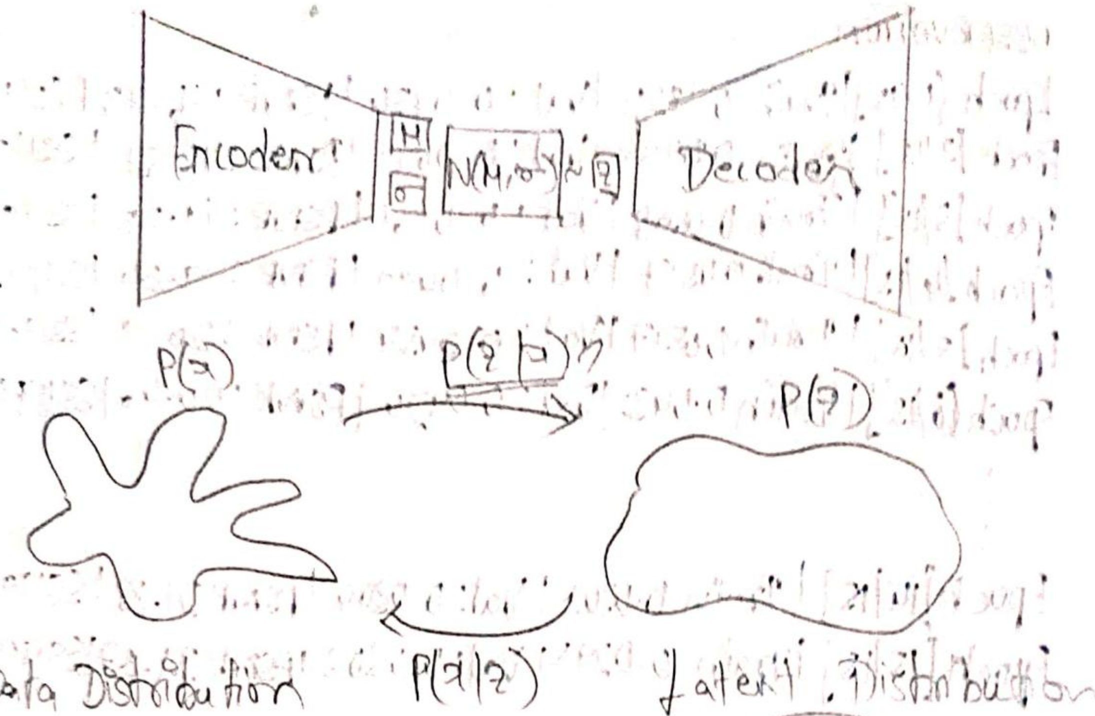


Let us assume $P(z) = N(0,1)$

aprox posterior

$$q(z|x) \approx p(z|x)$$

gaussion distribution

$$q(z|x) = \underbrace{N(\mu, \sigma)}_{\text{Variational bayers}}$$

Optimiziation can be given by

Evidence lower bound (ELBO)

$$\mathcal{L}(x) = \underbrace{\mathbb{E}_{q(z|x)}\left[\log_p (x|z)\right]}_{\substack{\text{Data consistancy} \\ \text{follow L2}}} - \underbrace{KL(q(z|x) \,|\, P(z))}_{\substack{\text{Regularization} \\ \text{term}}}$$

Exp 11

EXPERIMENTS USING VARIATIONAL AUTOENCODER

AIM

To implement a Variational Autoencoder (VAE) for the MNIST dataset learn probabilistic latent representation and evaluate.

OBJECTIVES

* To understand the architecture and concept of Variational Autoencoders (VAEs)
* To train a VAE on the MNIST dataset for unsupervised image generation and compression
* To compute reconstruction metrics such as MSE, PSNR, SSIM
* To visualize the training loss trend (Reconstruction + KL Divergence) and latentspace.

PSEUDOCODE:

↳ Import necessary libraries

↳ Load MNIST Dataset

↳ Define Variational Autoencoder (VAE) model.

Encoder:

Input Image → Flatten → Dense → μ (mean), $\log \sigma^2$ (log variance)

Sampling:

Reparameterise $z = \mu + \sigma * \varepsilon$ $\varepsilon \sim N(0, 1)$

Decoder:

z → Dense → Reconstruct image

↳ Define loss function

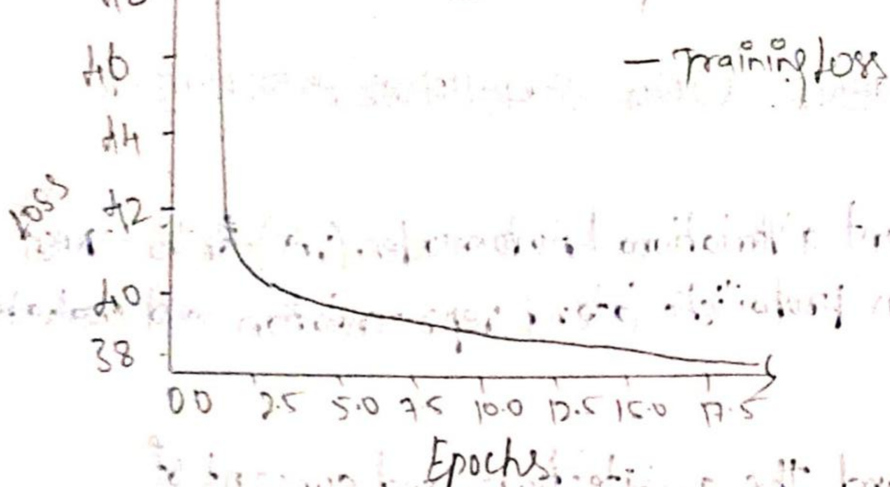
Reconstruction loss = MSE(x, x_reconstructed)

KL Divergence $= 0.5 * \sum(\mu^2 + \sigma^2 - \log \sigma^2 - 1)$

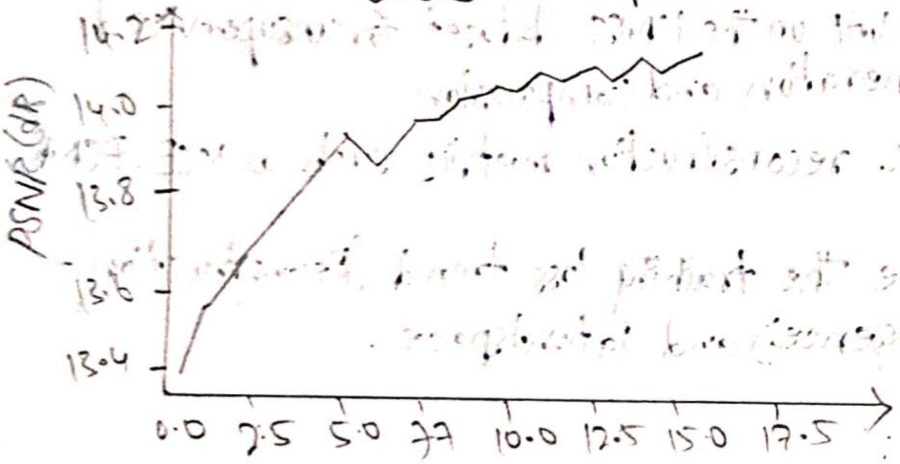
Total Loss = Reconstruction + β * KL ($\beta = 1$)

↳ Train for N epochs:

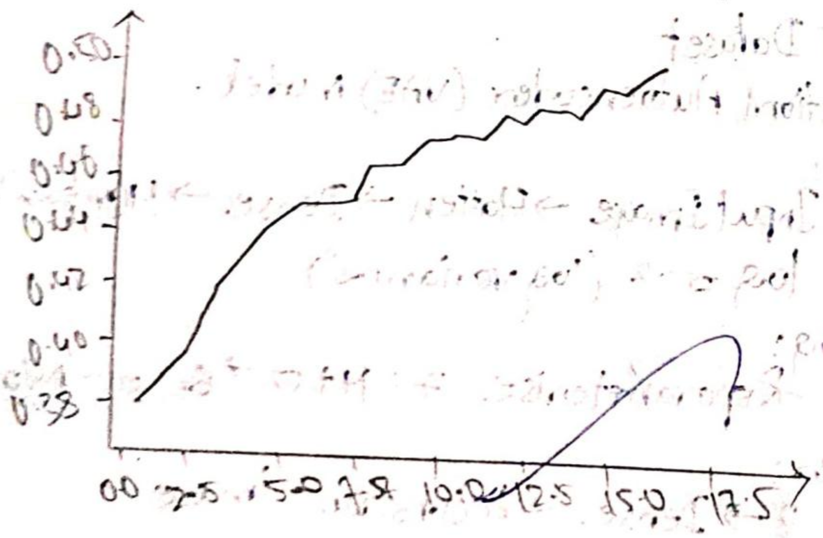
VAE Training Loss



PSNR per Epoch



SSIM



→ Evaluate performance:
  * Compute average MSE, PSNR, SSIM on test data.
→ Visulize:

CONCLUTIONS / OBSERVATIONS:
Epoch [1/20] | loss: 49.2570 | PSNR: 13.347 | SSIM: 0.381
Epoch [2/20] | loss: 42.5184 | PSNR: 13.565 | SSIM: 0.403
Epoch [3/20] | loss: 41.4425 | PSNR: 13.672 | SSIM: 0.422
Epoch [4/20] | loss: 40.7862 | PSNR: 13.771 | SSIM: 0.441
Epoch [5/20] | loss: 40.3012 | PSNR: 13.864 | SSIM: 0.449.
⋮
Epoch [18/20] | loss: 38.0021 | PSNR: 14.147 | SSIM: 0.493
Epoch [20/20] | Loss: 37.9765 | PSNR: 14.172 | SSIM: 0.499.

Final Evaluation:
Average Trainig Loss: 39.4563
Final PSNR: 14.172
Final SSIM: 0.499

** In the models latent Space Representant (2D) the Class '9' is more scattered so we got more number of '9' in reconstruction. **

RESULTS:
We have implementaed a Variational Autoencoder for MNIST with 0.499 SSIM. successfully

Lab 11: Variational Autoencoder on MNIST

```python
import torch
import torch.nn as nn
import torch.optim as optim
from torchvision import datasets, transforms
from torch.utils.data import DataLoader
import matplotlib.pyplot as plt
import numpy as np
from skimage.metrics import peak_signal_noise_ratio as psnr, structural_similarity as ssim

# Device
device = torch.device("cuda" if torch.cuda.is_available() else "cpu")
```

```python
import kagglehub
path = kagglehub.dataset_download("arnavsharma45/mnist-dataset")
print("Path to dataset files:", path)
```

```
Using Colab cache for faster access to the 'mnist-dataset' dataset.
Path to dataset files: /kaggle/input/mnist-dataset
```

Dataset Preparation

```python
transform = transforms.Compose([
    transforms.ToTensor()
])
```


```
Using Colab cache for faster access to the 'mnist-dataset' dataset.
Path to dataset files: /kaggle/input/mnist-dataset
```

Dataset Preparation

```python
transform = transforms.Compose([
    transforms.ToTensor()
])
```


```python
train_data = datasets.MNIST(root='./data', train=True, download=True, transform=transform)
test_data = datasets.MNIST(root='./data', train=False, download=True, transform=transform)

train_loader = DataLoader(train_data, batch_size=128, shuffle=True)
test_loader = DataLoader(test_data, batch_size=128, shuffle=False)
```

Define VAE Model

```python
class VAE(nn.Module):
    def __init__(self, latent_dim=2):
        super(VAE, self).__init__()
        # Encoder
        self.fc1 = nn.Linear(28*28, 400)
        self.fc21 = nn.Linear(400, latent_dim)   # Mean (μ)
        self.fc22 = nn.Linear(400, latent_dim)   # Log variance (logσ²)
        # Decoder
        self.fc3 = nn.Linear(latent_dim, 400)
        self.fc4 = nn.Linear(400, 28*28)
```

Define VAE Model

```python
class VAE(nn.Module):
    def __init__(self, latent_dim=2):
        super(VAE, self).__init__()
        # Encoder
        self.fc1 = nn.Linear(28*28, 400)
        self.fc21 = nn.Linear(400, latent_dim)   # Mean (μ)
        self.fc22 = nn.Linear(400, latent_dim)   # Log variance (logσ²)
        # Decoder
        self.fc3 = nn.Linear(latent_dim, 400)
        self.fc4 = nn.Linear(400, 28*28)
        self.relu = nn.ReLU()
        self.sigmoid = nn.Sigmoid()

    def encode(self, x):
        h1 = self.relu(self.fc1(x))
        return self.fc21(h1), self.fc22(h1)  # μ and logσ²

    def reparameterize(self, mu, logvar):
        std = torch.exp(0.5 * logvar)
        eps = torch.randn_like(std)
        return mu + eps * std  # z = μ + σ * ε

    def decode(self, z):
        h3 = self.relu(self.fc3(z))
        return self.sigmoid(self.fc4(h3))
```

Loss Function

```python
def vae_loss(recon_x, x, mu, logvar):
    MSE = nn.functional.mse_loss(recon_x, x.view(-1, 28*28), reduction='sum')
    KLD = -0.5 * torch.sum(1 + logvar - mu.pow(2) - logvar.exp())
    return MSE + KLD
```

Initialize Model & Optimizer

```python
model = VAE(latent_dim=2).to(device)
optimizer = optim.Adam(model.parameters(), lr=1e-3)

epochs = 20
train_losses, psnr_history, ssim_history = [], [], []
```

Training & Metric Evaluation per Epoch

```python
for epoch in range(epochs):
    model.train()
    train_loss = 0

    for data, _ in train_loader:
        data = data.to(device)
        optimizer.zero_grad()
        recon_batch, mu, logvar = model(data)
        loss = vae_loss(recon_batch, data, mu, logvar)
```

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```
    train_losses, psnr_history, ssim_history = [], [], []
```

Training & Metric Evaluation per Epoch

```
for epoch in range(epochs):
    model.train()
    train_loss = 0

    for data, _ in train_loader:
        data = data.to(device)
        optimizer.zero_grad()
        recon_batch, mu, logvar = model(data)
        loss = vae_loss(recon_batch, data, mu, logvar)
        loss.backward()
        train_loss += loss.item()
        optimizer.step()

    avg_train_loss = train_loss / len(train_loader.dataset)
    train_losses.append(avg_train_loss)

    # ---- Validation ----
    model.eval()
    mse_list, psnr_list, ssim_list = [], [], []
    with torch.no_grad():
        for data, _ in test_loader:
            data = data.to(device)
            recon_batch, mu, logvar = model(data)
            x_orig = data.cpu().numpy()
            x_recon = recon_batch.view(-1, 1, 28, 28).cpu().numpy()
```

Variables Terminal

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```
    # ---- Validation ----
    model.eval()
    mse_list, psnr_list, ssim_list = [], [], []
    with torch.no_grad():
        for data, _ in test_loader:
            data = data.to(device)
            recon_batch, mu, logvar = model(data)
            x_orig = data.cpu().numpy()
            x_recon = recon_batch.view(-1, 1, 28, 28).cpu().numpy()

            for i in range(len(x_orig)):
                orig = x_orig[i, 0]
                rec = x_recon[i, 0]
                mse_val = np.mean((orig - rec) ** 2)
                mse_list.append(mse_val)
                psnr_list.append(psnr(orig, rec, data_range=1))
                ssim_list.append(ssim(orig, rec, data_range=1))

    psnr_history.append(np.mean(psnr_list))
    ssim_history.append(np.mean(ssim_list))

    print(f"Epoch [{epoch+1}/{epochs}] | Loss: {avg_train_loss:.4f} | "
          f"PSNR: {np.mean(psnr_list):.3f} | SSIM: {np.mean(ssim_list):.3f}")
```

```
Epoch [1/20] | Loss: 49.2570 | PSNR: 13.347 | SSIM: 0.381
Epoch [2/20] | Loss: 42.5184 | PSNR: 13.565 | SSIM: 0.403
Epoch [3/20] | Loss: 41.4425 | PSNR: 13.672 | SSIM: 0.422
Epoch [4/20] | Loss: 40.7862 | PSNR: 13.771 | SSIM: 0.441
Epoch [5/20] | Loss: 40.3012 | PSNR: 13.864 | SSIM: 0.449
Epoch [6/20] | Loss: 39.9422 | PSNR: 13.836 | SSIM: 0.451
```

Variables Terminal

```
        print(f"Epoch [{epoch+1}/{epochs}] | Loss: {avg_train_loss:.4f} | "
              f"PSNR: {np.mean(psnr_list):.3f} | SSIM: {np.mean(ssim_list):.3f}")
```

```
Epoch [1/20] | Loss: 49.2570 | PSNR: 13.347 | SSIM: 0.381
Epoch [2/20] | Loss: 42.5184 | PSNR: 13.565 | SSIM: 0.403
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Epoch [4/20] | Loss: 40.7862 | PSNR: 13.771 | SSIM: 0.441
Epoch [5/20] | Loss: 40.3012 | PSNR: 13.864 | SSIM: 0.449
Epoch [6/20] | Loss: 39.9422 | PSNR: 13.836 | SSIM: 0.451
Epoch [7/20] | Loss: 39.6417 | PSNR: 13.935 | SSIM: 0.465
Epoch [8/20] | Loss: 39.4002 | PSNR: 13.942 | SSIM: 0.465
Epoch [9/20] | Loss: 39.1871 | PSNR: 13.978 | SSIM: 0.473
Epoch [10/20] | Loss: 39.0195 | PSNR: 14.015 | SSIM: 0.474
Epoch [11/20] | Loss: 38.8723 | PSNR: 14.014 | SSIM: 0.479
Epoch [12/20] | Loss: 38.7233 | PSNR: 14.031 | SSIM: 0.477
Epoch [13/20] | Loss: 38.6062 | PSNR: 14.093 | SSIM: 0.487
Epoch [14/20] | Loss: 38.4940 | PSNR: 14.084 | SSIM: 0.485
Epoch [15/20] | Loss: 38.3804 | PSNR: 14.108 | SSIM: 0.489
Epoch [16/20] | Loss: 38.2775 | PSNR: 14.130 | SSIM: 0.490
Epoch [17/20] | Loss: 38.2031 | PSNR: 14.103 | SSIM: 0.489
Epoch [18/20] | Loss: 38.0947 | PSNR: 14.181 | SSIM: 0.497
Epoch [19/20] | Loss: 38.0021 | PSNR: 14.147 | SSIM: 0.493
Epoch [20/20] | Loss: 37.9765 | PSNR: 14.172 | SSIM: 0.499
```

Evaluation

```
print("\n📊 Final Evaluation:")
print(f"Average Training Loss: {np.mean(train_losses):.4f}")
print(f"Final PSNR: {psnr_history[-1]:.3f}")
print(f"Final SSIM: {ssim_history[-1]:.3f}")
```

Evaluation

```
print("\n📊 Final Evaluation:")
print(f"Average Training Loss: {np.mean(train_losses):.4f}")
print(f"Final PSNR: {psnr_history[-1]:.3f}")
print(f"Final SSIM: {ssim_history[-1]:.3f}")
```


```
📊 Final Evaluation:
Average Training Loss: 39.7563
Final PSNR: 14.172
Final SSIM: 0.499
```

Visualizations

```
# (a) Loss Curve
plt.figure(figsize=(6,4))
plt.plot(train_losses, label="Training Loss", color='tab:red', linewidth=2)
plt.xlabel("Epochs"); plt.ylabel("Loss")
plt.title("VAE Training Loss")
plt.legend(); plt.grid(True)
plt.show()

# (b) PSNR Curve
plt.figure(figsize=(6,4))
plt.plot(psnr_history, label="PSNR", color='tab:blue', marker='o')
plt.xlabel("Epochs"); plt.ylabel("PSNR (dB)")
```

```
Final PSNR: 14.172
Final SSIM: 0.499
```

Visualizations

```python
# (a) Loss Curve
plt.figure(figsize=(6,4))
plt.plot(train_losses, label="Training Loss", color='tab:red', linewidth=2)
plt.xlabel("Epochs"); plt.ylabel("Loss")
plt.title("VAE Training Loss")
plt.legend(); plt.grid(True)
plt.show()

# (b) PSNR Curve
plt.figure(figsize=(6,4))
plt.plot(psnr_history, label="PSNR", color='tab:blue', marker='o')
plt.xlabel("Epochs"); plt.ylabel("PSNR (dB)")
plt.title("PSNR per Epoch")
plt.legend(); plt.grid(True)
plt.show()

# (c) SSIM Curve
plt.figure(figsize=(6,4))
plt.plot(ssim_history, label="SSIM", color='tab:green', marker='s')
plt.xlabel("Epochs"); plt.ylabel("SSIM")
plt.title("SSIM per Epoch")
plt.legend(); plt.grid(True)
plt.show()
```



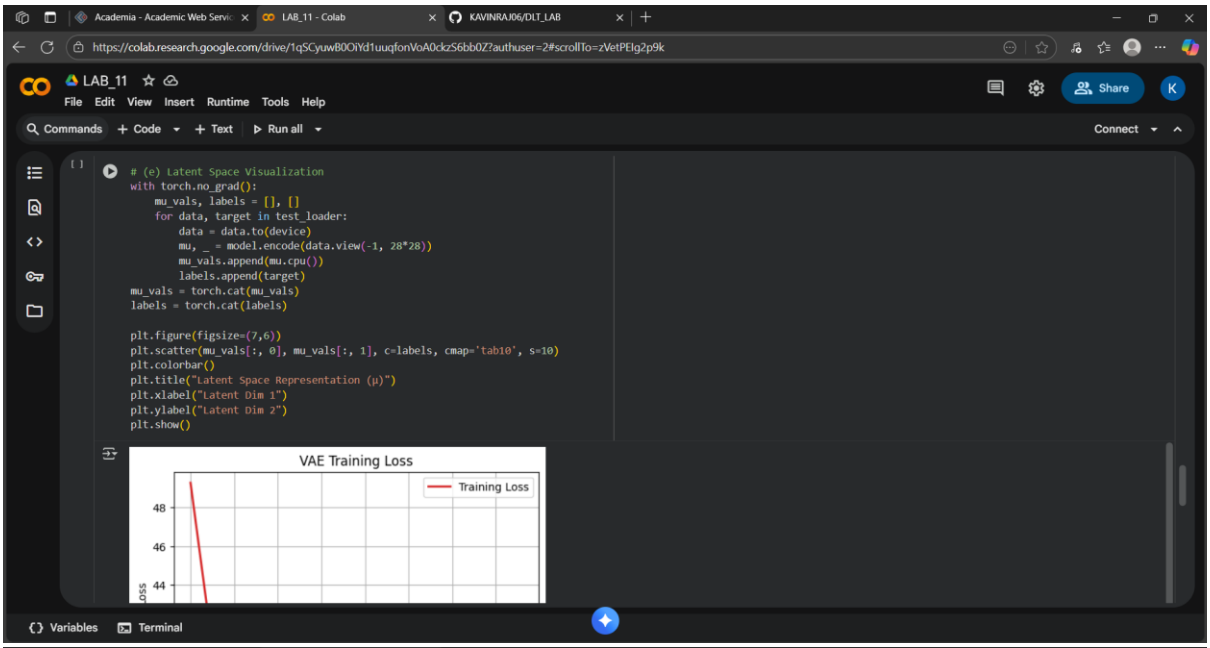
```python
# (c) SSIM Curve
plt.figure(figsize=(6,4))
plt.plot(ssim_history, label="SSIM", color='tab:green', marker='s')
plt.xlabel("Epochs"); plt.ylabel("SSIM")
plt.title("SSIM per Epoch")
plt.legend(); plt.grid(True)
plt.show()
```



```python
# (d) Reconstruction Visualization
test_iter = iter(test_loader)
test_imgs, _ = next(test_iter)
test_imgs = test_imgs.to(device)
reconstructed, _, _ = model(test_imgs)
reconstructed = reconstructed.view(-1, 1, 28, 28).cpu().detach()

fig, axes = plt.subplots(2, 10, figsize=(12, 3))
for i in range(10):
    axes[0, i].imshow(test_imgs[i, 0].cpu(), cmap='gray')
    axes[0, i].axis('off')
    axes[1, i].imshow(reconstructed[i, 0], cmap='gray')
    axes[1, i].axis('off')
axes[0, 0].set_title("Original")
axes[1, 0].set_title("Reconstructed")
plt.suptitle("VAE Reconstruction Results")
plt.show()

# (e) Latent Space Visualization
with torch.no_grad():
    mu_vals, labels = [], []
```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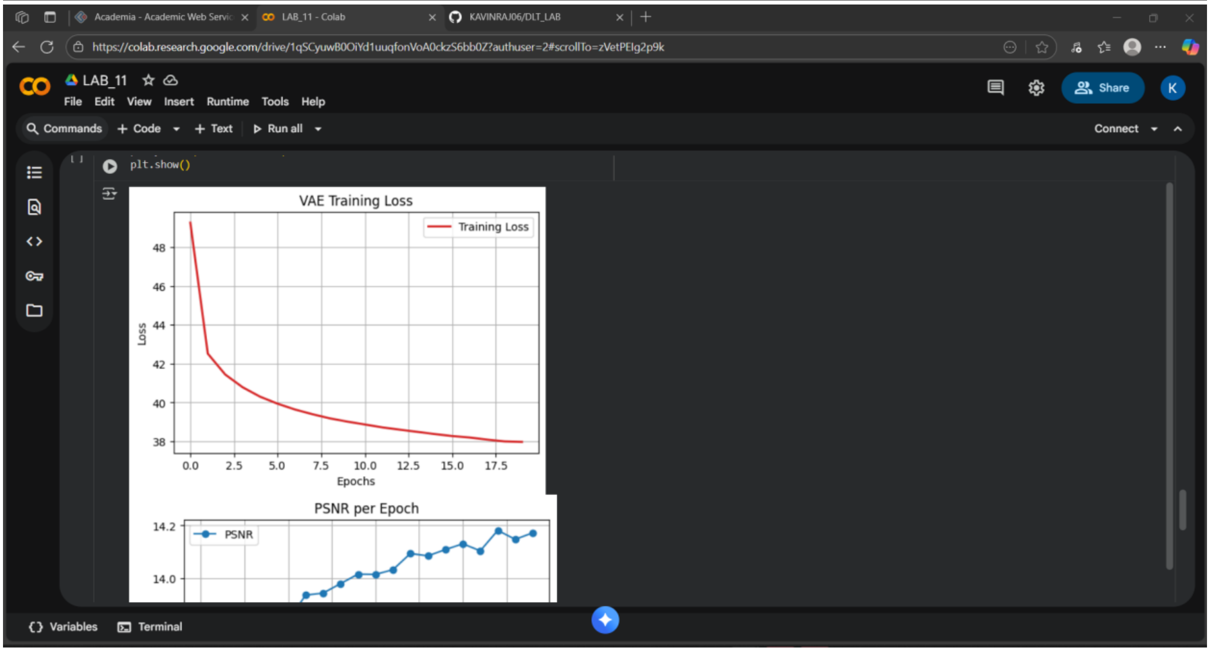
(e) Latent Space Visualization
with torch.no_grad():
mu_vals, labels = [], []
for data, target in test_loader:
data = data.to(device)
mu, _ = model.encode(data.view(-1, 28*28))
mu_vals.append(mu.cpu())
labels.append(target)
mu_vals = torch.cat(mu_vals)
labels = torch.cat(labels)
plt.figure(figsize=(7,6))
plt.scatter(mu_vals[:, 0], mu_vals[:, 1], c=labels, cmap='tab10', s=10)
plt.colorbar()
plt.title("Latent Space Representation (μ)")
plt.xlabel("Latent Dim 1")
plt.ylabel("Latent Dim 2")
plt.show()
VAE Training Loss
Training Loss
48
46
44
Loss
Variables
Terminal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Training Loss
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PSNR per Epoch
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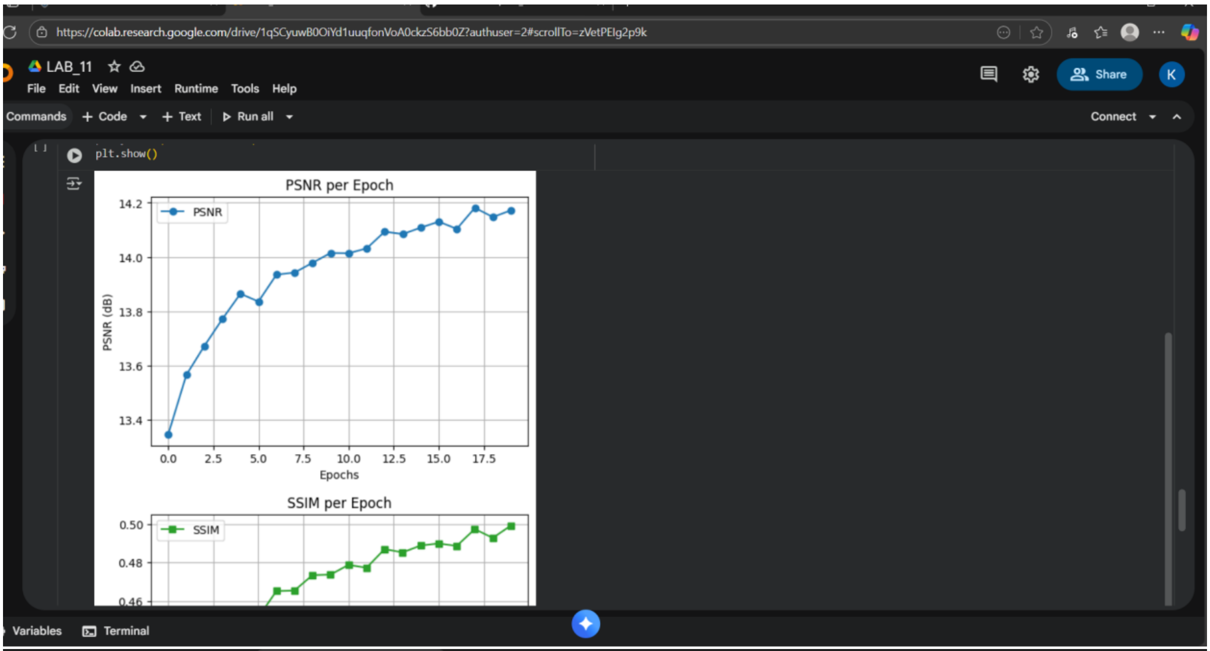
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PSNR per Epoch
PSNR
PSNR (dB)
Epochs
SSIM per Epoch
SSIM
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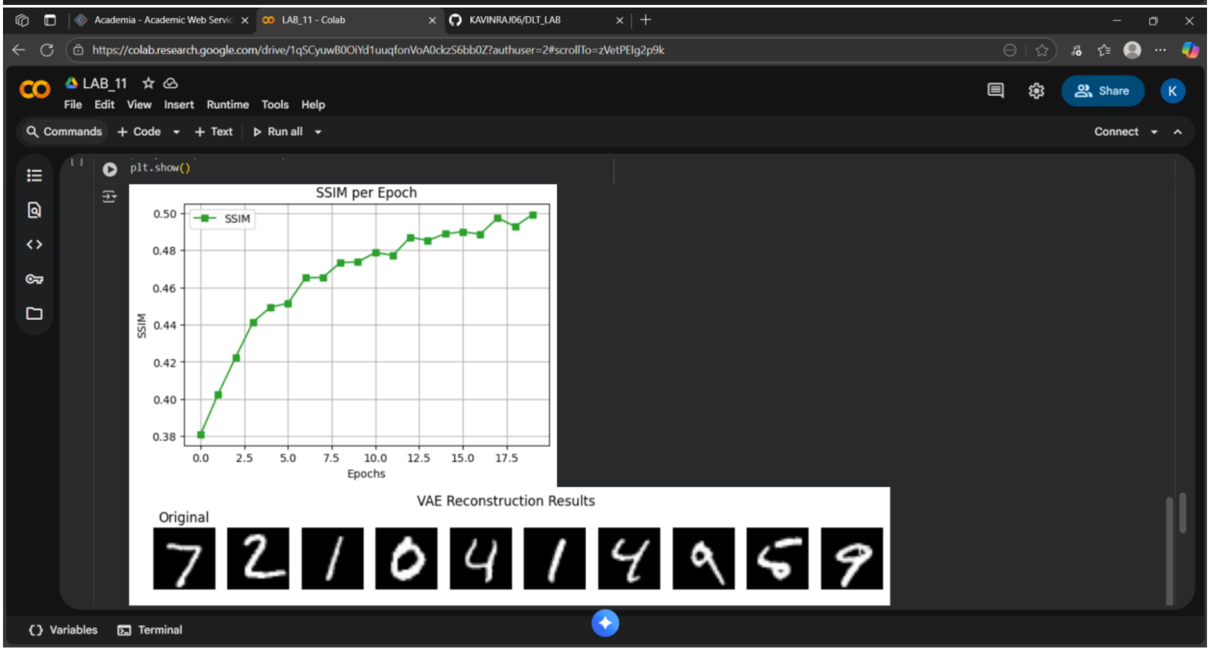
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SSIM
Epochs
VAE Reconstruction Results
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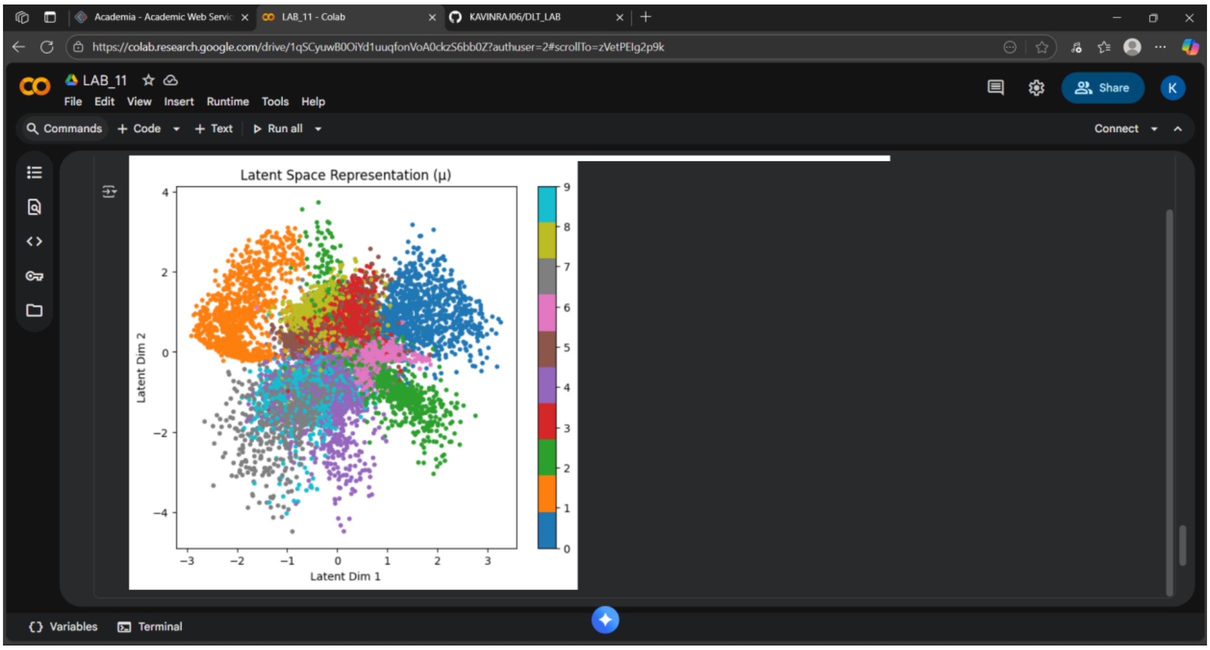
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Connect
Latent Space Representation (μ)
Latent Dim 1
Latent Dim 2
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Terminal