

# Week 0e: Generative AI

## The Creation Challenge

Machine Learning for Smarter Innovation

BSc-Level Course

September 28, 2025

1 Act 1: The Challenge

2 Act 2: Variational Autoencoders

3 Act 3: Adversarial & Diffusion

4 Act 4: Synthesis

# The Creation Challenge

Moving Beyond Classification

## Traditional ML: “What is this?”

- Email: spam or not?
- Image: cat or dog?
- Text: positive sentiment?
- Patient: high risk?

**Limitation:** Analysis only

## Generative AI: “Create something new”

- Generate: realistic images
- Write: coherent articles
- Compose: original music
- Design: novel molecules

**Power:** Creation & innovation

The fundamental shift: from understanding existing data to creating new possibilities

# Mathematical Foundation

Two Approaches to Learning

## Discriminative Models

Learn:  $P(y|x)$

"Given input  $x$ , what's the label  $y$ ?"

**Examples:**

- Logistic regression
- Random Forest
- Neural networks (classification)
- SVM

**Goal:** Decision boundaries

Discriminative: "Is this a cat?" — Generative: "Draw me a cat"

## Generative Models

Learn:  $P(x)$  or  $P(x,y)$

"What does the data distribution look like?"

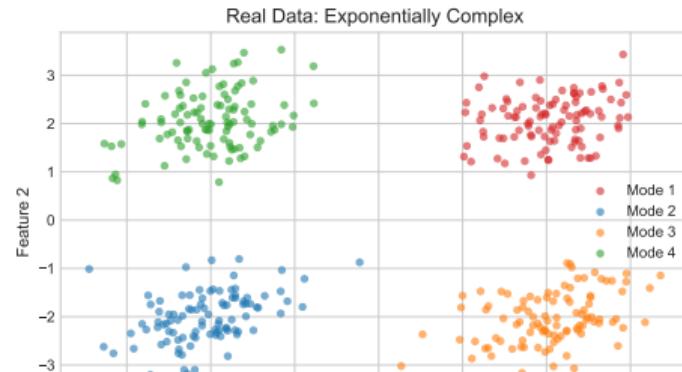
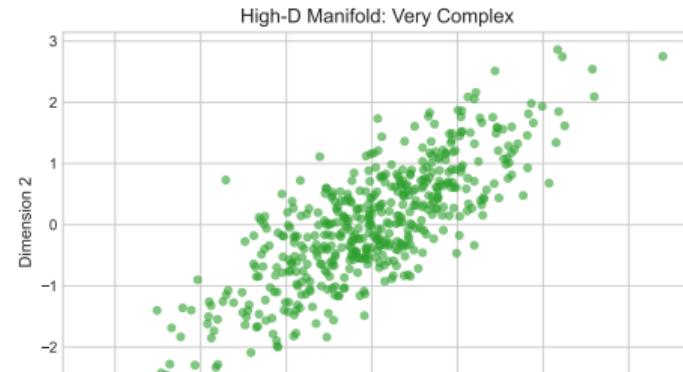
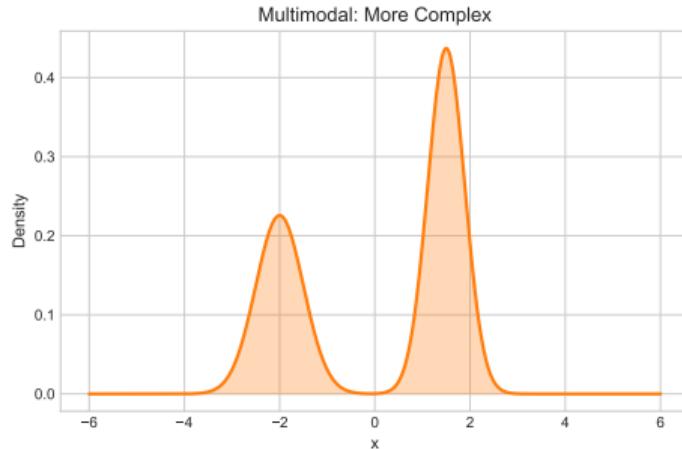
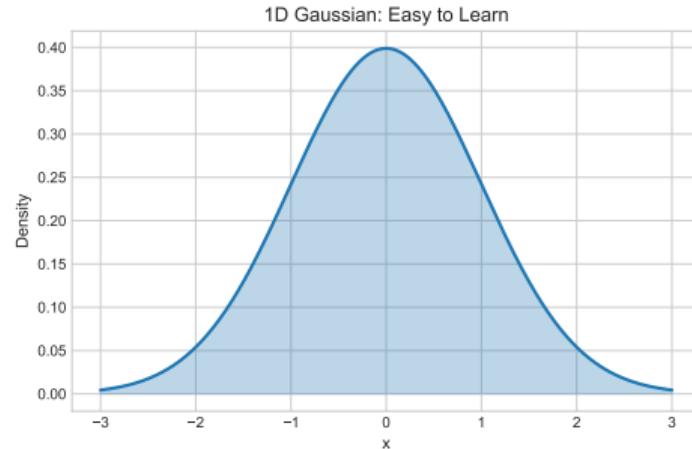
**Examples:**

- Gaussian Mixture Models
- Variational Autoencoders
- GANs
- Diffusion models

**Goal:** Data generation

# The Hard Problem

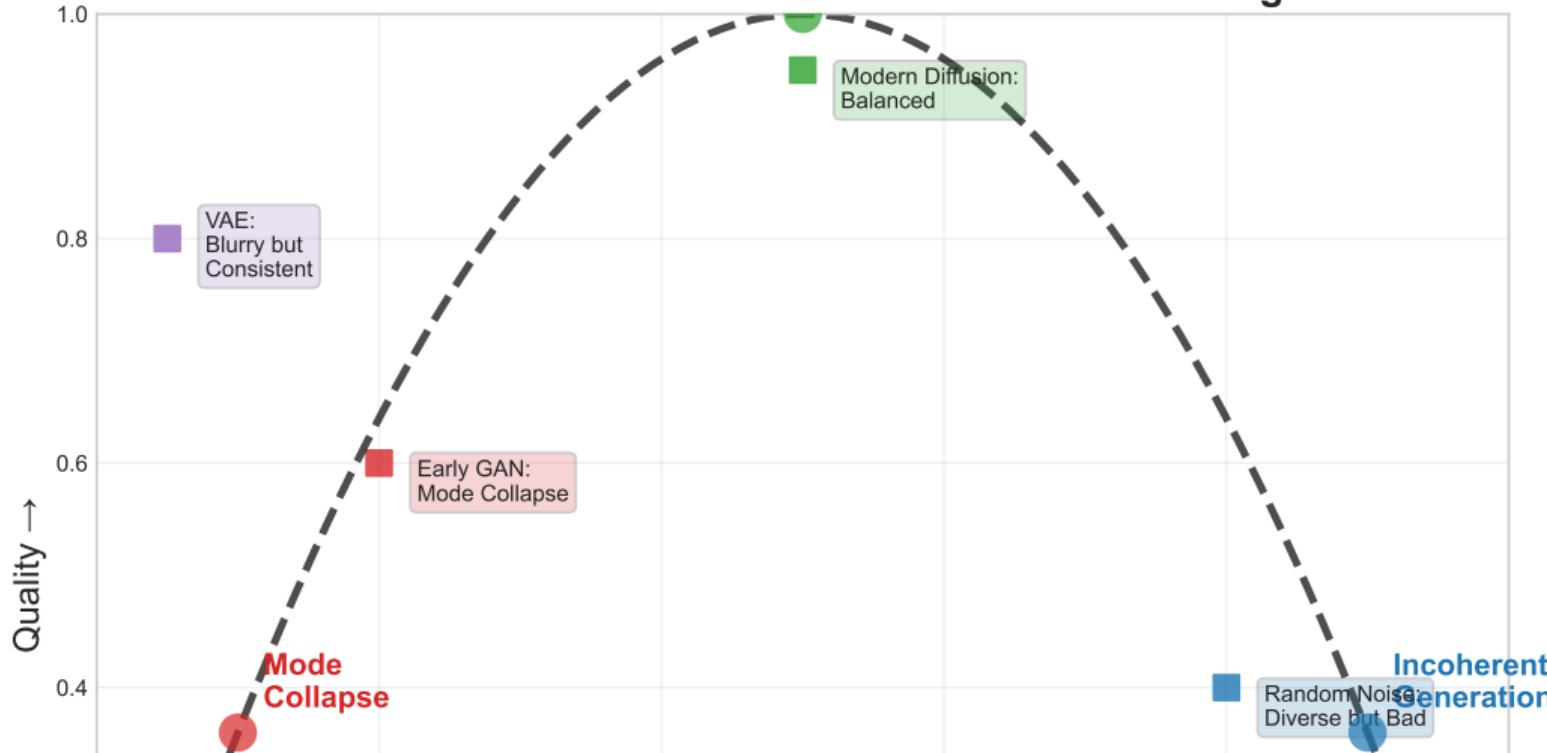
Why Generation is Fundamentally Difficult



# The Fundamental Tradeoff

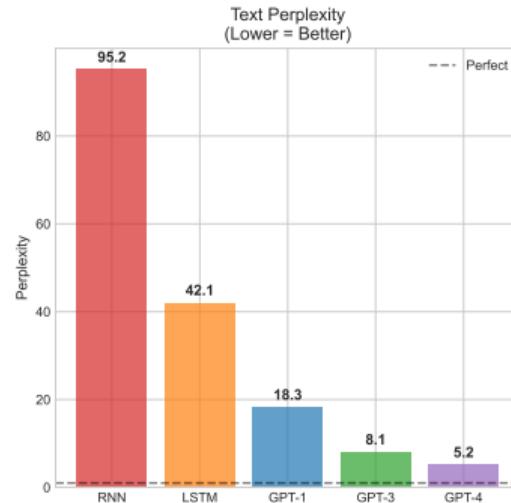
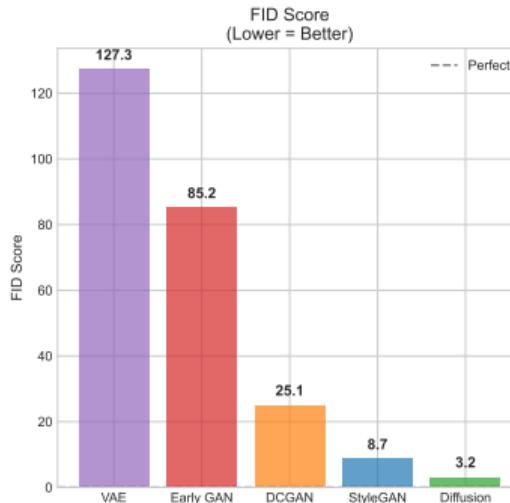
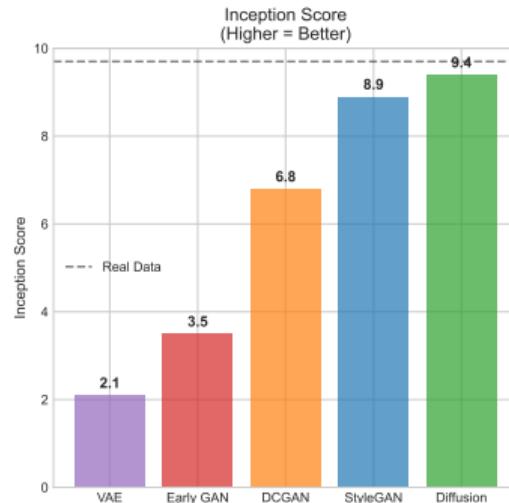
Quality vs Diversity Dilemma

## The Fundamental Tradeoff in Generative Modeling



# Measuring Generation Quality

## Metrics for Evaluating Generative Models



### Inception Score (IS)

- Range: 1-1000+
- Higher = better
- Quality & diversity
- $IS = \exp(E[KL(p(y|x)||p(y))])$

Quantitative evaluation: IS=300+ (excellent), FID<10 (photorealistic), Perplexity<20 (human-like text)

### FID Score

- Range: 0-500+
- Lower = better
- Feature distance
- Real vs generated

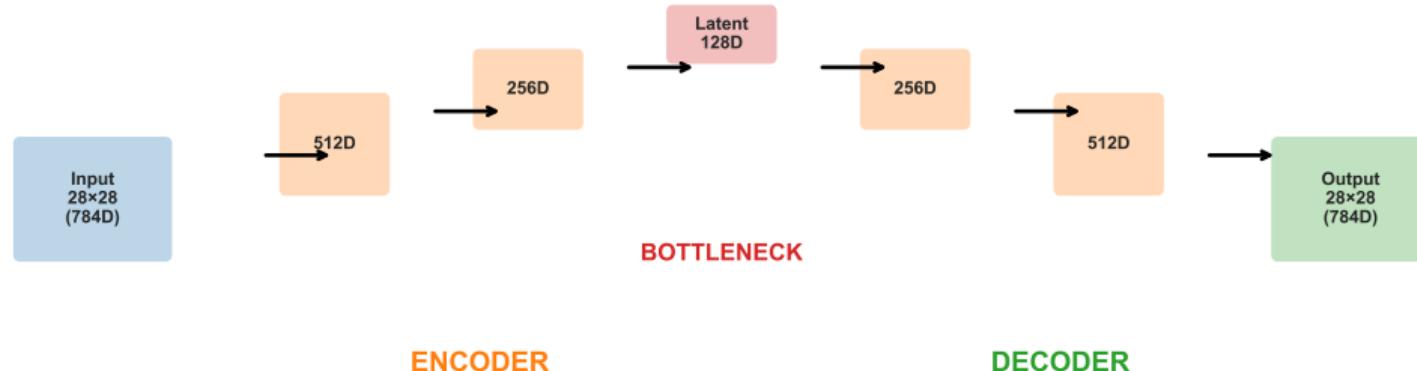
### Perplexity (Text)

- Range: 1-10,000+
- Lower = better
- Predictability
- Language fluency

# Autoencoders: The Foundation

## Learning Compressed Representations

### Autoencoder Architecture: Compression Through Reconstruction



#### Encoder

- Input: 784D (28x28 image)

#### Latent Space

- Bottleneck: 128D

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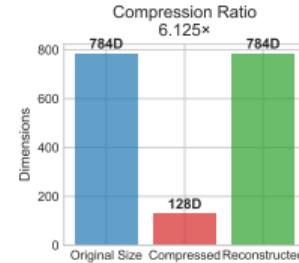
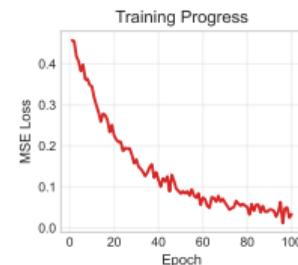
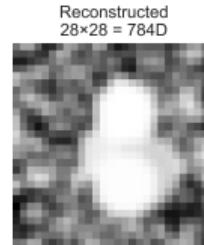
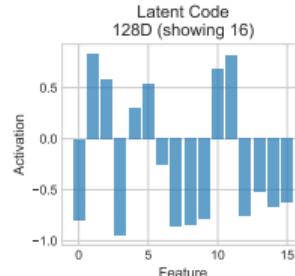
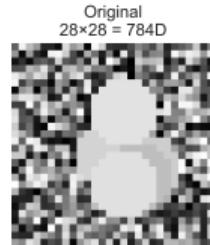
#### Decoder

- Latent: 128D

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# Worked Example: MNIST Compression

From 784 Pixels to 128 Features



## Architecture Details:

- Input:  $28 \times 28 = 784$  pixels
- Encoder:  $784 \rightarrow 512 \rightarrow 256 \rightarrow 128$
- Decoder:  $128 \rightarrow 256 \rightarrow 512 \rightarrow 784$
- Activation: ReLU (hidden), Sigmoid (output)

## Training Process:

- Loss:  $L = \|x - \hat{x}\|^2$
- Optimizer: Adam, lr=0.001
- Epochs: 100
- Compression ratio:  $784/128 = 6.125\times$

Reconstruction loss: MSE drops from 0.45 to 0.03 over 100 epochs

# Autoencoder Successes

What Works Well

Autoencoder Successes

Visualization Placeholder

(Chart 12)



# Autoencoder Limitations

## The Generation Problem

Autoencoder Failures

Visualization Placeholder

(Chart 13)



# Root Cause Analysis

Why Autoencoders Generate Poorly

Averaging Problem

Visualization Placeholder

(Chart 14)

# Variational Autoencoders (VAEs)

The Probabilistic Solution

Vae Framework

Visualization Placeholder

(Chart 15)



# Human Learning Analogy

How Artists Develop Mastery

Artist Learning Process

Visualization Placeholder

(Chart 16)



# Two Revolutionary Approaches

Beyond VAEs to Better Generation

Two Approaches

Visualization Placeholder

(Chart 17)



# GANs: The Forger vs Detective Game

Adversarial Training in Plain English

Forger Detective Analogy

Visualization Placeholder

(Chart 18)



# Diffusion: The Reverse Corruption Process

Denoising in Plain English

Reverse Corruption Analogy

Visualization Placeholder

(Chart 19)



# GAN Dynamics: Geometric View

Understanding the Adversarial Process

Gan Geometric Dynamics

Visualization Placeholder

(Chart 20)



# GAN Training: Step-by-Step Example

Real Loss Values from MNIST Training

Gan Training Walkthrough

Visualization Placeholder

(Chart 21)



# Diffusion Mathematical Framework

## Forward and Reverse Processes

Diffusion Mathematics

Visualization Placeholder

(Chart 22)



# Latent Space Interpolation

Smooth Transitions in Generated Content

Latent Interpolation

Visualization Placeholder

(Chart 23)



# Diffusion Denoising Visualization

From Noise to Image in 1000 Steps

Denoising Steps

Visualization Placeholder

(Chart 24)



# Why Adversarial Training Works

The Mathematical Guarantee

Adversarial Theory

Visualization Placeholder

(Chart 25)



# Experimental Validation

Quality Metrics Throughout Training

Quality Metrics Over Time

Visualization Placeholder

(Chart 26)



# Implementation: Stable Diffusion API

Production-Ready Generative AI

Stable Diffusion Api

Visualization Placeholder

(Chart 27)



# The Generative AI Landscape

Four Fundamental Approaches

Generative Landscape

Visualization Placeholder

(Chart 28)



# Fundamental Trade-offs

No Free Lunch in Generative Modeling

Generative Tradeoffs

Visualization Placeholder

(Chart 29)



# State-of-the-Art Applications

Production Generative AI Systems

Modern Applications

Visualization Placeholder

(Chart 30)



# Summary & Ethical Considerations

## Power and Responsibility in Generative AI

Ethics Summary

Visualization Placeholder

(Chart 31)

