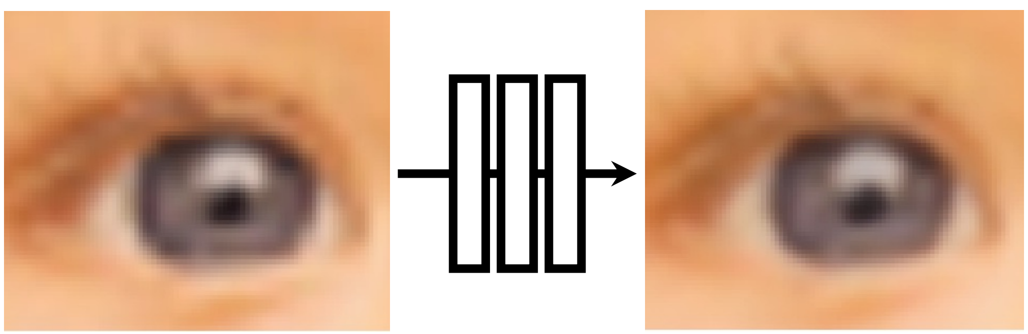
Image colorization



[Zhang, Isola, Efros, ECCV 2016]

L2 regression

Super-resolution

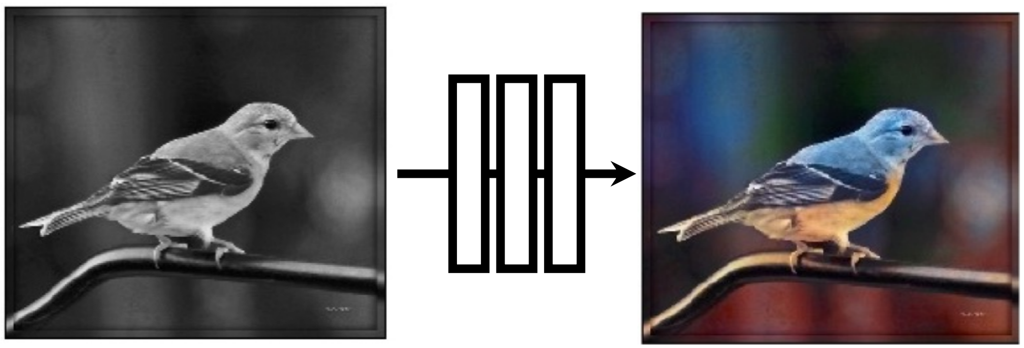


[Johnson, Alahi, Li, ECCV 2016]

L2 regression

Designing loss functions

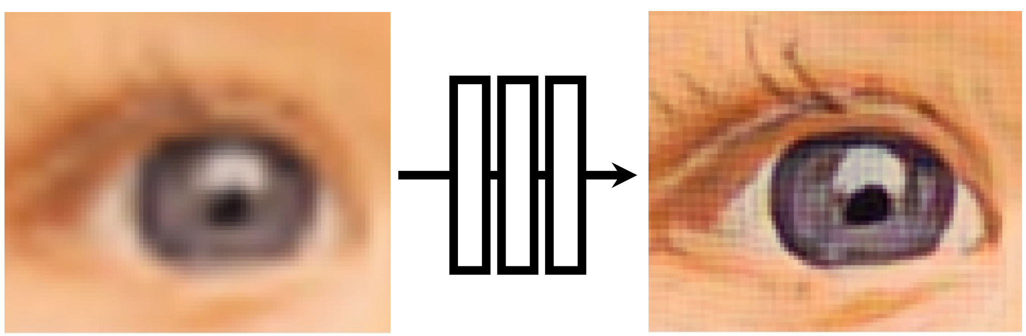
Image colorization



[Zhang, Isola, Efros, ECCV 2016]

Cross entropy objective, with colorfulness term

Super-resolution



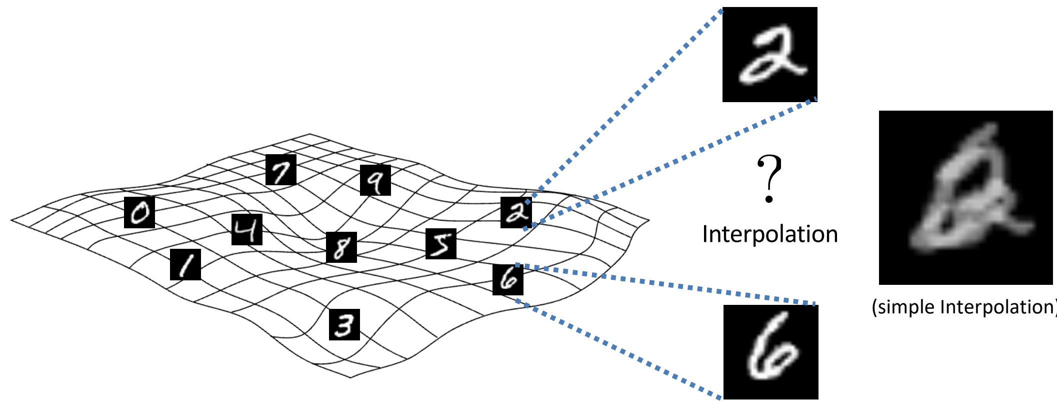
[Johnson, Alahi, Li, ECCV 2016]

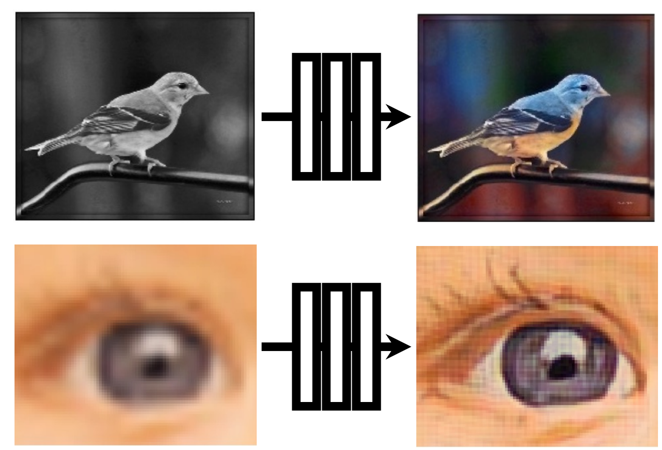
Deep feature covariance matching objective

Better Loss Function: Sticking to the Manifold

- How do we design a loss function that penalizes images that aren't on the image manifold?

- Key insight: we will *learn* our loss function by training a network to discriminate between images that are on the manifold and images that aren't



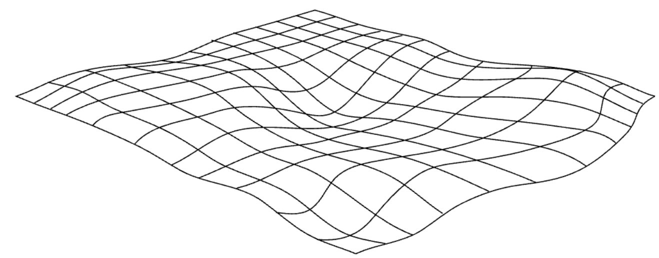


Abe Davis, with slides from Jin Sun and Phillip Isola

PART 3: GENERATIVE ADVERSARIAL NETWORKS (GANS)

Generative Adversarial Networks (GANs)

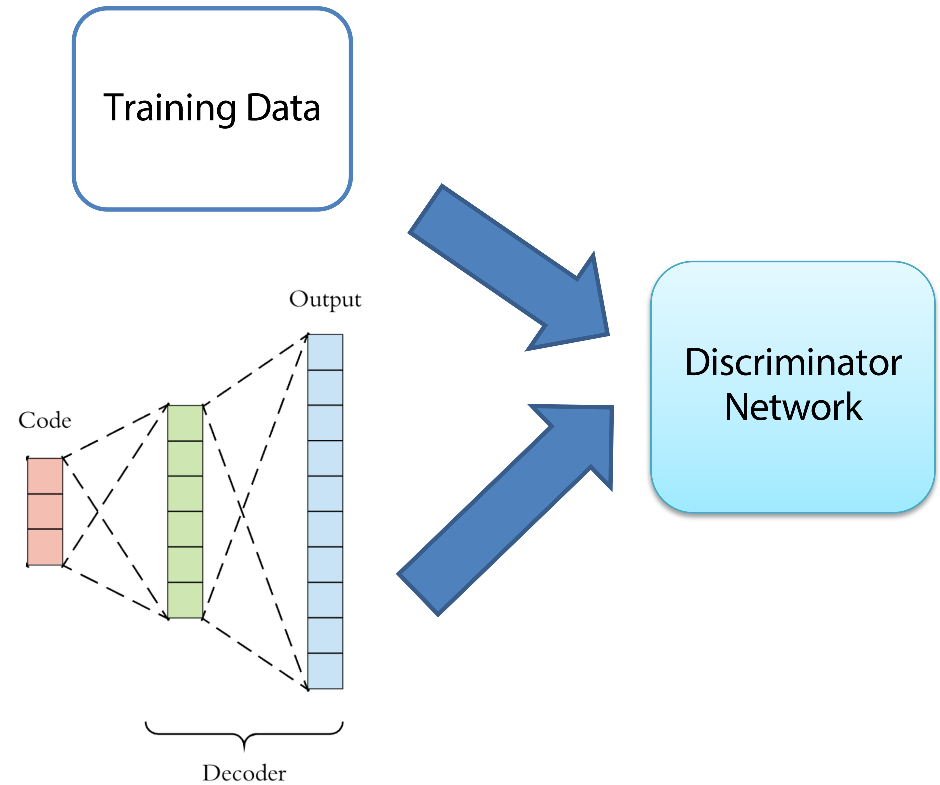
- Basic idea: Learn a mapping from some latent space to images on a particular manifold



- Example of a ***Generative Model:***
  - We can think of classification as a way to compute some P(x) that tells us the probability that image x is a member of a class.
  - Rather than simply evaluating this distribution, a generative model tries to learn a way to sample from it

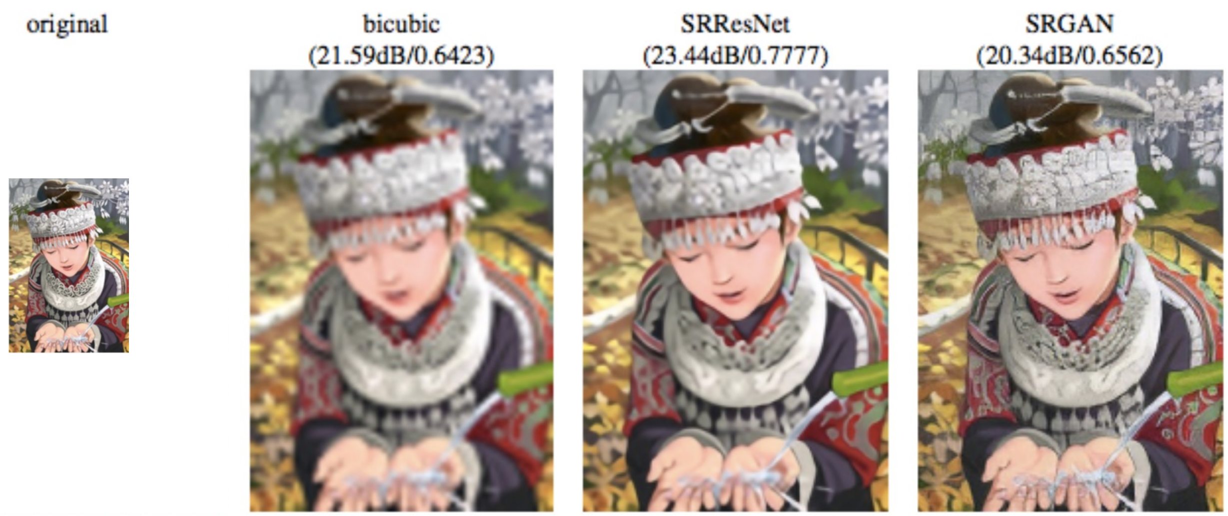
Generative Adversarial Networks (GANs)

- Generator network has similar structure to the decoder of our autoencoder
  - Maps from some latent space to images
- We train it in an adversarial manner against a discriminator network
  - Generator takes image noise, and tries to create output indistinguishable from training data
  - Discriminator tries to distinguish between generator output and training data

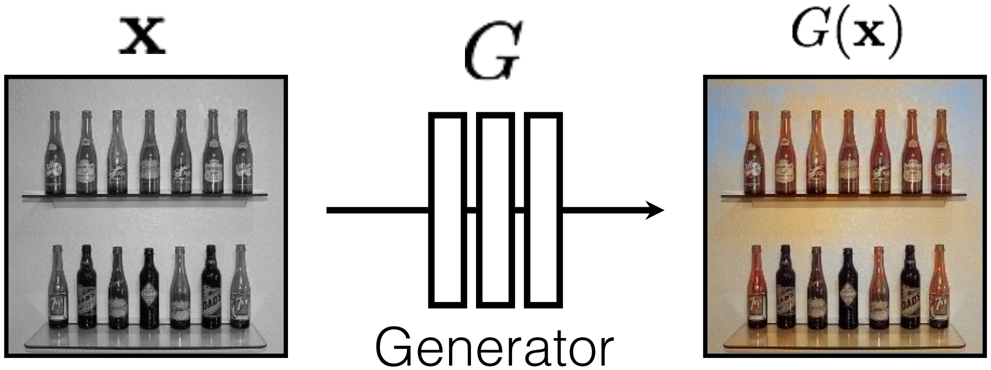


First: Conditional GANs

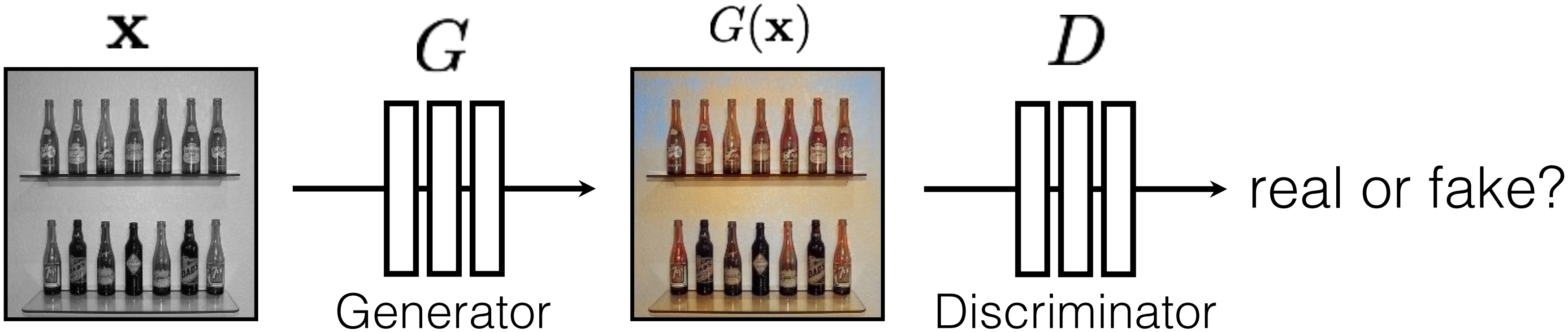
- Generate samples from a *conditional distribution* (conditioned on some other input)
- Example: generate high-resolution image conditioned on low resolution input



[Ledig et al 2016]



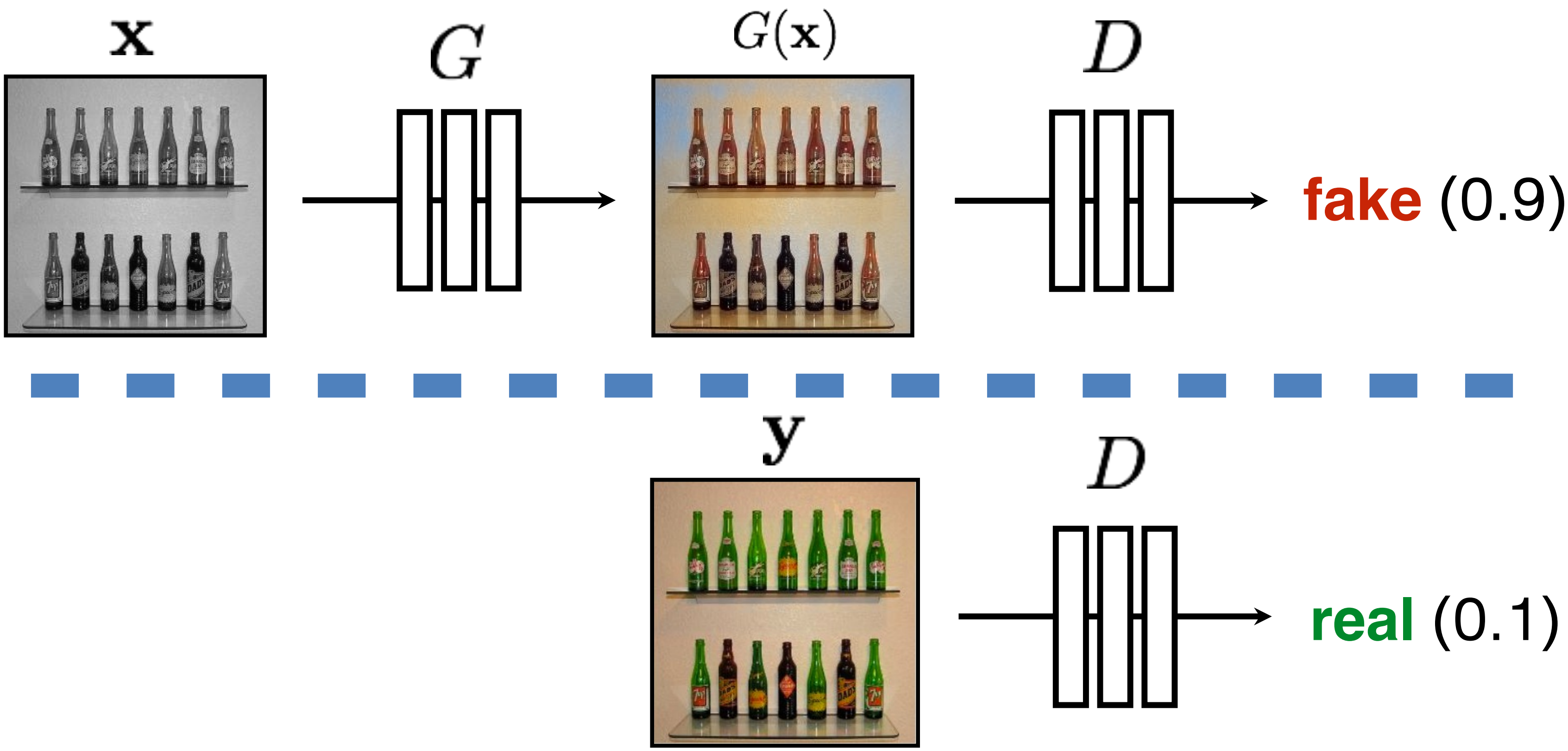
[Goodfellow et al., 2014]



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

D tries to identify the fakes

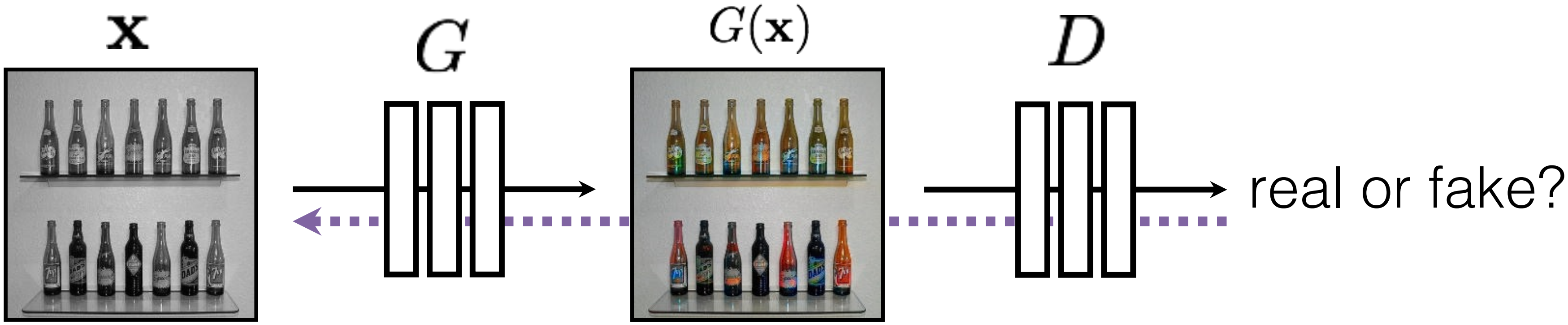
[Goodfellow et al., 2014]



(Identify generated images as fake) (Identify training images as real)

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

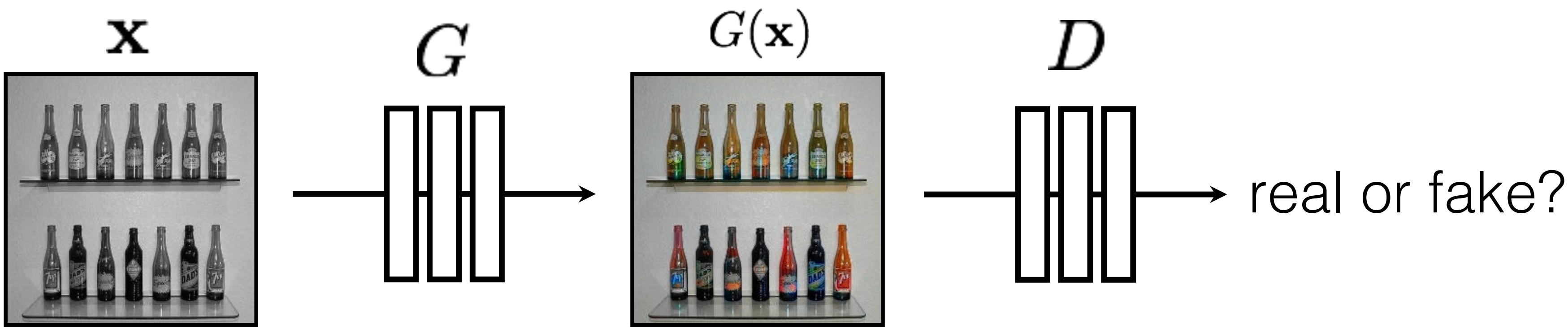
[Goodfellow et al., 2014]



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

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

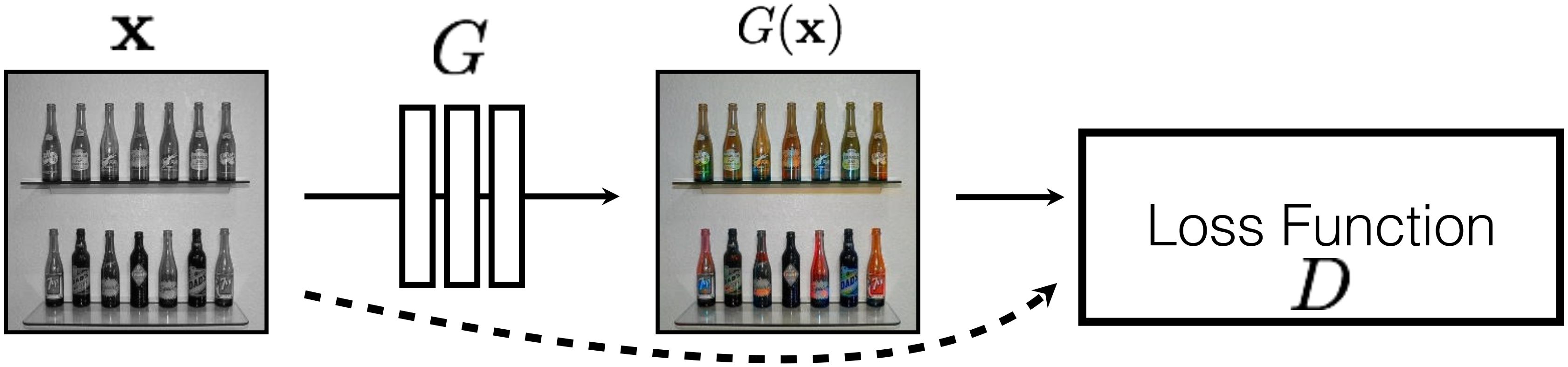
[Goodfellow et al., 2014]



G tries to synthesize fake images that ***fool*** the ***best*** **D**:

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

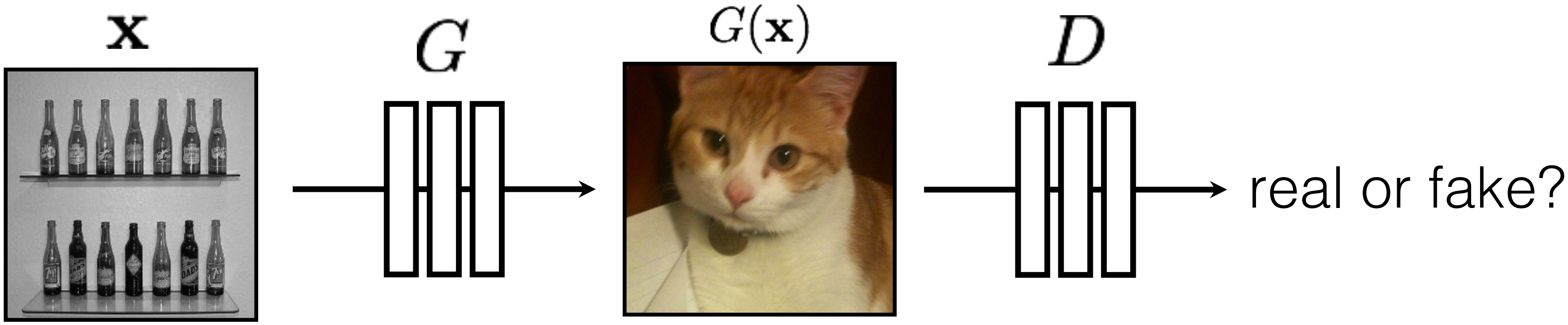
[Goodfellow et al., 2014]



G’s perspective: **D** is a loss function.

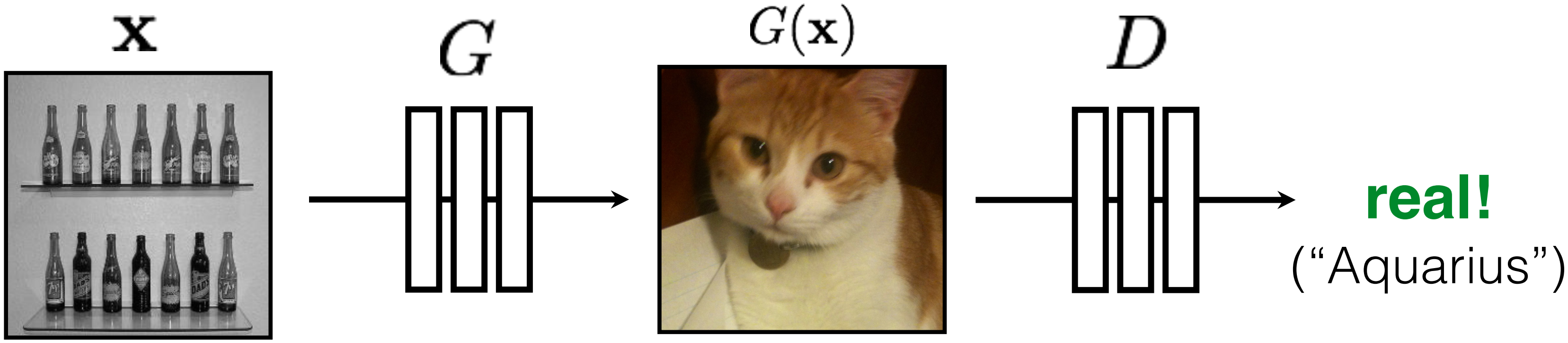
Rather than being hand-designed, it is *learned*.

[Goodfellow et al., 2014]
[Isola et al., 2017]



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

[Goodfellow et al., 2014]



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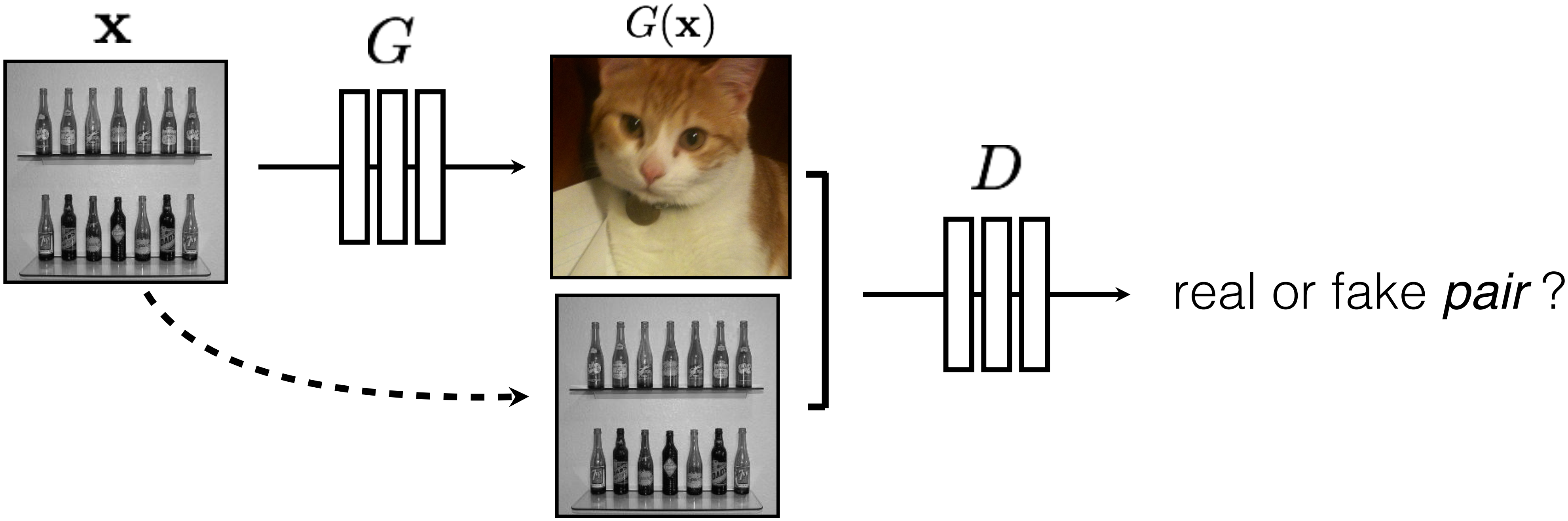
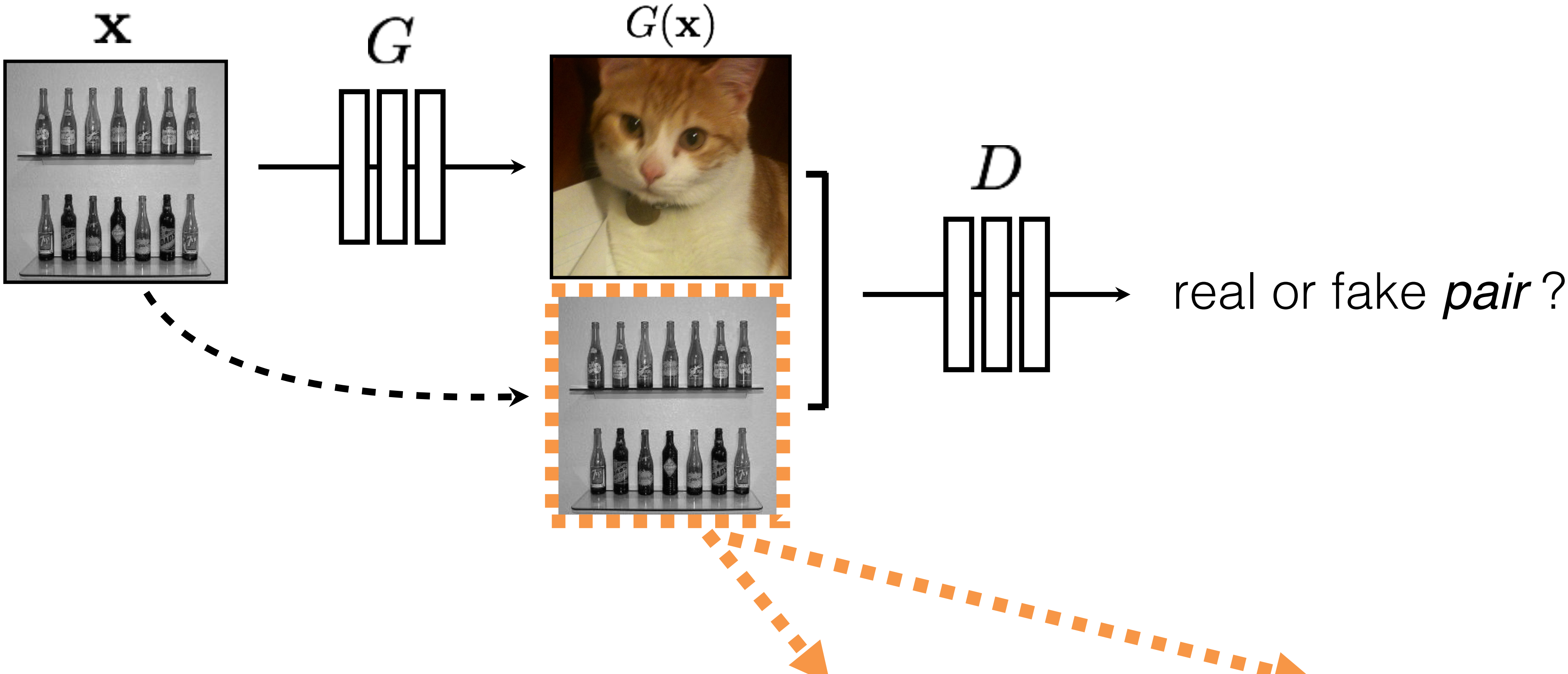


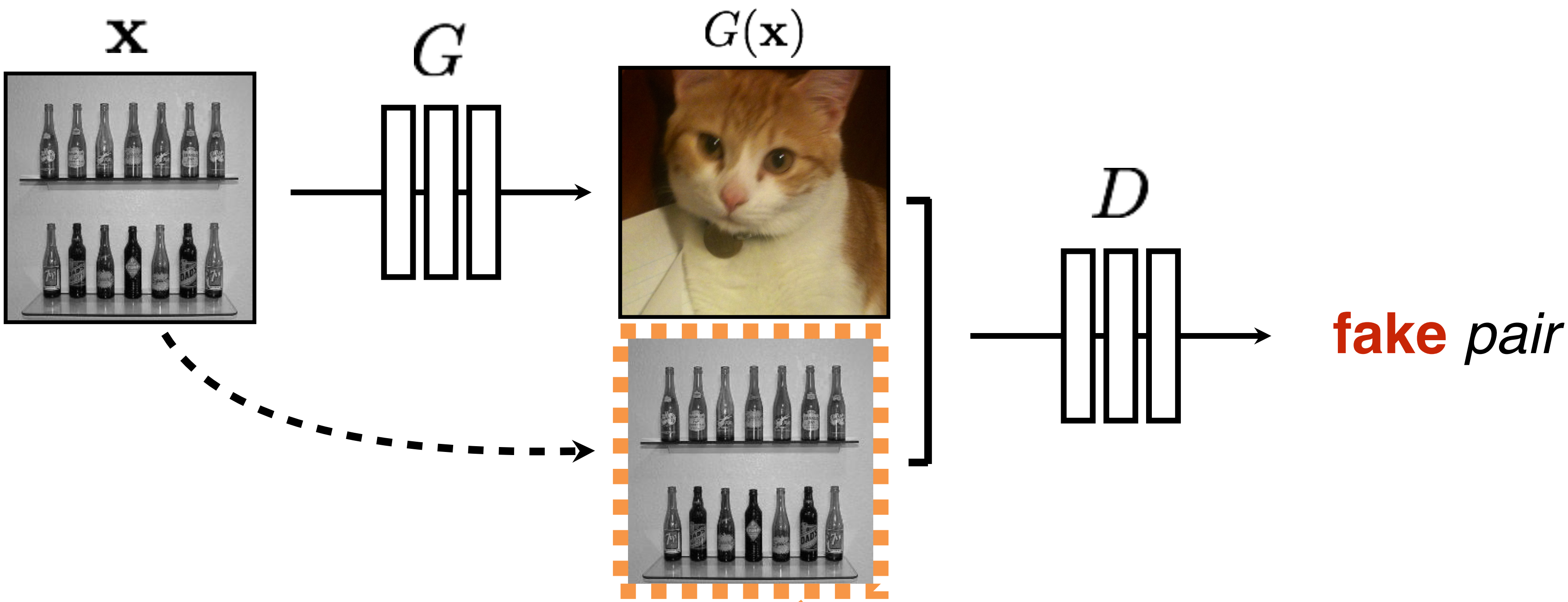
$$\arg\min_{G}\max_{D}\ \mathbb{E}_{\mathbf{x},\mathbf{y}}[\ \log D(G(\mathbf{x})) \quad + \quad \log(1 - D(\mathbf{y}))\ ]$$

[Goodfellow et al., 2014]
[Isola et al., 2017]



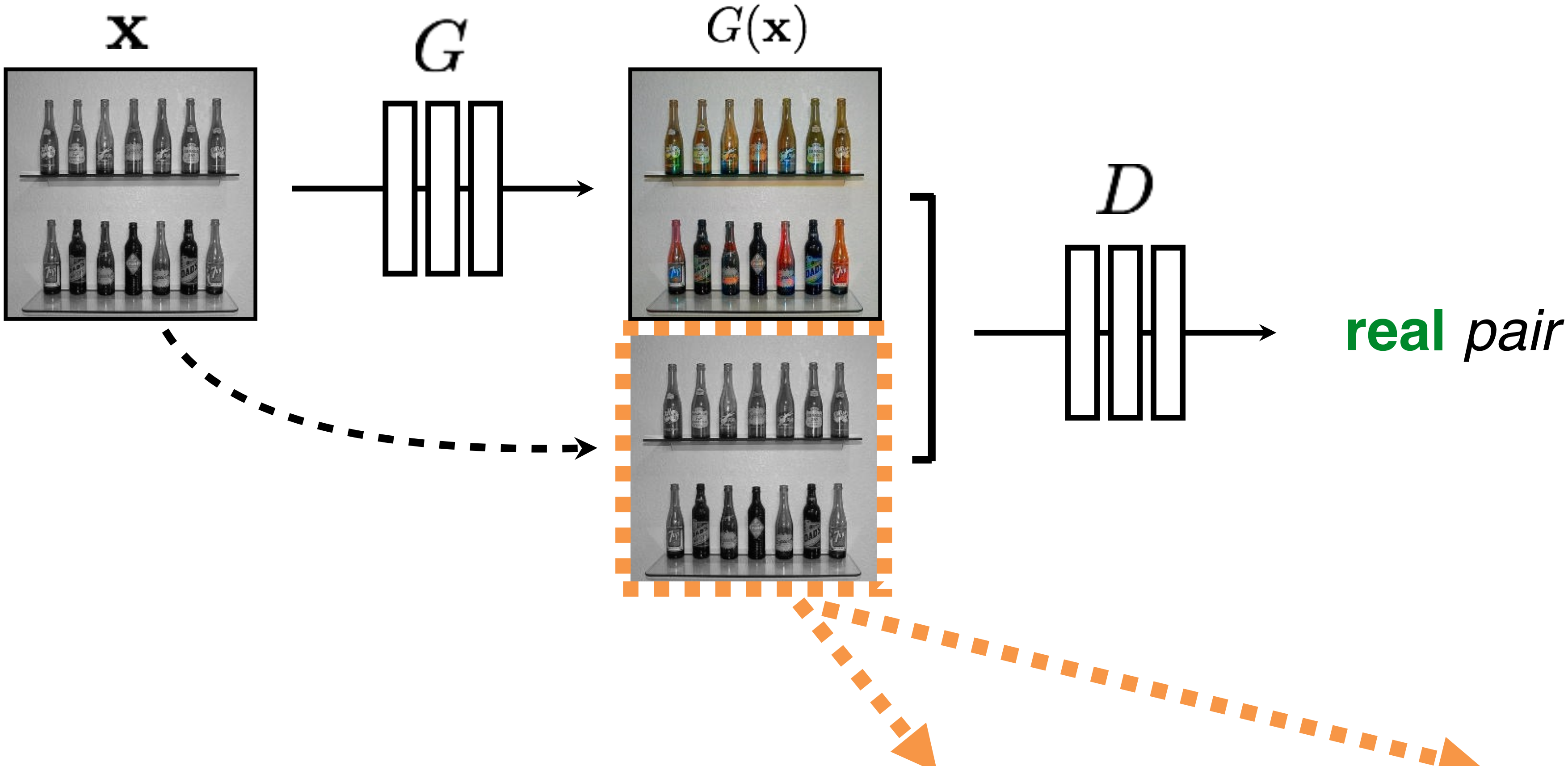
$$\arg\min_G \max_D \; \mathbb{E}_{\mathbf{x},\mathbf{y}}[\;\log D(\boxed{\mathbf{x}}, G(\mathbf{x})) + \log(1 - D(\boxed{\mathbf{x}}, \mathbf{y}))\;]$$

[Goodfellow et al., 2014]
[Isola et al., 2017]



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

[Goodfellow et al., 2014]
[Isola et al., 2017]



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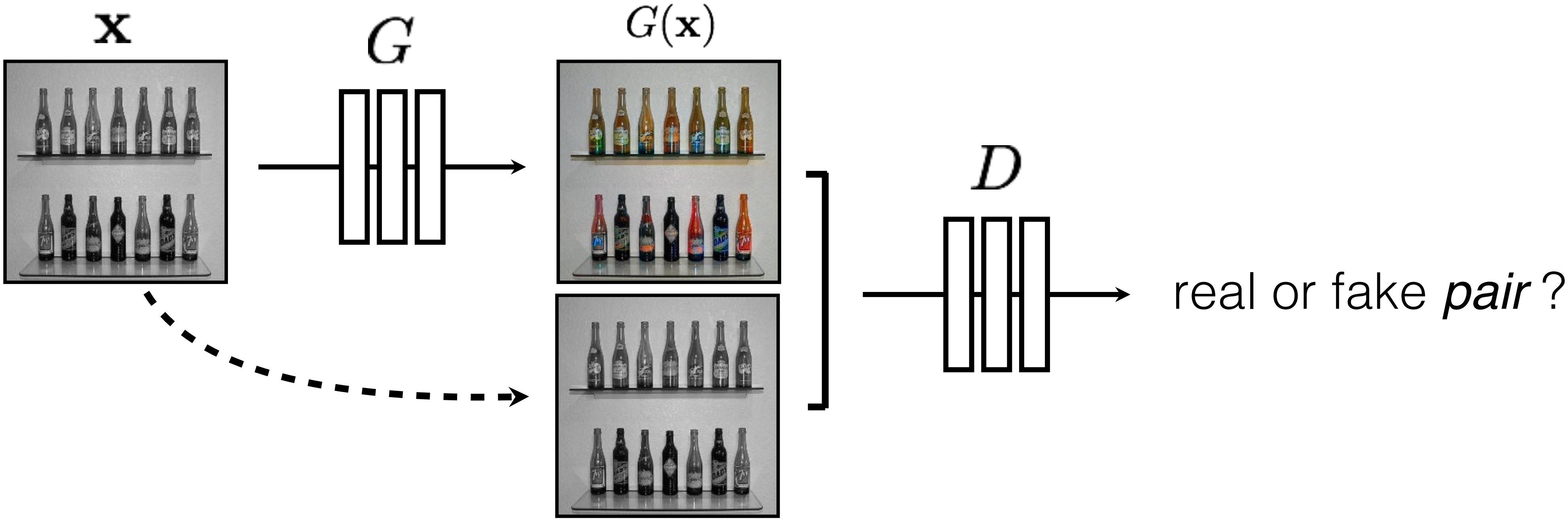
[Goodfellow et al., 2014]
[Isola et al., 2017]



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

[Goodfellow et al., 2014]
[Isola et al., 2017]

More Examples of Image-to-Image Translation with GANs

- We have pairs of corresponding training images
- Conditioned on one of the images, sample from the distribution of likely corresponding images

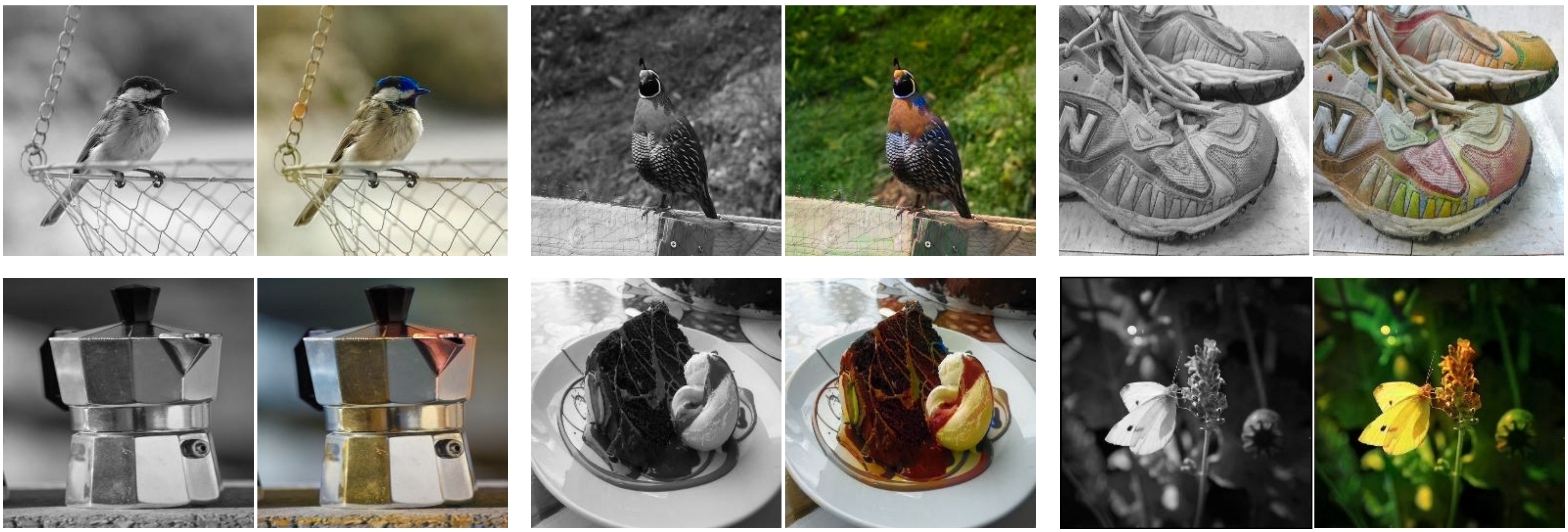
Segmentation to Street Image

Aerial Photo To Map

Edges to Image

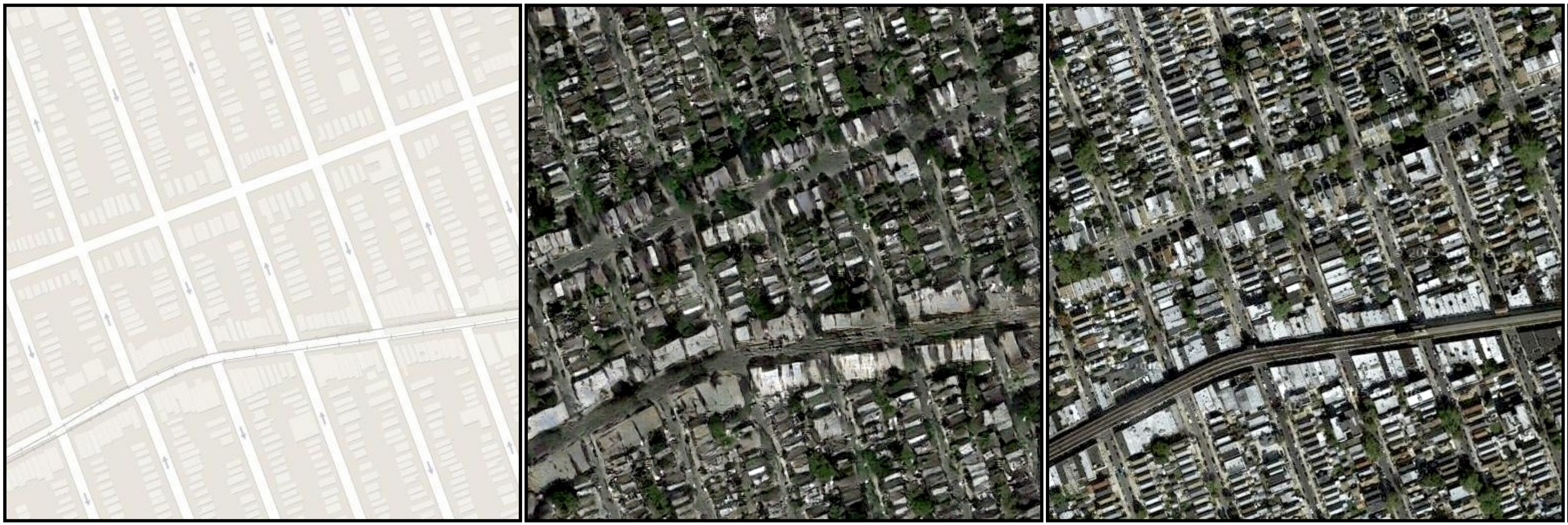
BW → Color

Input Output Input Output Input Output



Data from [Russakovsky et al. 2015]

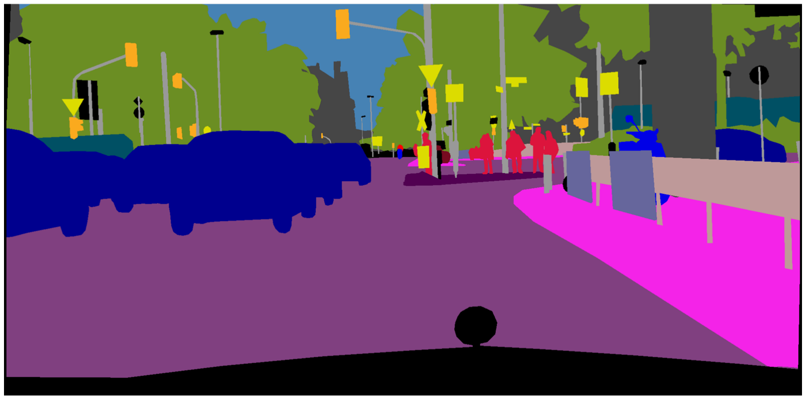
Input Output Groundtruth



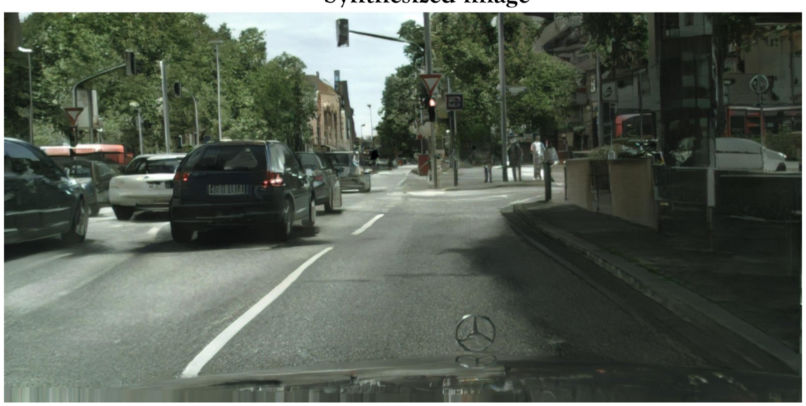
Data from
[maps.google.com]

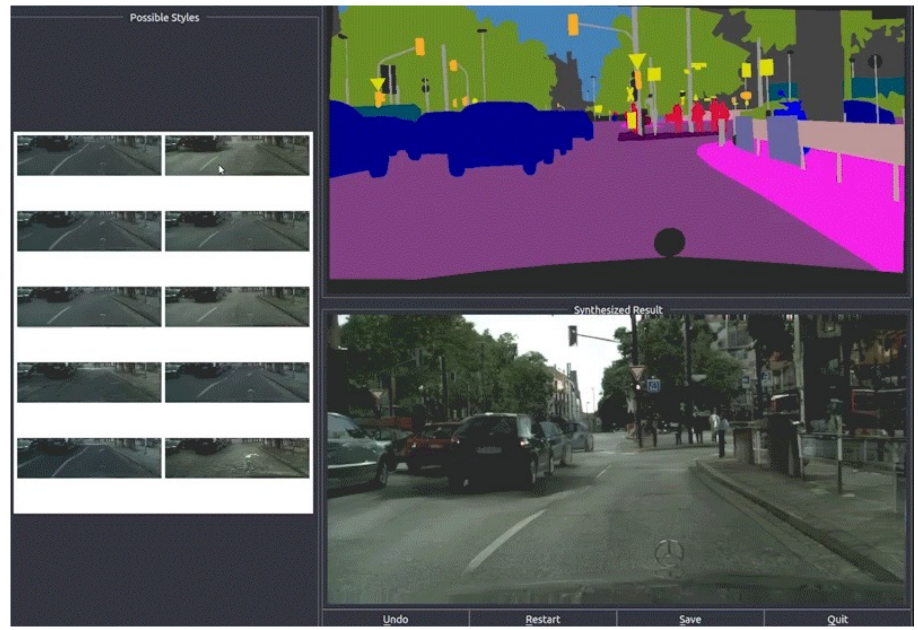
Labels → Street Views

Input labels



Synthesized image

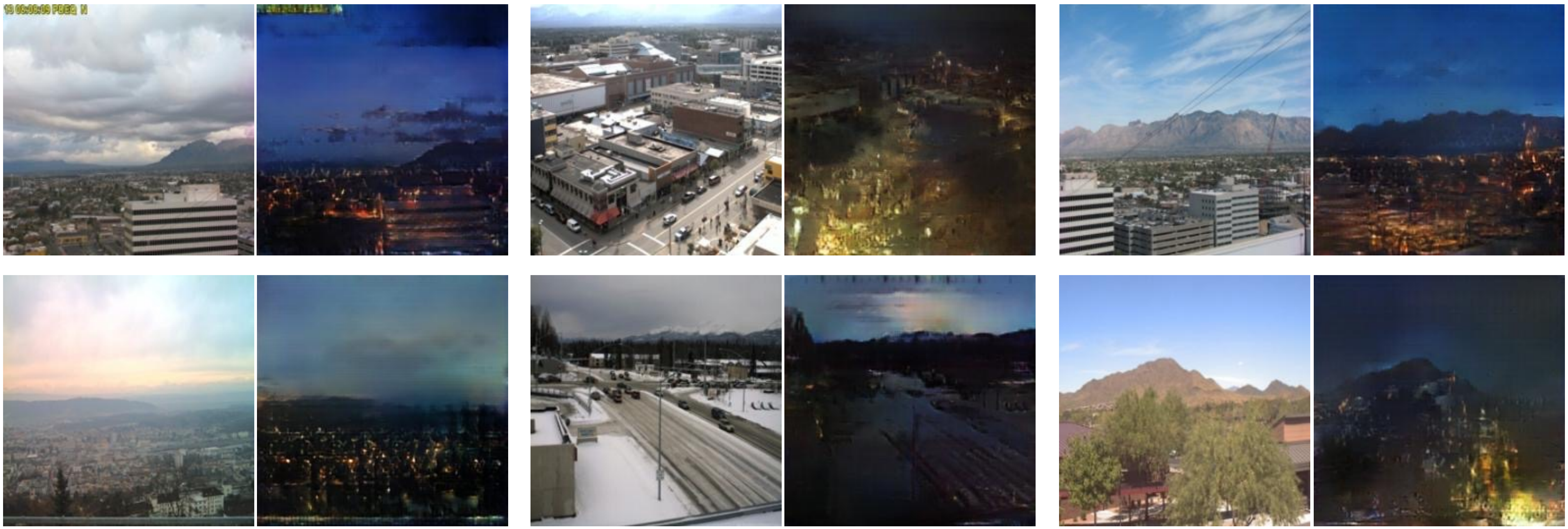




Data from [Wang et al, 2018]

Day → Night

Input Output Input Output Input Output

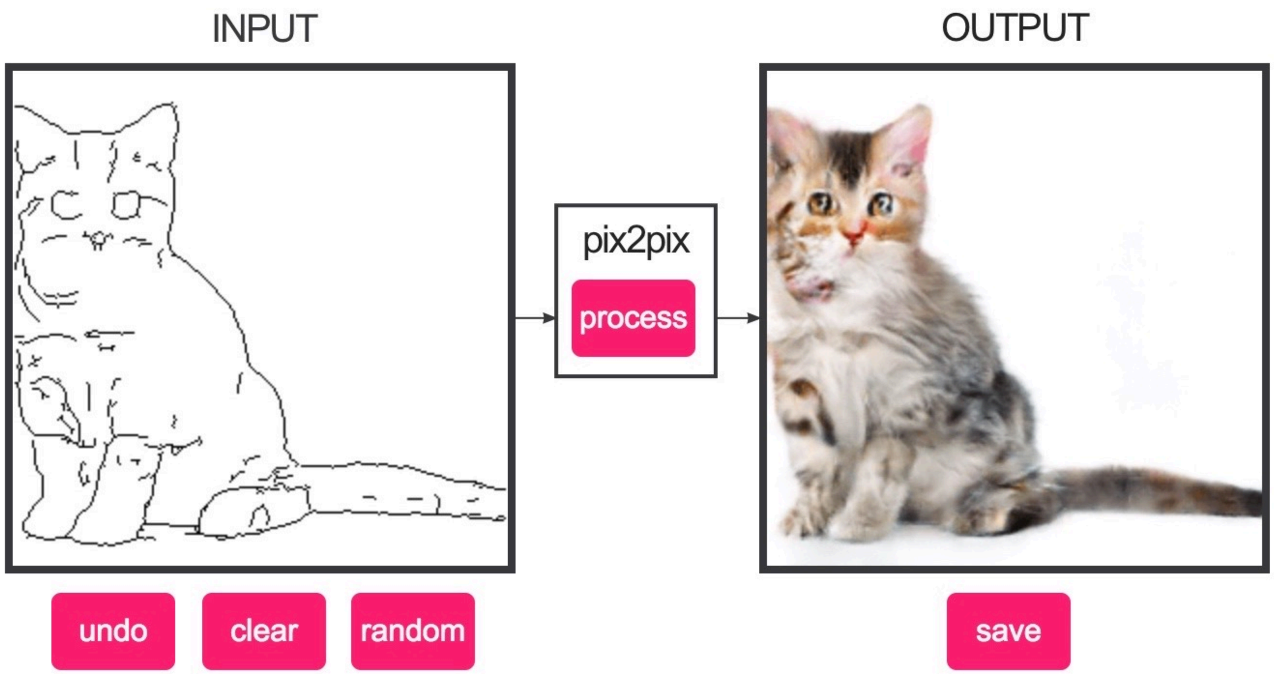


Data from [Laffont et al., 2014]

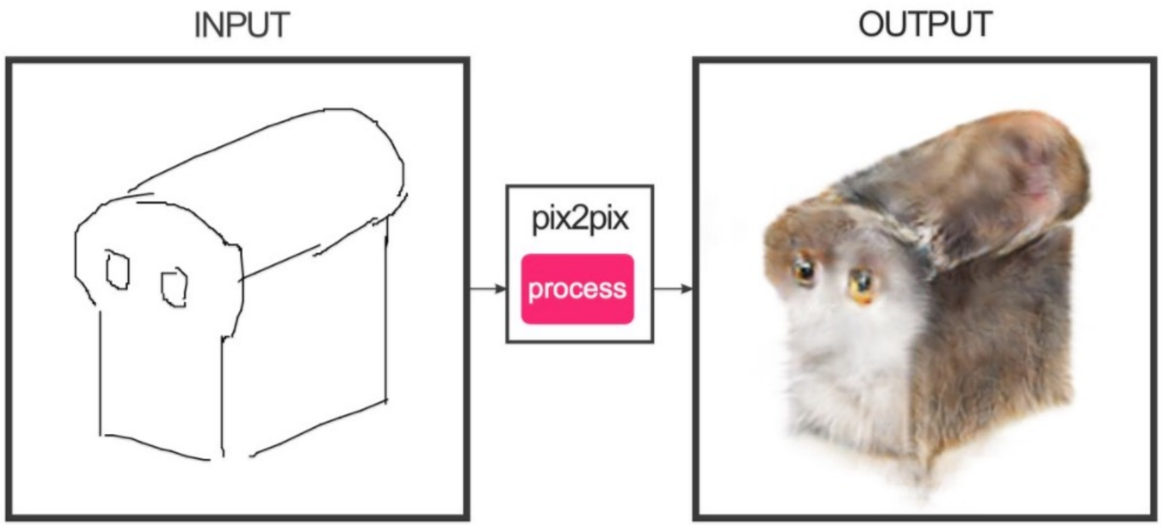
Edges → Images

Edges from [Xie & Tu, 2015]

Demo



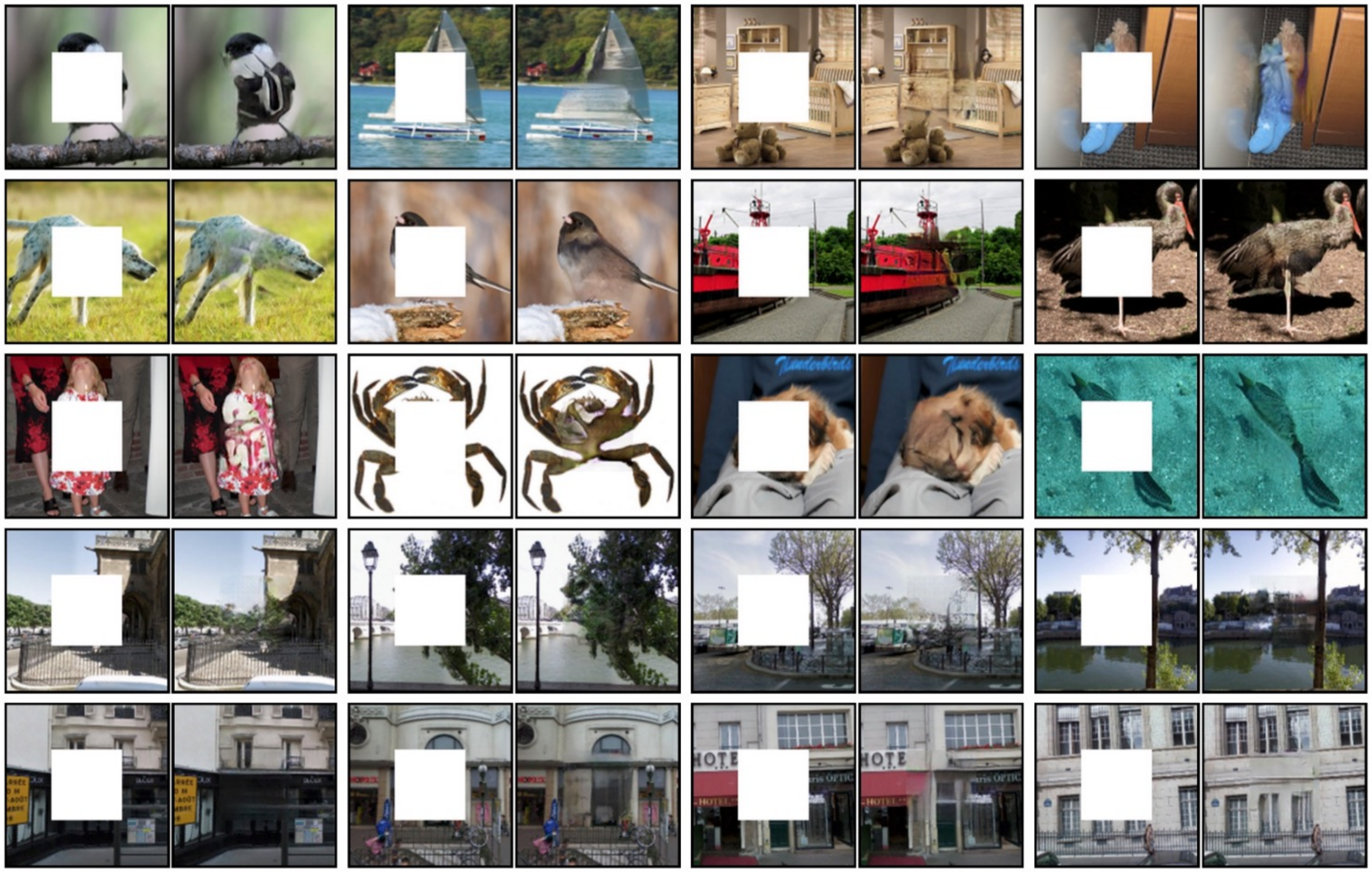
https://affinelayer.com/pixsrv/



Ivy Tasi @ivymyt

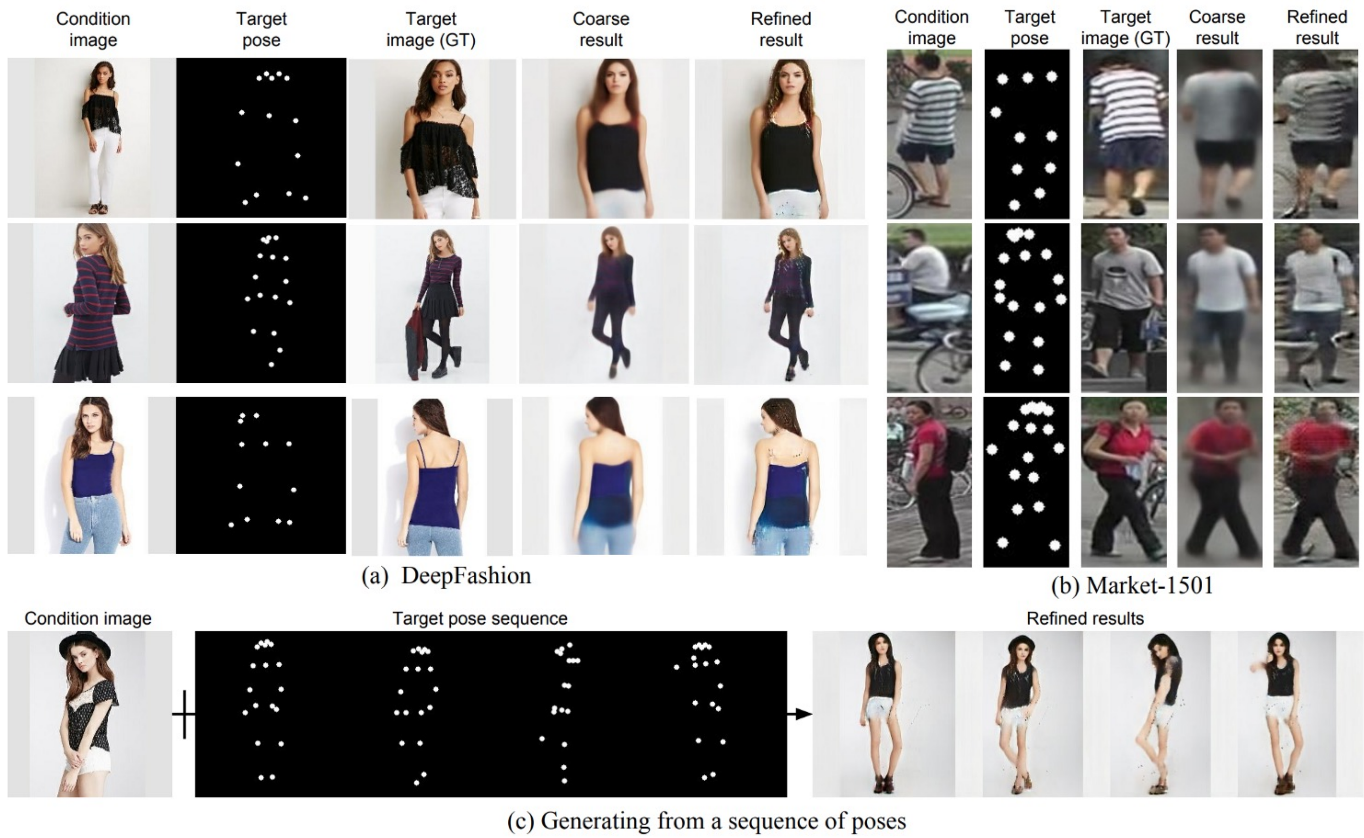
Vitaly Vidmirov @vvid

Image Inpainting



Data from [Pathak et al., 2016]

Pose-guided Generation



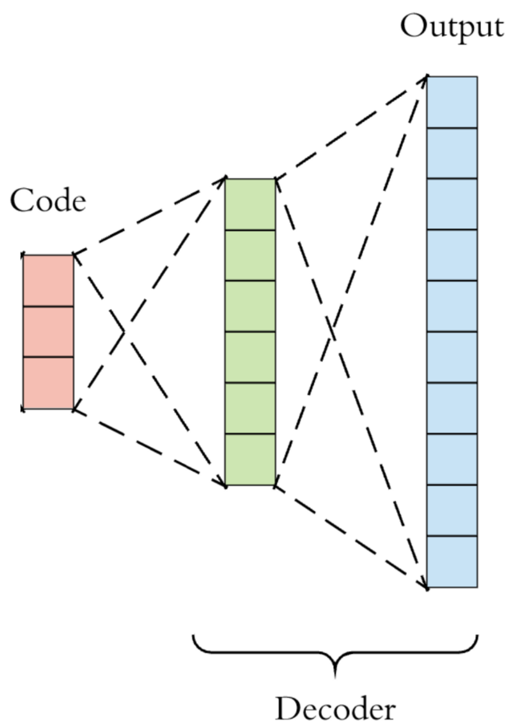
Data from [Ma et al., 2018]

Challenges —> Solutions

- Output is high-dimensional, structured object
  - Approach: Use a deep net, D, to analyze output!
- Uncertainty in mapping; many plausible outputs
  - Approach: D only cares about “plausibility”, doesn’t hedge

Unconditional GANs:
Learning an image manifold for a category

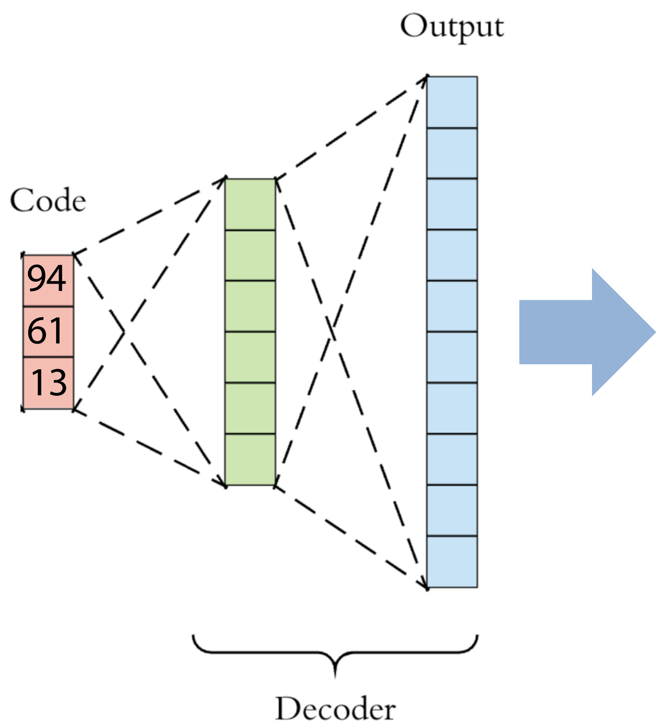
Category-specific
image dataset (FFHQ)



Latent code ("noise")-to-image decoder network

Unconditional GANs:
Learning an image manifold for a category

Category-specific
image dataset (FFHQ)

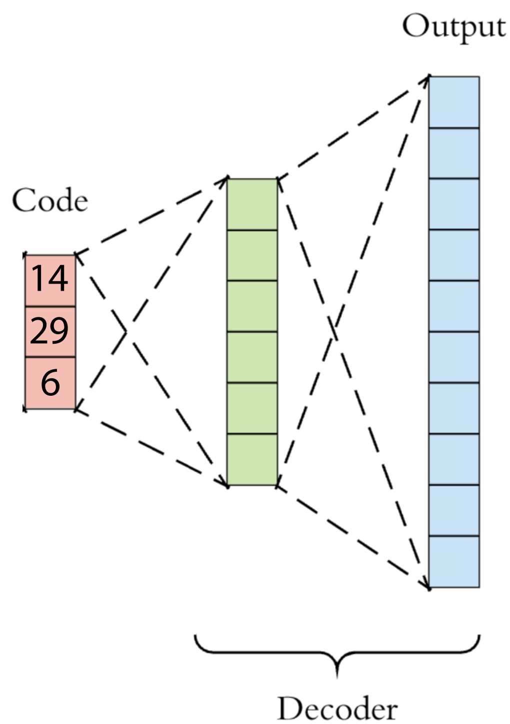


Latent code (“noise”)-to-image decoder network

Output image

Unconditional GANs:
Learning an image manifold for a category

Category-specific
image dataset (FFHQ)

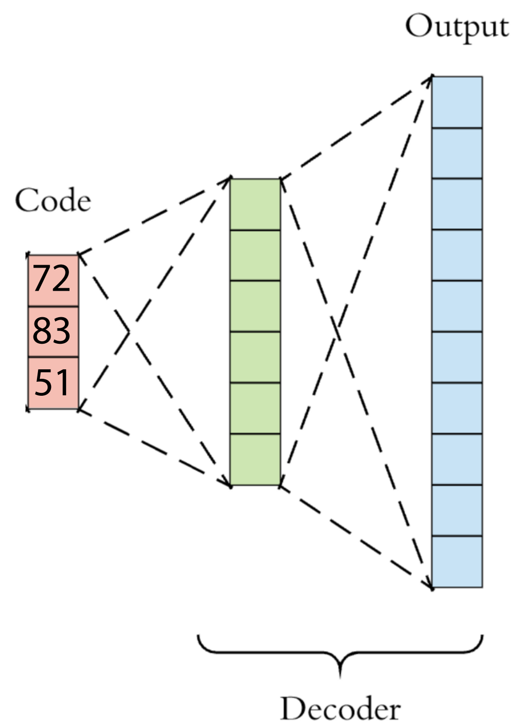


Output image

Latent code (“noise”)-to-image decoder network

Unconditional GANs:
Learning an image manifold for a category

Category-specific
image dataset (FFHQ)



Output image

Latent code (“noise”)-to-image decoder network

Example: Randomly Sampling the Space of Face Images

A

B

Which face is real?

slido

Which face is real?

ⓘ Start presenting to display the poll results on this slide.

Example: Randomly Sampling the Space of Face Images

A

B

Which face is real?

StyleGAN

A Style-Based Generator Architecture for Generative Adversarial Networks

Tero Karras, Samuli Laine, Timo Aila

https://github.com/NVlabs/stylegan

StyleGAN2 [2020]

Analyzing and Improving the Image Quality of StyleGAN

Tero Karras, Samuli Laine, Miika Aittala, Janne Hellsten, Jaakko Lehtinen, Timo Aila

https://github.com/NVlabs/stylegan2

StyleGAN3 [2021]

Alias-Free Generative Adversarial Networks (StyleGAN3)

Tero Karras, Miika Aittala, Samuli Laine, Erik Härkönen, Janne Hellsten, Jaakko Lehtinen, Timo Aila

GAN models trained on animal faces: interpolating between latent codes

GAN models trained on MetFaces: interpolating between latent codes

GANs for 3D

EG3D: Efficient Geometry-aware 3D Generative Adversarial Networks

Eric Ryan Chan [*1,2] Connor Zhizhen Lin [*1] Matthew Aaron Chan [*1]
Koki Nagano [*2] Boxiao Pan [1] Shalini De Mello [2] Orazio Gallo [2]
Leonidas Guibas [1] Jonathan Tremblay [2] Sameh Khamis [2] Tero Karras [2]
Gordon Wetzstein [1]

[1] Stanford University [2] NVIDIA

[*] Equal contribution.

https://nvlabs.github.io/eg3d

Limitations

- The unconditional models above must be trained per-category:
  - We have a separate model for every category – an animal face model, broccoli model, horse model, etc…
- What if we want to generate an image from **any** description?
- Next time: diffusion and text-to-image models

Questions?