Dataset link (contains a single zip file) Notebook Link

Q1 Code

```
import kagglehub
# Download latest version
path = kagglehub.dataset_download("hojjatk/mnist-dataset")
print("Path to dataset files:", path)

import numpy as np
import struct
def read_idx_images_np(images_path):
    with open(images_path, "rb") as f:
        magic, size, rows, cols = struct.unpack(">IIII", f.read(16))
        assert magic == 2051, f"Bad image magic: {magic}"
        data = np.frombuffer(f.read(), dtype=np.uint8)
        return data.reshape(size, rows, cols)
def read_idx_labels_np(labels_path):
    with open(labels_path, "rb") as f:
        magic, size = struct.unpack(">II", f.read(8))
        assert magic == 2049, f"Bad label magic: {magic}"
        return np.frombuffer(f.read(), dtype=np.uint8)


from os.path import join
training_images_filepath = join(path, 'train-images-idx3-ubyte/train-images-idx3-ubyte')
training_labels_filepath = join(path, 'train-labels-idx1-ubyte/train-labels-idx1-ubyte')
test_images_filepath     = join(path, 't10k-images-idx3-ubyte/t10k-images-idx3-ubyte')
test_labels_filepath     = join(path, 't10k-labels-idx1-ubyte/t10k-labels-idx1-ubyte')
x_train = read_idx_images_np(training_images_filepath)
y_train = read_idx_labels_np(training_labels_filepath)
x_test  = read_idx_images_np(test_images_filepath)
y_test  = read_idx_labels_np(test_labels_filepath)
x_train = np.ascontiguousarray(x_train, dtype=np.uint8)
x_test  = np.ascontiguousarray(x_test,  dtype=np.uint8)
y_train = np.ascontiguousarray(y_train, dtype=np.uint8)
y_test  = np.ascontiguousarray(y_test,  dtype=np.uint8)
print(x_train.shape, y_train.shape, x_test.shape, y_test.shape)
```

Q1(a) code

```
from pathlib import Path
import cv2 as cv
from tqdm import tqdm
import csv
import shutil
import random
PNG_FAST = [cv.IMWRITE_PNG_COMPRESSION, 1]
LOCAL_ROOT = Path("/content/ee604")
LOCAL_ROOT.mkdir(parents=True, exist_ok=True)
```

```
DRIVE_ROOT = Path("/content/drive/MyDrive/ee604")
def otsu_mask_fast(img_u8: np.ndarray) -> np.ndarray:
    _, m = cv.threshold(img_u8, 0, 255, cv.THRESH_BINARY + cv.THRESH_OTSU)
    return m
masks_train = np.stack([otsu_mask_fast(x) for x in tqdm(x_train, desc="Otsu train")], axis=0)
masks_test  = np.stack([otsu_mask_fast(x) for x in tqdm(x_test,  desc="Otsu test")],  axis=0)


Q1A_ROOT  = LOCAL_ROOT / "q1a_pairs"
TRAIN_OUT = Q1A_ROOT / "train"; TRAIN_OUT.mkdir(parents=True, exist_ok=True)
TEST_OUT  = Q1A_ROOT / "test";  TEST_OUT.mkdir(parents=True, exist_ok=True)
def write_pairs(xs, msks, out_dir: Path, desc: str):
    for i in tqdm(range(len(xs)), desc=desc):
        cv.imwrite(str(out_dir / f"{i:06d}_img.png"),  xs[i],   PNG_FAST)
        cv.imwrite(str(out_dir / f"{i:06d}_mask.png"), msks[i], PNG_FAST)
write_pairs(x_train, masks_train, TRAIN_OUT, "Q1(a) train")
write_pairs(x_test,  masks_test,  TEST_OUT,  "Q1(a) test")
print("Q1(a) saved at:", Q1A_ROOT)
```

Q1(b) code

```
from pathlib import Path
import cv2 as cv
import numpy as np
from tqdm import tqdm
import csv

Q1B_ROOT  = LOCAL_ROOT / "q1b_pairs"
Q1B_TRAIN = Q1B_ROOT / "train"; Q1B_TRAIN.mkdir(parents=True, exist_ok=True)
Q1B_TEST  = Q1B_ROOT / "test";  Q1B_TEST.mkdir(parents=True, exist_ok=True)

def circle_from_binary(binary: np.ndarray) -> np.ndarray:
    cnts, _ = cv.findContours((binary>0).astype(np.uint8), cv.RETR_EXTERNAL, cv.CHAIN_APPROX_SIMPLE)
    if not cnts:
        return np.zeros_like(binary)
    c = max(cnts, key=cv.contourArea)
    (cx, cy), r = cv.minEnclosingCircle(c)
    out = np.zeros_like(binary)
    cv.circle(out, (int(round(cx)), int(round(cy))), int(np.ceil(r)), 255, -1, lineType=cv.LINE_AA)
    return out

def build_q1b(x_arr, m_arr, y_arr, out_dir: Path, desc: str):
    manifest = [("img_path","circle_mask_path","label")]
    N = len(x_arr)
    for i in tqdm(range(N), desc=desc):
        cm = circle_from_binary(m_arr[i])
        p_img  = out_dir / f"{i:06d}_img.png"
        p_cmsk = out_dir / f"{i:06d}_circle.png"
        cv.imwrite(str(p_img),  x_arr[i], PNG_FAST)
        cv.imwrite(str(p_cmsk), cm,       PNG_FAST)
        manifest.append((str(p_img), str(p_cmsk), int(y_arr[i])))
    import csv
    with open(out_dir / "manifest.csv", "w", newline="") as f:
        csv.writer(f).writerows(manifest)

build_q1b(x_train, masks_train, y_train, Q1B_TRAIN, "Q1(b) train")
build_q1b(x_test,  masks_test,  y_test,  Q1B_TEST,  "Q1(b) test")
print("Q1(b) saved at:", Q1B_ROOT)
```

Q1(c) code

```
Q1C_ROOT  = LOCAL_ROOT / "q1c_semseg"
Q1C_TRAIN = Q1C_ROOT / "train"; (Q1C_TRAIN / "images").mkdir(parents=True, exist_ok=True); (Q1C_TRAIN /
"labels").mkdir(parents=True, exist_ok=True)
Q1C_TEST  = Q1C_ROOT / "test";  (Q1C_TEST / "images").mkdir(parents=True, exist_ok=True);  (Q1C_TEST /
"labels").mkdir(parents=True, exist_ok=True)

def compose_2x2_from_arrays(indices, X, M, Y):
    comp = np.zeros((56,56), np.uint8)
    lab  = np.full((56,56), 255, np.uint8)
    coords = [(0,0),(0,28),(28,0),(28,28)]
    for k, idx in enumerate(indices):
        r0,c0 = coords[k]
        comp[r0:r0+28, c0:c0+28] = X[idx]
        lab[r0:r0+28, c0:c0+28][M[idx]>0] = int(Y[idx])
    return comp, lab

def build_q1c(X, M, Y, out_dir: Path, total: int, seed: int, desc: str):
    N = len(Y)
    rng = np.random.default_rng(seed)
    seen = set()
    for i in tqdm(range(total), desc=desc):
        # sample unique ordered 4-tuple
        while True:
            quad = tuple(rng.integers(0, N, size=4).tolist())
            if quad not in seen:
                seen.add(quad); break
        comp, lab = compose_2x2_from_arrays(quad, X, M, Y)
        fn = f"{i:07d}.png"
        cv.imwrite(str((out_dir / "images" / fn)), comp, PNG_FAST)
        cv.imwrite(str((out_dir / "labels" / fn)), lab,  PNG_FAST)

N_TRAIN = 250_000
N_TEST  = 10_000
build_q1c(x_train, masks_train, y_train, Q1C_TRAIN, N_TRAIN, seed=12345, desc=f"Q1(c) TRAIN {N_TRAIN}")
build_q1c(x_test,  masks_test,  y_test,  Q1C_TEST,  N_TEST,  seed=2025,  desc=f"Q1(c) TEST  {N_TEST}")
print("Q1(c) saved at:", Q1C_ROOT)
```

Dataset Sample from Q1

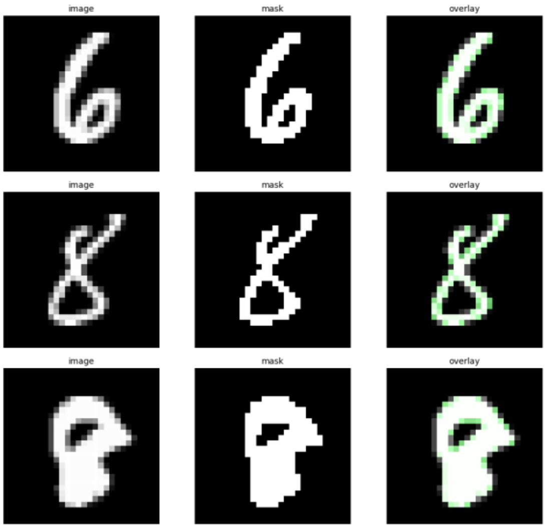


Figure 1: Dataset samples from q1(a)

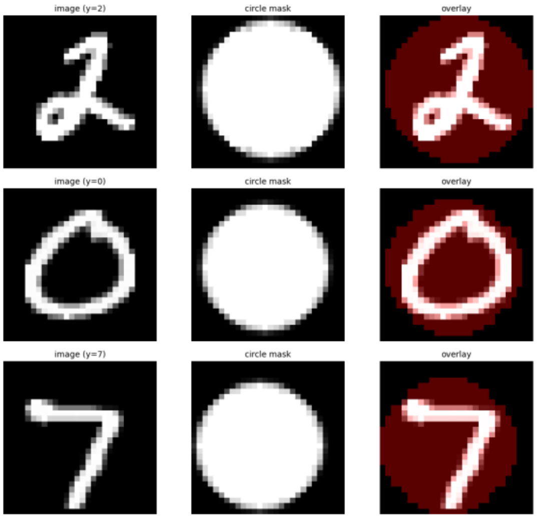


Figure 2: Dataset samples from q1(b)

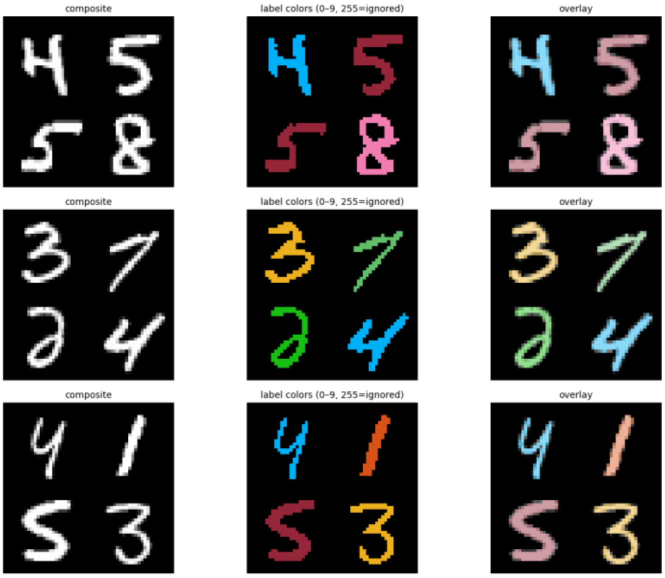

composite
label colors (0-9, 255=ignored)
overlay
composite
label colors (0-9, 255=ignored)
overlay
composite
label colors (0-9, 255=ignored)
overlay

Figure 3: Dataset samples from q1(c)

Q2 code

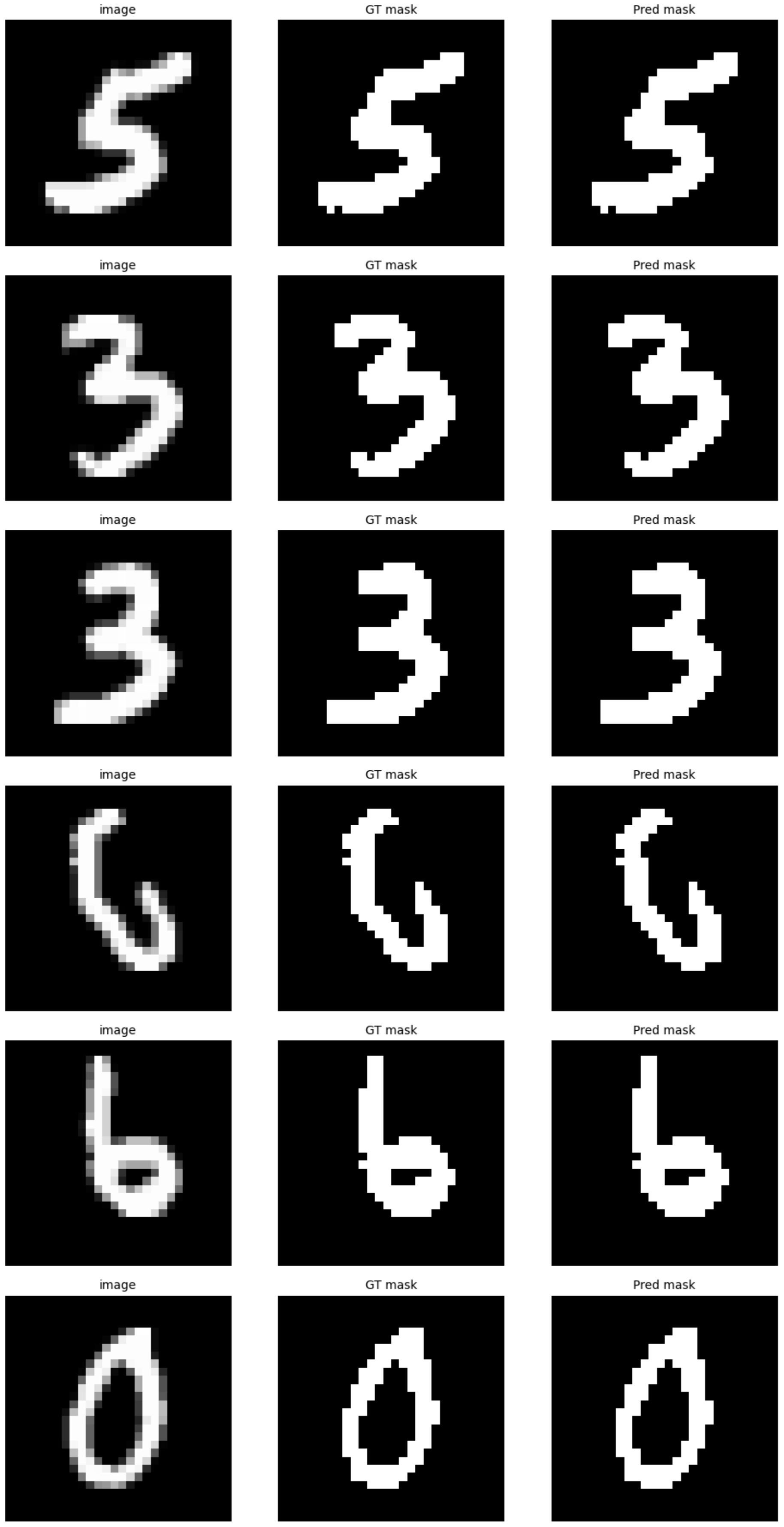
```python
import os, math, random
from pathlib import Path
import numpy as np
import cv2 as cv
import torch
import torch.nn as nn
from torch.utils.data import Dataset, DataLoader
import torch.nn.functional as F
from tqdm import tqdm
import matplotlib.pyplot as plt

# ---------- Paths ----------
LOCAL = Path("/content/ee604/q1a_pairs")
DRIVE = Path("/content/drive/MyDrive/ee604/q1a_pairs")
ROOT  = LOCAL if LOCAL.exists() else DRIVE
TRDIR = ROOT / "train"
TEDIR = ROOT / "test"
assert TRDIR.exists() and TEDIR.exists(), f"Q1(a) not found at {ROOT}"

# ---------- Dataset ----------
class Q1aPairs(Dataset):
    def __init__(self, root, augment=False):
        self.root = Path(root)
        self.imgs = sorted(self.root.glob("*_img.png"))
        self.augment = augment

    def __len__(self): return len(self.imgs)

    def __getitem__(self, idx):
        ip = self.imgs[idx]
        mp = ip.with_name(ip.name.replace("_img.png", "_mask.png"))
        img = cv.imread(str(ip), cv.IMREAD_GRAYSCALE)       # (28,28) uint8
        msk = cv.imread(str(mp), cv.IMREAD_GRAYSCALE)       # (28,28) uint8 {0,255}

        # light augment (optional)
        if self.augment and random.random() < 0.5:
            img = np.ascontiguousarray(np.fliplr(img))
            msk = np.ascontiguousarray(np.fliplr(msk))
        if self.augment and random.random() < 0.5:
            img = np.ascontiguousarray(np.flipud(img))
            msk = np.ascontiguousarray(np.flipud(msk))

        # to tensors in [0,1]
        img = torch.from_numpy(img).float().unsqueeze(0) / 255.0       # (1,28,28)
        msk = torch.from_numpy((msk > 0).astype(np.float32)).unsqueeze(0)   # (1,28,28) {0,1}
        return img, msk
```

```
# ---------- Model: U-Net  ----------
class DoubleConv(nn.Module):
    def __init__(self, c_in, c_out):
        super().__init__()
        self.block = nn.Sequential(
            nn.Conv2d(c_in, c_out, 3, padding=1), nn.BatchNorm2d(c_out), nn.ReLU(inplace=True),
            nn.Conv2d(c_out, c_out, 3, padding=1), nn.BatchNorm2d(c_out), nn.ReLU(inplace=True),
        )
    def forward(self, x): return self.block(x)

class TinyUNet(nn.Module):
    def __init__(self, base=16):
        super().__init__()
        self.d1 = DoubleConv(1, base)          # 28x28
        self.p1 = nn.MaxPool2d(2)              # 14x14
        self.d2 = DoubleConv(base, base*2)     # 14x14
        self.p2 = nn.MaxPool2d(2)              # 7x7
        self.b  = DoubleConv(base*2, base*4)   # 7x7

        self.up2 = nn.Upsample(scale_factor=2, mode='bilinear', align_corners=False)  # 14x14
        self.u2  = DoubleConv(base*4 + base*2, base*2)
        self.up1 = nn.Upsample(scale_factor=2, mode='bilinear', align_corners=False)  # 28x28
        self.u1  = DoubleConv(base*2 + base, base)

        self.out = nn.Conv2d(base, 1, kernel_size=1)

    def forward(self, x):
        x1 = self.d1(x)
        x2 = self.d2(self.p1(x1))
        xb = self.b(self.p2(x2))
        x  = self.up2(xb); x = self.u2(torch.cat([x, x2], dim=1))
        x  = self.up1(x);  x = self.u1(torch.cat([x, x1], dim=1))
        return self.out(x)   # logits

# ---------- IoU metric ----------
@torch.no_grad()
def iou_score(pred_logits, target, thr=0.5, eps=1e-7):
    # pred_logits: (B,1,H,W), target: (B,1,H,W) in {0,1}
    pred = (torch.sigmoid(pred_logits) > thr).float()
    inter = (pred * target).sum(dim=(1,2,3))
    union = (pred + target - pred*target).sum(dim=(1,2,3))
    iou = (inter + eps) / (union + eps)
    return iou.mean().item()

# ---------- Training ----------
def train_q2(epochs=40, batch_size=64, lr=1e-3, weight_decay=1e-5, base_ch=16, aug=True):
    device = torch.device("cuda" if torch.cuda.is_available() else "cpu")
    ds_tr = Q1aPairs(TRDIR, augment=aug)
    ds_te = Q1aPairs(TEDIR, augment=False)
    dl_tr = DataLoader(ds_tr, batch_size=batch_size, shuffle=True, num_workers=2, pin_memory=True)
    dl_te = DataLoader(ds_te, batch_size=1024, shuffle=False, num_workers=2, pin_memory=True)

    model = TinyUNet(base=base_ch).to(device)
    opt = torch.optim.AdamW(model.parameters(), lr=lr, weight_decay=weight_decay)
    # BCEWithLogits is perfect for foreground extraction
    loss_fn = nn.BCEWithLogitsLoss()

    best_iou, best_state = 0.0, None
    for ep in range(1, epochs+1):
        model.train()
        running = 0.0
        for x, y in tqdm(dl_tr, desc=f"Epoch {ep}/{epochs}", leave=False):
            x = x.to(device, non_blocking=True)
            y = y.to(device, non_blocking=True)
            opt.zero_grad(set_to_none=True)
            logits = model(x)
            loss = loss_fn(logits, y)
            loss.backward()
            opt.step()
            running += loss.item() * x.size(0)
        tr_loss = running / len(ds_tr)

        # eval IoU
        model.eval()
        ious = []
        with torch.no_grad():
            for x, y in dl_te:
                x = x.to(device, non_blocking=True)
                y = y.to(device, non_blocking=True)
                logits = model(x)
                ious.append(iou_score(logits, y))
        te_iou = float(np.mean(ious))

        print(f"[ep {ep}] train_loss={tr_loss:.4f}  test_IoU={te_iou:.4f}")
        if te_iou > best_iou:
            best_iou, best_state = te_iou, {k:v.cpu() for k,v in model.state_dict().items()}

    if best_state is not None:
        model.load_state_dict(best_state)
    print(f"Best test IoU: {best_iou:.4f}")
    return model, best_iou

model, best_iou = train_q2()
```

Training logs from Q2 model (Result: `Best test IoU: 0.9968`)

```
[ep 1] train_loss=0.1283  test_IoU=0.9907
[ep 2] train_loss=0.0074  test_IoU=0.9922
[ep 3] train_loss=0.0039  test_IoU=0.9933
[ep 4] train_loss=0.0030  test_IoU=0.9917
[ep 5] train_loss=0.0025  test_IoU=0.9926
[ep 6] train_loss=0.0022  test_IoU=0.9930
[ep 7] train_loss=0.0020  test_IoU=0.9942
[ep 8] train_loss=0.0019  test_IoU=0.9926
[ep 9] train_loss=0.0017  test_IoU=0.9947
[ep 10] train_loss=0.0016  test_IoU=0.9935
[ep 11] train_loss=0.0016  test_IoU=0.9934
[ep 12] train_loss=0.0015  test_IoU=0.9957
[ep 13] train_loss=0.0015  test_IoU=0.9939
[ep 14] train_loss=0.0014  test_IoU=0.9948
[ep 15] train_loss=0.0014  test_IoU=0.9938
[ep 16] train_loss=0.0014  test_IoU=0.9890
[ep 17] train_loss=0.0014  test_IoU=0.9953
[ep 18] train_loss=0.0013  test_IoU=0.9958
[ep 19] train_loss=0.0013  test_IoU=0.9960
[ep 20] train_loss=0.0013  test_IoU=0.9963
[ep 21] train_loss=0.0013  test_IoU=0.9963
[ep 22] train_loss=0.0012  test_IoU=0.9960
[ep 23] train_loss=0.0013  test_IoU=0.9909
[ep 24] train_loss=0.0012  test_IoU=0.9954
[ep 25] train_loss=0.0012  test_IoU=0.9962
[ep 26] train_loss=0.0011  test_IoU=0.9958
[ep 27] train_loss=0.0011  test_IoU=0.9963
[ep 28] train_loss=0.0011  test_IoU=0.9917
[ep 29] train_loss=0.0011  test_IoU=0.9966
[ep 30] train_loss=0.0011  test_IoU=0.9964
[ep 31] train_loss=0.0011  test_IoU=0.9968
[ep 32] train_loss=0.0010  test_IoU=0.9963
[ep 33] train_loss=0.0011  test_IoU=0.9964
[ep 34] train_loss=0.0011  test_IoU=0.9964
[ep 35] train_loss=0.0010  test_IoU=0.9965
[ep 36] train_loss=0.0010  test_IoU=0.9958
[ep 37] train_loss=0.0010  test_IoU=0.9934
[ep 38] train_loss=0.0010  test_IoU=0.9946
[ep 39] train_loss=0.0010  test_IoU=0.9965
[ep 40] train_loss=0.0010  test_IoU=0.9967
Best test IoU: 0.9968
```

TESTED SAMPLES FROM Q2 MODEL



Q3 code

```
import os, math, random, shutil
from pathlib import Path
import numpy as np
import cv2 as cv
import torch
import torch.nn as nn
import torch.nn.functional as F
from torch.utils.data import Dataset, DataLoader
from tqdm import tqdm
import csv

# ---------------- Paths ----------------
LOCAL_Q1B = Path("/content/ee604/q1b_pairs")
DRIVE_Q1B = Path("/content/drive/MyDrive/ee604/q1b_pairs")
Q1B_ROOT  = LOCAL_Q1B if LOCAL_Q1B.exists() else DRIVE_Q1B
TRDIR = Q1B_ROOT / "train"
TEDIR = Q1B_ROOT / "test"
assert (TRDIR / "manifest.csv").exists() and (TEDIR / "manifest.csv").exists(), "Q1(b) not found."

# Where to save best model
LOCAL_MODEL_DIR = Path("/content/ee604/models"); LOCAL_MODEL_DIR.mkdir(parents=True, exist_ok=True)
BEST_LOCAL = LOCAL_MODEL_DIR / "q3_best.pt"
DRIVE_MODEL_DIR = Path("/content/drive/MyDrive/ee604/models"); DRIVE_MODEL_DIR.mkdir(parents=True,
exist_ok=True)
BEST_DRIVE = DRIVE_MODEL_DIR / BEST_LOCAL.name

# ---------------- Dataset ----------------
class Q1bCirclization(Dataset):
    """
    Returns:
      img  : float tensor (1,28,28) in [0,1]
      cmsk : float tensor (1,28,28) in {0,1}
      y    : long scalar in [0..9]
    """
    def __init__(self, split_dir: Path):
        self.rows = []
        man = split_dir / "manifest.csv"
        with open(man, newline="") as f:
            r = csv.reader(f)
            header = next(r, None)  # ["img_path","circle_mask_path","label"]
            for row in r:
                self.rows.append((row[0], row[1], int(row[2])))

    def __len__(self): return len(self.rows)

    def __getitem__(self, idx):
        p_img, p_cmsk, y = self.rows[idx]
        img  = cv.imread(p_img,  cv.IMREAD_GRAYSCALE)
        cmsk = cv.imread(p_cmsk, cv.IMREAD_GRAYSCALE)
        # to tensors
        img_t  = torch.from_numpy(img).float().unsqueeze(0) / 255.0          # (1,28,28)
        cmsk_t = torch.from_numpy((cmsk > 0).astype(np.float32)).unsqueeze(0)# (1,28,28)
        y_t    = torch.tensor(y, dtype=torch.long)
        return img_t, cmsk_t, y_t

# ---------------- Model (shared encoder + 2 heads) ----------------
class DoubleConv(nn.Module):
    def __init__(self, c_in, c_out):
        super().__init__()
        self.net = nn.Sequential(
            nn.Conv2d(c_in, c_out, 3, padding=1), nn.BatchNorm2d(c_out), nn.ReLU(inplace=True),
            nn.Conv2d(c_out, c_out, 3, padding=1), nn.BatchNorm2d(c_out), nn.ReLU(inplace=True),
        )
    def forward(self, x): return self.net(x)

class CirclizationNet(nn.Module):
    """
    Shared encoder -> (a) class head, (b) mask head
    Small UNet-ish decoder for mask; global pooled features for class.
    """
    def __init__(self, base=16, num_classes=10):
        super().__init__()
        # encoder
        self.d1 = DoubleConv(1, base)          # 28x28
        self.p1 = nn.MaxPool2d(2)              # 14x14
        self.d2 = DoubleConv(base, base*2)     # 14x14
        self.p2 = nn.MaxPool2d(2)              # 7x7
        self.b  = DoubleConv(base*2, base*4)   # 7x7

        # decoder for mask
        self.up2 = nn.Upsample(scale_factor=2, mode='bilinear', align_corners=False) # 14x14
        self.u2  = DoubleConv(base*4 + base*2, base*2)
        self.up1 = nn.Upsample(scale_factor=2, mode='bilinear', align_corners=False) # 28x28
        self.u1  = DoubleConv(base*2 + base, base)
        self.mask_out = nn.Conv2d(base, 1, kernel_size=1)  # logits

        # class head
        self.cls_pool = nn.AdaptiveAvgPool2d((1,1))
        self.cls_fc   = nn.Linear(base*4, num_classes)

    def forward(self, x):
        x1 = self.d1(x)              # 28x28
        x2 = self.d2(self.p1(x1))    # 14x14
        xb = self.b(self.p2(x2))     # 7x7
        # class path
        g = self.cls_pool(xb).flatten(1)     # (B, base*4)
        logits_cls = self.cls_fc(g)          # (B,10)

        # mask path
        y = self.up2(xb); y = self.u2(torch.cat([y, x2], dim=1))
        y = self.up1(y);  y = self.u1(torch.cat([y, x1], dim=1))
        logits_mask = self.mask_out(y)       # (B,1,28,28)
        return logits_cls, logits_mask

# ---------------- Metrics ----------------
@torch.no_grad()
def gated_iou(pred_cls_logits, pred_mask_logits, y_true, m_true, thr=0.5, eps=1e-7):
    """
    Gated IoU: IoU is 0 if predicted class != y_true; else IoU(mask_pred, m_true).
    """
    # class predictions
    y_pred = pred_cls_logits.argmax(dim=1)  # (B,)
    cls_ok = (y_pred == y_true).float()     # (B,)

    # mask predictions
    m_pred = (torch.sigmoid(pred_mask_logits) > thr).float()  # (B,1,H,W)
    inter = (m_pred * m_true).sum(dim=(1,2,3))
    union = (m_pred + m_true - m_pred*m_true).sum(dim=(1,2,3))
    iou = (inter + eps) / (union + eps)                       # (B,)

    # gate by class correctness
    gated = iou * cls_ok
    return gated.mean().item()

# ---------------- Train/Eval ----------------
def train_q3(epochs=8, batch_size=256, lr=1e-3, wd=1e-5, base_ch=16, lambda_mask=1.0, lambda_cls=1.0):
    device = torch.device("cuda" if torch.cuda.is_available() else "cpu")
    ds_tr = Q1bCirclization(TRDIR)
    ds_te = Q1bCirclization(TEDIR)

    # show load progress once
    print(f"Train samples: {len(ds_tr)} | Test samples: {len(ds_te)}")

    dl_tr = DataLoader(ds_tr, batch_size=batch_size, shuffle=True,  num_workers=2, pin_memory=True)
    dl_te = DataLoader(ds_te, batch_size=1024,      shuffle=False, num_workers=2, pin_memory=True)

    model = CirclizationNet(base=base_ch).to(device)
    opt   = torch.optim.AdamW(model.parameters(), lr=lr, weight_decay=wd)
    loss_mask = nn.BCEWithLogitsLoss()
    loss_cls  = nn.CrossEntropyLoss()

    best_iou, best_state = 0.0, None
```

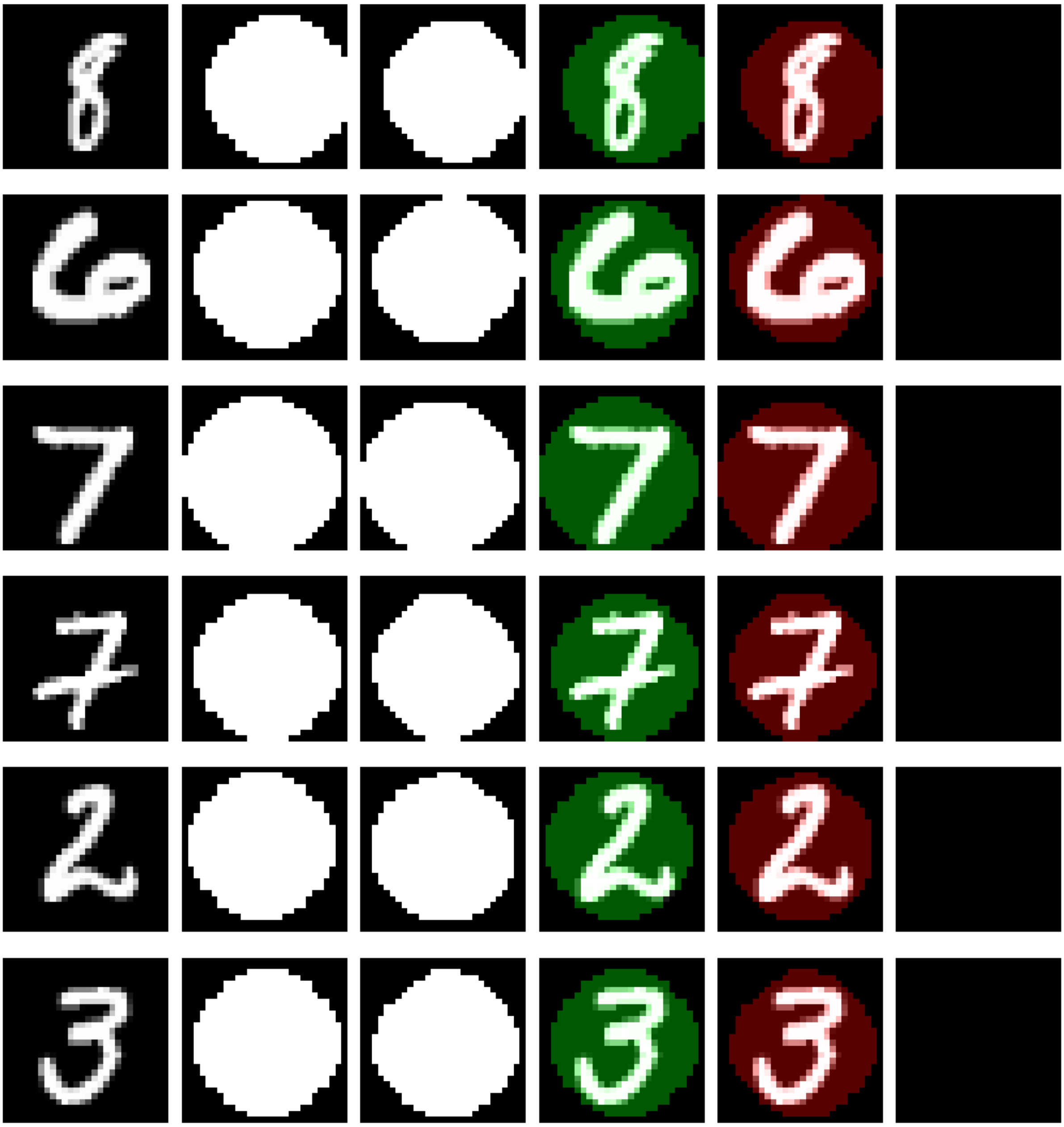
```
for ep in range(1, epochs+1):
    model.train()
    running = 0.0
    pbar = tqdm(dl_tr, desc=f"Epoch {ep}/{epochs} [train]")
    for img, cmsk, y in pbar:
        img = img.to(device, non_blocking=True)
        cmsk = cmsk.to(device, non_blocking=True)
        y = y.to(device, non_blocking=True)

        opt.zero_grad(set_to_none=True)
        logits_cls, logits_mask = model(img)
        L = lambda_mask * loss_mask(logits_mask, cmsk) + lambda_cls * loss_cls(logits_cls, y)
        L.backward()
        opt.step()
        running += L.item() * img.size(0)
        pbar.set_postfix(loss=f"{L.item():.4f}")

    tr_loss = running / len(ds_tr)

    # eval with gated IoU
    model.eval()
    ious = []
    pbar = tqdm(dl_te, desc=f"Epoch {ep}/{epochs} [eval]")
    with torch.no_grad():
        for img, cmsk, y in pbar:
            img = img.to(device, non_blocking=True)
            cmsk = cmsk.to(device, non_blocking=True)
            y = y.to(device, non_blocking=True)
            logits_cls, logits_mask = model(img)
            giou = gated_iou(logits_cls, logits_mask, y, cmsk, thr=0.5)
            ious.append(giou)
            pbar.set_postfix(gIoU=f"{giou:.4f}")
    te_giou = float(np.mean(ious))
    print(f"[ep {ep}] train_loss={tr_loss:.4f}  test_gated_IoU={te_giou:.4f}")

    if te_giou > best_iou:
        best_iou, best_state = te_giou, {k: v.cpu() for k, v in model.state_dict().items()}

if best_state is not None:
    model.load_state_dict(best_state)
    torch.save(model.state_dict(), BEST_LOCAL)
    # copy to Drive
    shutil.copy2(BEST_LOCAL, BEST_DRIVE)
    print(f"Saved best model (gIoU={best_iou:.4f}) to:\n- Local: {BEST_LOCAL}\n- Drive: {BEST_DRIVE}")
else:
    print("No improvement recorded.")
    return model, best_iou


# -------- run training --------
model_q3, best_giou = train_q3(
    epochs=15,
    batch_size=256,
    lr=1e-3,
    wd=1e-5,
    base_ch=16,
    lambda_mask=1.0,
    lambda_cls=1.0
)
```

Training logs from Q3 model (Result: Best IoU=0.9250)

```
Train samples: 60000 | Test samples: 10000
Epoch 1/15 [train]: 100%|██████████| 235/235 [05:58<00:00,  1.53s/it, loss=0.2382]
Epoch 1/15 [eval]: 100%|██████████| 10/10 [00:40<00:00,  4.08s/it, gIoU=0.8956]
[ep 1] train_loss=0.7450  test_gated_IoU=0.8886
Epoch 2/15 [train]: 100%|██████████| 235/235 [05:38<00:00,  1.44s/it, loss=0.1631]
Epoch 2/15 [eval]: 100%|██████████| 10/10 [00:28<00:00,  2.80s/it, gIoU=0.9105]
[ep 2] train_loss=0.2006  test_gated_IoU=0.9056
Epoch 3/15 [train]: 100%|██████████| 235/235 [05:44<00:00,  1.46s/it, loss=0.1362]
Epoch 3/15 [eval]: 100%|██████████| 10/10 [00:26<00:00,  2.62s/it, gIoU=0.9136]
[ep 3] train_loss=0.1596  test_gated_IoU=0.9093
Epoch 4/15 [train]: 100%|██████████| 235/235 [05:40<00:00,  1.45s/it, loss=0.1827]
Epoch 4/15 [eval]: 100%|██████████| 10/10 [00:28<00:00,  2.87s/it, gIoU=0.9118]
[ep 4] train_loss=0.1419  test_gated_IoU=0.9122
Epoch 5/15 [train]: 100%|██████████| 235/235 [05:44<00:00,  1.47s/it, loss=0.1784]
Epoch 5/15 [eval]: 100%|██████████| 10/10 [00:26<00:00,  2.65s/it, gIoU=0.9164]
[ep 5] train_loss=0.1311  test_gated_IoU=0.9107
Epoch 6/15 [train]: 100%|██████████| 235/235 [05:40<00:00,  1.45s/it, loss=0.1028]
Epoch 6/15 [eval]: 100%|██████████| 10/10 [00:27<00:00,  2.76s/it, gIoU=0.9194]
[ep 6] train_loss=0.1249  test_gated_IoU=0.9186
Epoch 7/15 [train]: 100%|██████████| 235/235 [05:40<00:00,  1.45s/it, loss=0.1117]
Epoch 7/15 [eval]: 100%|██████████| 10/10 [00:28<00:00,  2.83s/it, gIoU=0.9241]
[ep 7] train_loss=0.1176  test_gated_IoU=0.9175
Epoch 8/15 [train]: 100%|██████████| 235/235 [05:38<00:00,  1.44s/it, loss=0.1050]
Epoch 8/15 [eval]: 100%|██████████| 10/10 [00:27<00:00,  2.79s/it, gIoU=0.9223]
[ep 8] train_loss=0.1149  test_gated_IoU=0.9157
Epoch 9/15 [train]: 100%|██████████| 235/235 [05:39<00:00,  1.44s/it, loss=0.1198]
Epoch 9/15 [eval]: 100%|██████████| 10/10 [00:27<00:00,  2.78s/it, gIoU=0.9220]
[ep 9] train_loss=0.1118  test_gated_IoU=0.9188
Epoch 10/15 [train]: 100%|██████████| 235/235 [05:39<00:00,  1.44s/it, loss=0.1051]
Epoch 10/15 [eval]: 100%|██████████| 10/10 [00:27<00:00,  2.73s/it, gIoU=0.9227]
[ep 10] train_loss=0.1085  test_gated_IoU=0.9186
Epoch 11/15 [train]: 100%|██████████| 235/235 [05:37<00:00,  1.44s/it, loss=0.1149]
Epoch 11/15 [eval]: 100%|██████████| 10/10 [00:27<00:00,  2.70s/it, gIoU=0.9235]
[ep 11] train_loss=0.1053  test_gated_IoU=0.9226
Epoch 12/15 [train]: 100%|██████████| 235/235 [05:40<00:00,  1.45s/it, loss=0.0963]
Epoch 12/15 [eval]: 100%|██████████| 10/10 [00:27<00:00,  2.75s/it, gIoU=0.9272]
[ep 12] train_loss=0.1027  test_gated_IoU=0.9235
Epoch 13/15 [train]: 100%|██████████| 235/235 [05:38<00:00,  1.44s/it, loss=0.0992]
Epoch 13/15 [eval]: 100%|██████████| 10/10 [00:27<00:00,  2.78s/it, gIoU=0.9272]
[ep 13] train_loss=0.1015  test_gated_IoU=0.9245
Epoch 14/15 [train]: 100%|██████████| 235/235 [05:38<00:00,  1.44s/it, loss=0.0974]
Epoch 14/15 [eval]: 100%|██████████| 10/10 [00:28<00:00,  2.89s/it, gIoU=0.9275]
[ep 14] train_loss=0.0990  test_gated_IoU=0.9222
Epoch 15/15 [train]: 100%|██████████| 235/235 [05:39<00:00,  1.44s/it, loss=0.0949]
Epoch 15/15 [eval]: 100%|██████████| 10/10 [00:27<00:00,  2.78s/it, gIoU=0.9291]
[ep 15] train_loss=0.0974  test_gated_IoU=0.9250
Saved best model (gIoU=0.9250) to:
- Local: /content/ee604/models/q3_best.pt
- Drive: /content/drive/MyDrive/ee604/models/q3_best.pt
```

TESTED SAMPLES FROM Q3 MODEL

Q3 sanity: image | GT circle | Pred circle | GT overlay | Pred overlay | spacer



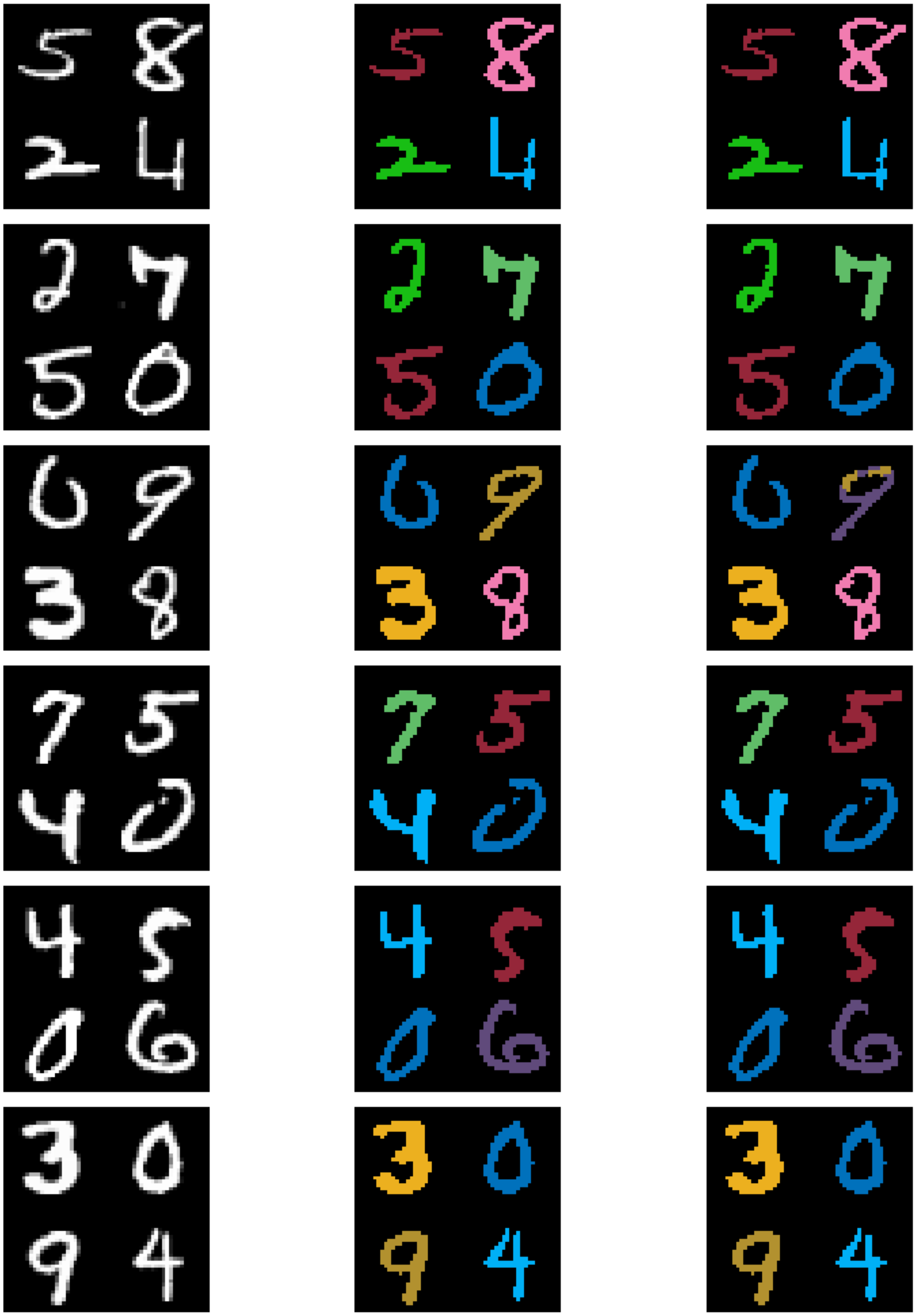
Q4 Code

```
import os, gc, ctypes, shutil, random
from pathlib import Path
import numpy as np
import cv2 as cv
import torch
import torch.nn as nn
from torch.utils.data import Dataset, DataLoader
from tqdm import tqdm

LOCAL_Q1C = Path("/content/ee604/q1c_semseg")
DRIVE_Q1C = Path("/content/drive/MyDrive/ee604/q1c_semseg")
Q1C_ROOT  = LOCAL_Q1C if LOCAL_Q1C.exists() else DRIVE_Q1C
TR_IMG, TR_LBL = Q1C_ROOT/"train/images", Q1C_ROOT/"train/labels"
TE_IMG, TE_LBL = Q1C_ROOT/"test/images",  Q1C_ROOT/"test/labels"

class Q1c(Dataset):
    def __init__(self, img_dir, lbl_dir, limit=None, augment=False):
        self.imgs = sorted(Path(img_dir).glob("*.png"))
        if limit is not None: self.imgs = self.imgs[:int(limit)]
        self.lbl_dir = Path(lbl_dir); self.augment = augment
    def __len__(self): return len(self.imgs)
    def __getitem__(self, idx):
        ip = self.imgs[idx]; lp = self.lbl_dir / ip.name
        img = cv.imread(str(ip), cv.IMREAD_GRAYSCALE)
        lbl = cv.imread(str(lp), cv.IMREAD_GRAYSCALE).copy()
        lbl[lbl == 255] = 10  # map ignore to class 10 (background)
        if self.augment and random.random() < 0.5:
            img = np.ascontiguousarray(np.fliplr(img)); lbl = np.ascontiguousarray(np.fliplr(lbl))
        if self.augment and random.random() < 0.5:
            img = np.ascontiguousarray(np.flipud(img)); lbl = np.ascontiguousarray(np.flipud(lbl))
        img_t = torch.from_numpy(img).float().unsqueeze(0) / 255.0
        lbl_t = torch.from_numpy(lbl.astype(np.int64))
        return img_t, lbl_t

class DoubleConv(nn.Module):
    def __init__(self, c_in, c_out):
        super().__init__()
        self.net = nn.Sequential(
            nn.Conv2d(c_in, c_out, 3, padding=1), nn.BatchNorm2d(c_out), nn.ReLU(inplace=True),
            nn.Conv2d(c_out, c_out, 3, padding=1), nn.BatchNorm2d(c_out), nn.ReLU(inplace=True),
        )
    def forward(self, x): return self.net(x)

class LiteUNetMC(nn.Module):
    def __init__(self, base=24, n_classes=10):
        super().__init__()
        self.d1 = DoubleConv(1, base); self.p1 = nn.MaxPool2d(2)
        self.d2 = DoubleConv(base, base*2); self.p2 = nn.MaxPool2d(2)
        self.b  = DoubleConv(base*2, base*4)
        self.up2 = nn.Upsample(scale_factor=2, mode='bilinear', align_corners=False)
        self.u2  = DoubleConv(base*4 + base*2, base*2)
        self.up1 = nn.Upsample(scale_factor=2, mode='bilinear', align_corners=False)
        self.u1  = DoubleConv(base*2 + base, base)
        self.out = nn.Conv2d(base, n_classes, 1)
    def forward(self, x):
        x1 = self.d1(x); x2 = self.d2(self.p1(x1)); xb = self.b(self.p2(x2))
        y  = self.up2(xb); y = self.u2(torch.cat([y, x2], dim=1))
        y  = self.up1(y);  y = self.u1(torch.cat([y, x1], dim=1))
        return self.out(y)

@torch.no_grad()
def dice_mc(logits, target, eps=1e-7):
    pred = logits.argmax(1)
    dices = []
    for c in range(11):
        p = (pred == c); t = (target == c)
        if p.any() or t.any():
            inter = (p & t).sum().item()
            denom = p.sum().item() + t.sum().item()
            dices.append((2*inter + eps) / (denom + eps))
    return float(np.mean(dices)) if dices else 0.0

def train_q4(
    epochs=10, base_ch=24, lr=1e-3, wd=1e-5,
    batch_size=1024, limit_train=None, limit_test=None
):
    device = torch.device("cuda" if torch.cuda.is_available() else "cpu")
    torch.backends.cudnn.benchmark = True
    use_amp = torch.cuda.is_available()

    ds_tr = Q1c(TR_IMG, TR_LBL, limit=limit_train, augment=True)
    ds_te = Q1c(TE_IMG, TE_LBL, limit=limit_test,  augment=False)
    print(f"Train={len(ds_tr)}  Test={len(ds_te)}")

    dl_tr = DataLoader(ds_tr, batch_size=batch_size, shuffle=True,
                       num_workers=0, pin_memory=False, persistent_workers=False)
    dl_te = DataLoader(ds_te, batch_size=1024, shuffle=False,
                       num_workers=0, pin_memory=False, persistent_workers=False)

    model = LiteUNetMC(base=base_ch, n_classes=11).to(device).to(memory_format=torch.channels_last)
    loss_ce = nn.CrossEntropyLoss()  # no ignore index
    opt = torch.optim.AdamW(model.parameters(), lr=lr, weight_decay=wd)
    scaler = torch.amp.GradScaler('cuda', enabled=use_amp)

    LOCAL_MODEL_DIR = Path("/content/ee604/models"); LOCAL_MODEL_DIR.mkdir(parents=True, exist_ok=True)
    DRIVE_MODEL_DIR = Path("/content/drive/MyDrive/ee604/models"); DRIVE_MODEL_DIR.mkdir(parents=True, exist_ok=True)
    BEST_LOCAL  = LOCAL_MODEL_DIR / "q4_semseg_best_11cls.pt"
    FINAL_LOCAL = LOCAL_MODEL_DIR / "q4_semseg_final_11cls.pt"
    BEST_DRIVE  = DRIVE_MODEL_DIR / BEST_LOCAL.name
    FINAL_DRIVE = DRIVE_MODEL_DIR / FINAL_LOCAL.name

    best_dice = -1.0

    for ep in range(1, epochs+1):
        model.train()
        run_loss, seen = 0.0, 0
        for img, lbl in tqdm(dl_tr, desc=f"Epoch {ep}/{epochs} [train]"):
            img = img.to(device, memory_format=torch.channels_last)
            lbl = lbl.to(device)

            opt.zero_grad(set_to_none=True)
            with torch.amp.autocast('cuda', enabled=use_amp):
                logits = model(img)
                L = loss_ce(logits, lbl)
            scaler.scale(L).backward()
            scaler.step(opt); scaler.update()

            bs = img.size(0); run_loss += L.item() * bs; seen += bs
            del img, lbl, logits, L
            if torch.cuda.is_available(): torch.cuda.empty_cache()

        tr_loss = run_loss / max(1, seen)

        # eval
        model.eval()
        dice_sum = 0.0; n_batches = 0
        with torch.no_grad():
            for img, lbl in tqdm(dl_te, desc=f"Epoch {ep}/{epochs} [eval]"):
                img = img.to(device, memory_format=torch.channels_last)
                lbl = lbl.to(device)
                with torch.amp.autocast('cuda', enabled=use_amp):
                    logits = model(img)
                dice_sum += dice_mc(logits, lbl)
                n_batches += 1
                del img, lbl, logits
        te_dice = dice_sum / max(1, n_batches)
        print(f"[ep {ep}] train_loss={tr_loss:.4f}  test_Dice(11cls)={te_dice:.4f}")

        if te_dice > best_dice:
            best_dice = te_dice
            torch.save(model.state_dict(), BEST_LOCAL)
            shutil.copy2(BEST_LOCAL, BEST_DRIVE)
            print("NEW BEST →", BEST_DRIVE)


    torch.save(model.state_dict(), FINAL_LOCAL)
    shutil.copy2(FINAL_LOCAL, FINAL_DRIVE)
    print("FINAL →", FINAL_DRIVE)
    return model, best_dice


model_q4_11, best_dice = train_q4()
print("Best Dice (11 classes):", best_dice)
```

Training logs from Q4 model (Result: `Best Dice=0.9765453269441279`)

```
Train=250000  Test=10000
Epoch 1/10 [train]: 100%|██████████| 245/245 [02:51<00:00,  1.43it/s]
Epoch 1/10 [eval]: 100%|██████████| 10/10 [00:04<00:00,  2.16it/s]
[ep 1] train_loss=0.7462  test_Dice(11cls)=0.8666
NEW BEST → /content/drive/MyDrive/ee604/models/q4_semseg_best_11cls.pt
Epoch 2/10 [train]: 100%|██████████| 245/245 [02:34<00:00,  1.58it/s]
Epoch 2/10 [eval]: 100%|██████████| 10/10 [00:03<00:00,  2.60it/s]
[ep 2] train_loss=0.0792  test_Dice(11cls)=0.9091
NEW BEST → /content/drive/MyDrive/ee604/models/q4_semseg_best_11cls.pt
Epoch 3/10 [train]: 100%|██████████| 245/245 [02:41<00:00,  1.51it/s]
Epoch 3/10 [eval]: 100%|██████████| 10/10 [00:03<00:00,  2.57it/s]
[ep 3] train_loss=0.0316  test_Dice(11cls)=0.9588
NEW BEST → /content/drive/MyDrive/ee604/models/q4_semseg_best_11cls.pt
Epoch 4/10 [train]: 100%|██████████| 245/245 [02:38<00:00,  1.55it/s]
Epoch 4/10 [eval]: 100%|██████████| 10/10 [00:03<00:00,  2.61it/s]
[ep 4] train_loss=0.0194  test_Dice(11cls)=0.9661
NEW BEST → /content/drive/MyDrive/ee604/models/q4_semseg_best_11cls.pt
Epoch 5/10 [train]: 100%|██████████| 245/245 [02:36<00:00,  1.57it/s]
Epoch 5/10 [eval]: 100%|██████████| 10/10 [00:04<00:00,  2.30it/s]
[ep 5] train_loss=0.0138  test_Dice(11cls)=0.9645
Epoch 6/10 [train]: 100%|██████████| 245/245 [02:36<00:00,  1.56it/s]
Epoch 6/10 [eval]: 100%|██████████| 10/10 [00:03<00:00,  2.56it/s]
[ep 6] train_loss=0.0105  test_Dice(11cls)=0.9496
Epoch 7/10 [train]: 100%|██████████| 245/245 [02:36<00:00,  1.56it/s]
Epoch 7/10 [eval]: 100%|██████████| 10/10 [00:03<00:00,  2.66it/s]
[ep 7] train_loss=0.0085  test_Dice(11cls)=0.9765
NEW BEST → /content/drive/MyDrive/ee604/models/q4_semseg_best_11cls.pt
Epoch 8/10 [train]: 100%|██████████| 245/245 [02:36<00:00,  1.56it/s]
Epoch 8/10 [eval]: 100%|██████████| 10/10 [00:03<00:00,  2.52it/s]
[ep 8] train_loss=0.0070  test_Dice(11cls)=0.9562
Epoch 9/10 [train]: 100%|██████████| 245/245 [02:37<00:00,  1.56it/s]
Epoch 9/10 [eval]: 100%|██████████| 10/10 [00:04<00:00,  2.36it/s]
[ep 9] train_loss=0.0061  test_Dice(11cls)=0.9675
Epoch 10/10 [train]: 100%|██████████| 245/245 [02:36<00:00,  1.56it/s]
Epoch 10/10 [eval]: 100%|██████████| 10/10 [00:03<00:00,  2.61it/s]
[ep 10] train_loss=0.0052  test_Dice(11cls)=0.9660
FINAL → /content/drive/MyDrive/ee604/models/q4_semseg_final_11cls.pt
Best Dice (11 classes): 0.9765453269441279
```

TESTED SAMPLES FROM Q4 MODEL



Q4 sanity: Image | GT (11) | Pred (11)