

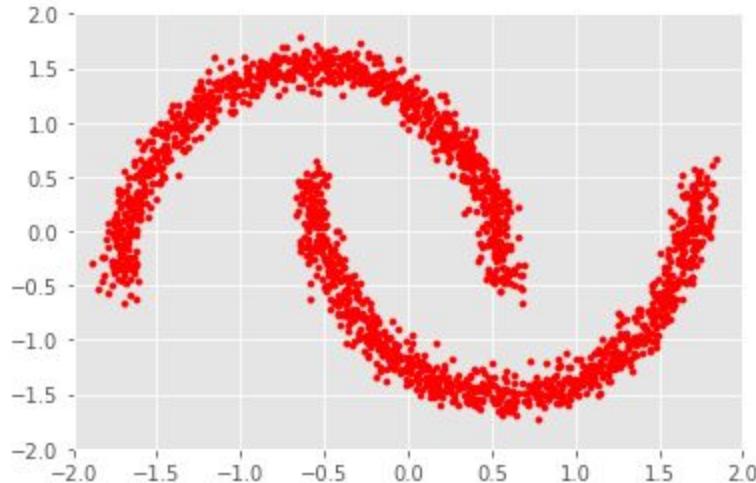
Normalizing Flows

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Goals

- Want to be able to represent an arbitrary probability distribution of examples in some domain
 - E.g., $p(x)$: distribution of all possible images
 - Can only infer this distribution given a (large) set of examples?
- Want to be able to:
 - Sample from this distribution
 - Construct realistic combinations of a set of examples

‘Half Moon’ Dataset



Transformations between Scalar Spaces

Approach:

- Assume a base distribution $p(z)$ that is easy to represent and sample from
 - E.g., $p(z) \sim N(0,1)$
- Construct a transformation for individual samples:
 - Generative direction: $x = f(z, \Phi)$
 - Must be invertible! Normalizing direction:

$$z = f^{-1}(x, \Phi)$$

Transformations between Scalar Spaces

Given: $x = f(z, \Phi)$

What is the relationship between $p(x)$ and $p(z)$?

Transformations between Scalar Spaces

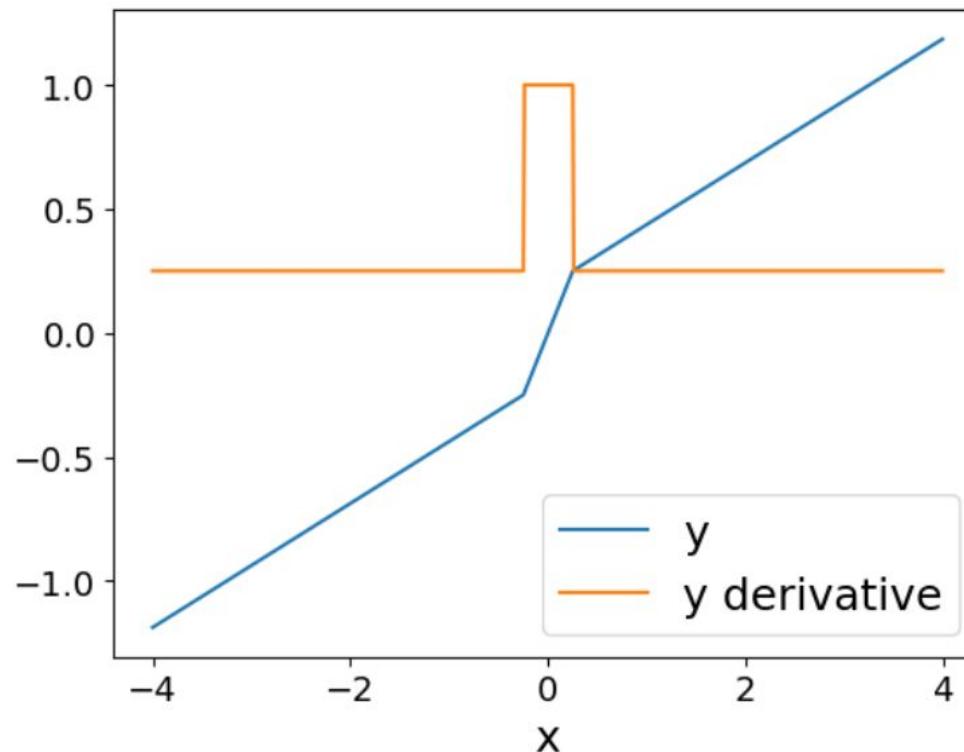
Given: $x = f(z, \Phi)$

What is the relationship between $p(x)$ and $p(z)$?

$$p(x) = \left[\frac{\partial f(z)}{\partial z} \right]^{-1} p(z)$$

The inverse of the derivative counteracts the stretching that $f()$ performs

Example: Piecewise Linear Function



Notebook ...

Transformations between Vector Spaces

- Multiple dimensions (e.g., images)
- The Z and X spaces must have the same dimensionality (otherwise we cannot have an invertible function)
- Base distribution is still a standard Normal: $z \sim N(0, I)$

Transformations between Vector Spaces

x and q are now vectors (assume both are dimensionality D):

$$x_i = f_i(z_0, z_1, \dots, z_{D-1}, \Phi_i)$$

And:

$$x = f(z, \Phi) = \begin{bmatrix} f_0(z_0, z_1, \dots, z_{D-1}, \Phi_0) \\ f_1(z_0, z_1, \dots, z_{D-1}, \Phi_1) \\ \vdots \end{bmatrix}$$

Transformations between Vector Spaces

Given: $x = f(z, \Phi)$

What is the relationship between $p(x)$ and $p(z)$?

Transformations between Vector Spaces

The Jacobian describes the local relationship between z and x :

$$J = \frac{\partial f(z, \Phi)}{\partial z} = \begin{bmatrix} \frac{\partial f_0()}{\partial z_0} & \frac{\partial f_0()}{\partial z_1} & \dots \\ \frac{\partial f_1()}{\partial z_0} & \frac{\partial f_1()}{\partial z_1} & \dots \\ \vdots & \vdots & \ddots \\ \vdots & \vdots & \ddots \\ \cdot & \cdot & \ddots \\ \cdot & \cdot & \ddots \\ \cdot & \cdot & 12 \end{bmatrix}$$

Transformations between Vector Spaces

Given: $x = f(z, \Phi)$

What is the relationship between $p(x)$ and $p(z)$?

$$p(x) = \left| \frac{\partial f(z, \Phi)}{\partial z} \right|^{-1} p(z)$$

The inverse of the determinant counteracts the stretching along all dimensions

Transformation Requirements

1. Expressive
2. Invertible
3. Inexpensive to compute inverse
4. Inexpensive to compute determinant of the Jacobian

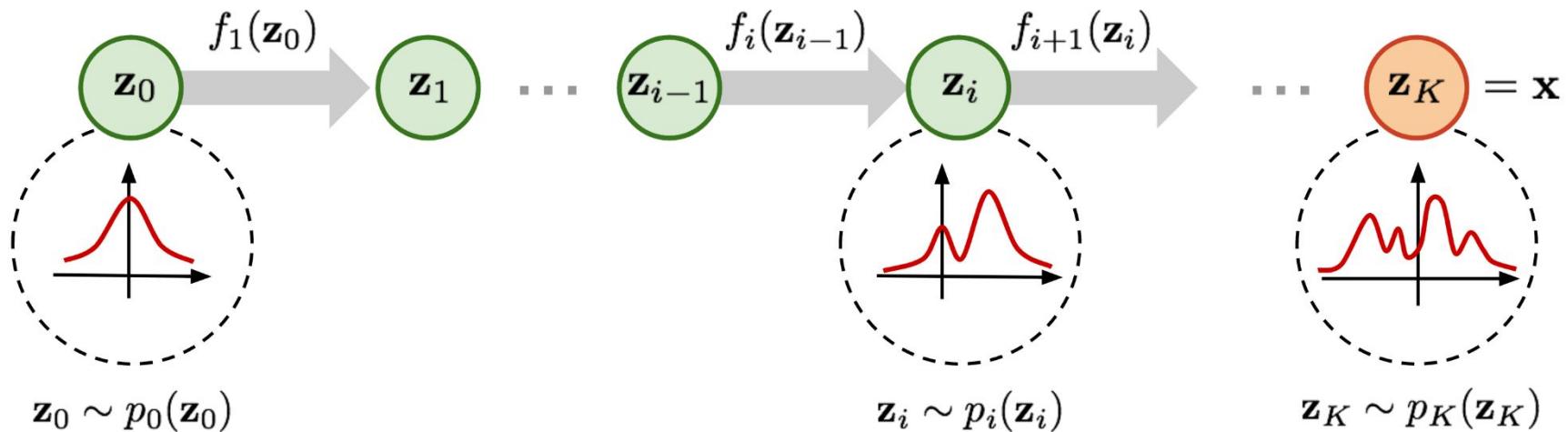
A general deep network is not guaranteed to satisfy these requirements.

Normalizing Flows

Approach:

- Construct a menu of simple transformation types
 - Individually, not very expressive
 - But: satisfy the other requirements
- Stack a sequence of these transformations together to achieve our needed expressive power

Stacking Simple Functions



Large Space of Options for Transformations

- Linear
- Elementwise non-linear
- Coupling
- Autoregressive

Permutation

$$z_{i+1} = P z_i$$

where P is a permutation matrix (all zeros, except exactly one ‘1’ in each column and row)

- Typically fixed & randomly generated
- Easy to invert
- Determinant is 1

Linear Flows

$$z_{i+1} = W^T z_i + \beta$$

- W and β are trainable parameters
- In the general form, inverting W or computing its determinant is $O(n^3)$
- For special forms of W (LU decomposed), inversion is $O(n^2)$ & determinant computation is $O(n)$

Linear Flows

Can implement limited transformations on the pdf:

- Translation
- Scaling along individual dimensions
- Skewing
- Rotation

Will never change the number of modes in the original distribution

Elementwise Flows

For every element j in the z_i vector:

$$z_{i+1,j} = f_i(z_{i,j}, \Phi_i)$$

Where:

- $f_i(\dots)$ is an invertible non-linear function
 - E.g., piecewise linear

Elementwise Flows

$$z_{i+1,j} = f_i(z_{i,j}, \Phi_i)$$

- Inverse: compute inverse for each element - $O(n)$
- Determinant: product of the absolute derivatives - $O(n)$

Coupling Flows

- Split z_i into two pieces: $z_i^{(1)}$ and $z_i^{(2)}$
- First component is
 - Used to compute parameters $\Phi(z_i^{(1)})$
- Second component is transformed:

$$z_{i+1}^{(2)} = g\left(z_i^{(2)}, \Phi\left(z_i^{(1)}\right)\right)$$

$$z_{i+1} = \begin{bmatrix} z_i^{(1)} \\ z_{i+1}^{(2)} \end{bmatrix}$$

Coupling Flows

- Computation of the inverse and determinant is as complex as computing these for $g()$

$$z_{i+1}^{(2)} = g \left(z_i^{(2)}, \Phi \left(z_i^{(1)} \right) \right)$$

- Typically preceded by a permutation transform
 - This allows sorting of the individual elements into the parameter / value sets

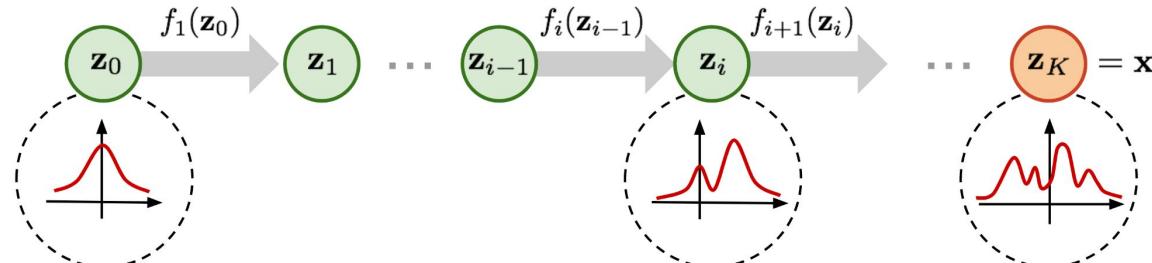
Inverse of a Flow

Computing the inverse of all steps:

- Sequentially evaluate individual inverses from right to left:

$$z_{K-1} = f_K^{-1}(x)$$

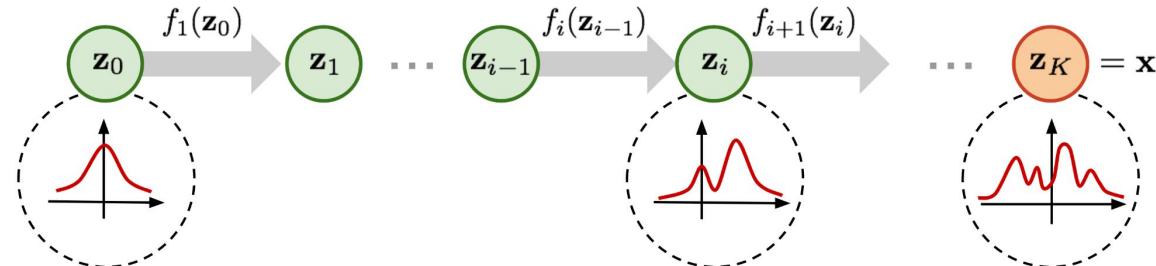
$$z_i = f_{i+1}^{-1}(z_{i+1})$$



Determinant of a Jacobian of a Flow

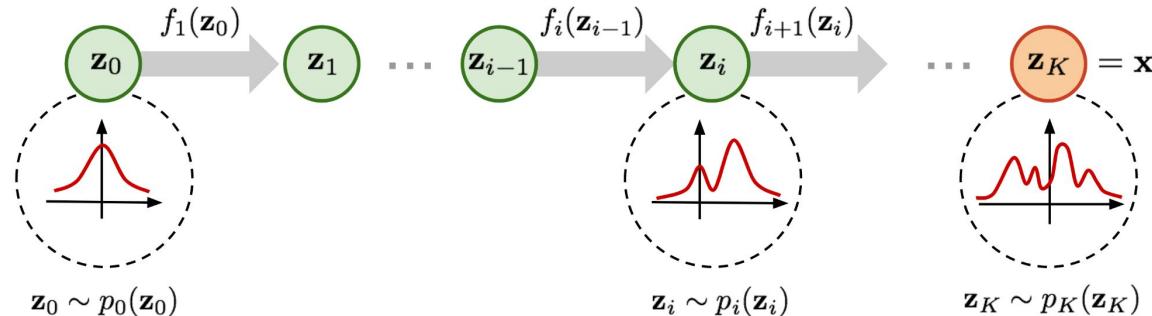
Product of the individual absolute determinants:

$$\left| \frac{\partial f(z)}{\partial z} \right| = \left| \frac{\partial f_K(z_{K-1})}{\partial z_{K-1}} \right| \times \left| \frac{\partial f_{K-1}(z_{K-2})}{\partial z_{K-2}} \right| \times \dots \times \left| \frac{\partial f_1(z_0)}{\partial z_0} \right|$$



Training a Normalizing Flow

- Each (or most) f 's have trainable parameters
- Given a set of samples, \mathbf{X} , we want to choose the set of parameters so we maximize the likelihood of these data



Training a Normalizing Flow

$$L = p(\mathbf{X}|\Phi)$$

Training a Normalizing Flow

$$\begin{aligned} L &= p(\mathbf{X}|\Phi) \\ &= p(x_0, x_1, \dots, x_{N-1}|\Phi) \end{aligned}$$

Training a Normalizing Flow

$$\begin{aligned} L &= p(\mathbf{X}|\Phi) \\ &= p(x_0, x_1, \dots, x_{N-1}|\Phi) \\ &= \prod_{i=0}^{N-1} p(x_i|\Phi) \end{aligned}$$

Training a Normalizing Flow

$$\begin{aligned} L &= p(\mathbf{X}|\Phi) \\ &= p(x_0, x_1, \dots, x_{N-1}|\Phi) \\ &= \prod_{i=0}^{N-1} p(x_i|\Phi) \\ &= \prod_{i=0}^{N-1} p(z_i|\Phi) \times \left| \frac{\partial f(z_i, \Phi)}{\partial z_i} \right|^{-1} \end{aligned}$$

Training a Normalizing Flow

$$L = \prod_{i=0}^{N-1} p(z_i | \Phi) \times \left| \frac{\partial f(z_i, \Phi)}{\partial z_i} \right|^{-1}$$

$$\log L = \sum_{i=0}^{N-1} -\log \left| \frac{\partial f(z_i, \Phi)}{\partial z_i} \right| \times \log p(z_i | \Phi)$$

Training a Normalizing Flow

$$\log L = \sum_{i=0}^{N-1} -\log \left| \frac{\partial f(z_i, \Phi)}{\partial z_i} \right| \times \log p(z_i | \Phi)$$

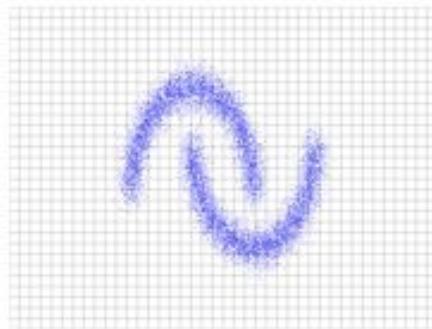
Follow the gradient: $\frac{\partial \log L}{\partial \Phi}$

Half Moon: Learned Transformation

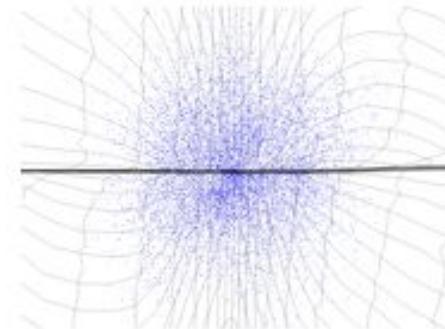
Inference

$$x \sim \hat{p}_X$$
$$z = f(x)$$

Data space \mathcal{X}

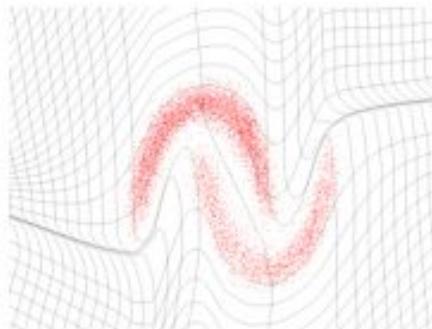


Latent space \mathcal{Z}



Generation

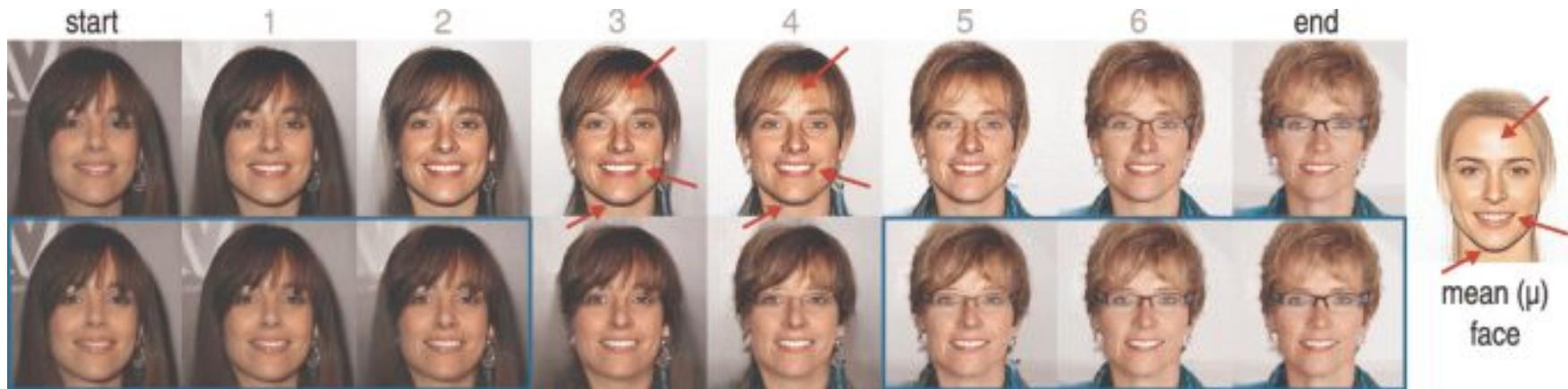
$$z \sim p_Z$$
$$x = f^{-1}(z)$$



Interpolation

- Interpolation between two x's:
 - Transform each into the latent space
 - Compute the weighted average of the two
 - Transform the new z back into x space
- Because the base distribution is compact, we can have high expectation that the resulting image is a reasonable one

Face Interpolation Example



Fadal et al. (2021)

Summary

- Normalizing flows are all about transforming data between two spaces
 - One is easy to sample from & measure likelihoods in
 - The other can have a likelihood function that has a complex shape
- Transformation functions must be invertible
- Relative to GANs: can be more stable and easier to train