

# Assignment 4: Implementing LeNet-5 and Hyperparameter Optimization

## Part 1 - Classic LeNet-5 Implementation

### Introduction

In this notebook, the classic LeNet-5 architecture is implemented from scratch as described by LeCun et al. (1998). The goal is to reproduce the architecture without modern deep learning techniques (like Batch Norm, Dropout, or Adam) and achieve at least 98% accuracy on the MNIST test set.

#### Requirements:

- Input size: 32x32 (requires resizing MNIST)
- Activation: Tanh (Original) instead of ReLU
- Pooling: Average Pooling instead of Max Pooling
- Optimizer: SGD

### Imports and Setup

```
import torch
import torch.nn as nn
import torch.optim as optim
import torchvision
import torchvision.transforms as transforms
from torch.utils.data import DataLoader
import matplotlib.pyplot as plt
import numpy as np

# Set device
device = torch.device('cuda' if torch.cuda.is_available() else 'cpu')
print(f"Using device: {device}")

# Reproducibility
torch.manual_seed(42)

Using device: cpu

<torch._C.Generator at 0x7a0eaa49f730>
```

### Data Loading (MNIST)

```
# LeNet-5 expects 32x32 inputs, but MNIST is 28x28. We must resize.
transform = transforms.Compose([
    transforms.Resize((32, 32)),
```

```

        transforms.ToTensor(),
        transforms.Normalize((0.1307,), (0.3081,)) # Standard MNIST
    mean/std
])

# Load Datasets (Complete dataset as per requirements)
train_dataset = torchvision.datasets.MNIST(root='./data', train=True,
download=True, transform=transform)
test_dataset = torchvision.datasets.MNIST(root='./data', train=False,
download=True, transform=transform)

# Data Loaders
train_loader = DataLoader(train_dataset, batch_size=64, shuffle=True)
test_loader = DataLoader(test_dataset, batch_size=64, shuffle=False)

print(f"Training samples: {len(train_dataset)}")
print(f"Test samples: {len(test_dataset)}")

100%|██████████| 9.91M/9.91M [00:00<00:00, 37.6MB/s]
100%|██████████| 28.9k/28.9k [00:00<00:00, 1.04MB/s]
100%|██████████| 1.65M/1.65M [00:00<00:00, 9.63MB/s]
100%|██████████| 4.54k/4.54k [00:00<00:00, 7.38MB/s]

Training samples: 60000
Test samples: 10000

```

## LeNet-5 Architecture

```

class LeNet5(nn.Module):
    def __init__(self):
        super(LeNet5, self).__init__()

        # Layer C1: Convolutional Layer (1 input -> 6 outputs, 5x5
kernel)
        self.c1 = nn.Conv2d(in_channels=1, out_channels=6,
kernel_size=5)

        # Layer S2: Subsampling (Average Pooling, 2x2, stride 2)
        # Note: Original paper used Scaled Avg Pooling, but standard
AvgPool is the accepted proxy in PyTorch
        self.s2 = nn.AvgPool2d(kernel_size=2, stride=2)

        # Layer C3: Convolutional Layer (6 inputs -> 16 outputs, 5x5
kernel)
        self.c3 = nn.Conv2d(in_channels=6, out_channels=16,
kernel_size=5)

        # Layer S4: Subsampling (Average Pooling, 2x2, stride 2)

```

```

    self.s4 = nn.AvgPool2d(kernel_size=2, stride=2)

    # Layer C5: Fully Connected (Convolutional in concept) (16*5*5
-> 120)
    self.c5 = nn.Linear(16 * 5 * 5, 120)

    # Layer F6: Fully Connected (120 -> 84)
    self.f6 = nn.Linear(120, 84)

    # Output Layer: (84 -> 10)
    self.output = nn.Linear(84, 10)

    # Activation Function: Tanh (Original LeNet used Sigmoid/Tanh,
not ReLU)
    self.act = nn.Tanh()

def forward(self, x):
    # C1 -> Tanh -> S2
    x = self.s2(self.act(self.c1(x)))

    # C3 -> Tanh -> S4
    x = self.s4(self.act(self.c3(x)))

    # Flatten
    x = x.view(-1, 16 * 5 * 5)

    # C5 -> Tanh
    x = self.act(self.c5(x))

    # F6 -> Tanh
    x = self.act(self.f6(x))

    # Output (No activation here, CrossEntropyLoss handles
Softmax)
    x = self.output(x)
    return x

model = LeNet5().to(device)
print(model)

LeNet5(
  (c1): Conv2d(1, 6, kernel_size=(5, 5), stride=(1, 1))
  (s2): AvgPool2d(kernel_size=2, stride=2, padding=0)
  (c3): Conv2d(6, 16, kernel_size=(5, 5), stride=(1, 1))
  (s4): AvgPool2d(kernel_size=2, stride=2, padding=0)
  (c5): Linear(in_features=400, out_features=120, bias=True)
  (f6): Linear(in_features=120, out_features=84, bias=True)
  (output): Linear(in_features=84, out_features=10, bias=True)
  (act): Tanh()
)

```

## Training Loop

```
# Hyperparameters
EPOCHS = 20 # As requested (20-30 reasonable)
LR = 0.01 # Standard SGD learning rate
MOMENTUM = 0.9

# Loss and Optimizer (No Adam allowed)
criterion = nn.CrossEntropyLoss()
optimizer = optim.SGD(model.parameters(), lr=LR, momentum=MOMENTUM)

# Metrics Storage
history = {
    'train_loss': [], 'train_acc': [],
    'test_loss': [], 'test_acc': []
}

print("Starting Training...")

for epoch in range(EPOCHS):
    # --- Training ---
    model.train()
    running_loss = 0.0
    correct_train = 0
    total_train = 0

    for images, labels in train_loader:
        images, labels = images.to(device), labels.to(device)

        optimizer.zero_grad()
        outputs = model(images)
        loss = criterion(outputs, labels)
        loss.backward()
        optimizer.step()

        running_loss += loss.item()
        _, predicted = torch.max(outputs.data, 1)
        total_train += labels.size(0)
        correct_train += (predicted == labels).sum().item()

    avg_train_loss = running_loss / len(train_loader)
    train_acc = 100 * correct_train / total_train

    # --- Evaluation ---
    model.eval()
    running_test_loss = 0.0
    correct_test = 0
    total_test = 0

    with torch.no_grad():
```

```

        for images, labels in test_loader:
            images, labels = images.to(device), labels.to(device)
            outputs = model(images)
            loss = criterion(outputs, labels)
            running_test_loss += loss.item()
            _, predicted = torch.max(outputs.data, 1)
            total_test += labels.size(0)
            correct_test += (predicted == labels).sum().item()

        avg_test_loss = running_test_loss / len(test_loader)
        test_acc = 100 * correct_test / total_test

    # Store metrics
    history['train_loss'].append(avg_train_loss)
    history['train_acc'].append(train_acc)
    history['test_loss'].append(avg_test_loss)
    history['test_acc'].append(test_acc)

    print(f"Epoch [{epoch+1}/{EPOCHS}] "
          f"Train Loss: {avg_train_loss:.4f} | Train Acc: "
          f"{train_acc:.2f}% | "
          f"Test Loss: {avg_test_loss:.4f} | Test Acc: {test_acc:.2f}%
          ")

print("Training Completed.")

Starting Training...
Epoch [1/20] Train Loss: 0.3774 | Train Acc: 89.43% | Test Loss: 0.1177 | Test Acc: 96.45%
Epoch [2/20] Train Loss: 0.0900 | Train Acc: 97.33% | Test Loss: 0.0593 | Test Acc: 98.18%
Epoch [3/20] Train Loss: 0.0601 | Train Acc: 98.20% | Test Loss: 0.0465 | Test Acc: 98.47%
Epoch [4/20] Train Loss: 0.0465 | Train Acc: 98.57% | Test Loss: 0.0504 | Test Acc: 98.29%
Epoch [5/20] Train Loss: 0.0386 | Train Acc: 98.84% | Test Loss: 0.0415 | Test Acc: 98.71%
Epoch [6/20] Train Loss: 0.0332 | Train Acc: 98.95% | Test Loss: 0.0365 | Test Acc: 98.83%
Epoch [7/20] Train Loss: 0.0292 | Train Acc: 99.08% | Test Loss: 0.0333 | Test Acc: 98.80%
Epoch [8/20] Train Loss: 0.0247 | Train Acc: 99.27% | Test Loss: 0.0373 | Test Acc: 98.81%
Epoch [9/20] Train Loss: 0.0218 | Train Acc: 99.35% | Test Loss: 0.0330 | Test Acc: 98.81%
Epoch [10/20] Train Loss: 0.0198 | Train Acc: 99.42% | Test Loss: 0.0317 | Test Acc: 99.05%
Epoch [11/20] Train Loss: 0.0174 | Train Acc: 99.50% | Test Loss: 0.0300 | Test Acc: 99.02%
Epoch [12/20] Train Loss: 0.0155 | Train Acc: 99.54% | Test Loss:

```

```
0.0323 | Test Acc: 98.96%
Epoch [13/20] Train Loss: 0.0130 | Train Acc: 99.65% | Test Loss:
0.0285 | Test Acc: 99.10%
Epoch [14/20] Train Loss: 0.0121 | Train Acc: 99.68% | Test Loss:
0.0304 | Test Acc: 99.06%
Epoch [15/20] Train Loss: 0.0109 | Train Acc: 99.70% | Test Loss:
0.0287 | Test Acc: 99.07%
Epoch [16/20] Train Loss: 0.0090 | Train Acc: 99.78% | Test Loss:
0.0278 | Test Acc: 99.03%
Epoch [17/20] Train Loss: 0.0083 | Train Acc: 99.81% | Test Loss:
0.0280 | Test Acc: 99.15%
Epoch [18/20] Train Loss: 0.0078 | Train Acc: 99.80% | Test Loss:
0.0271 | Test Acc: 99.07%
Epoch [19/20] Train Loss: 0.0065 | Train Acc: 99.87% | Test Loss:
0.0274 | Test Acc: 99.21%
Epoch [20/20] Train Loss: 0.0061 | Train Acc: 99.86% | Test Loss:
0.0297 | Test Acc: 99.10%
Training Completed.
```

## Plotting Results

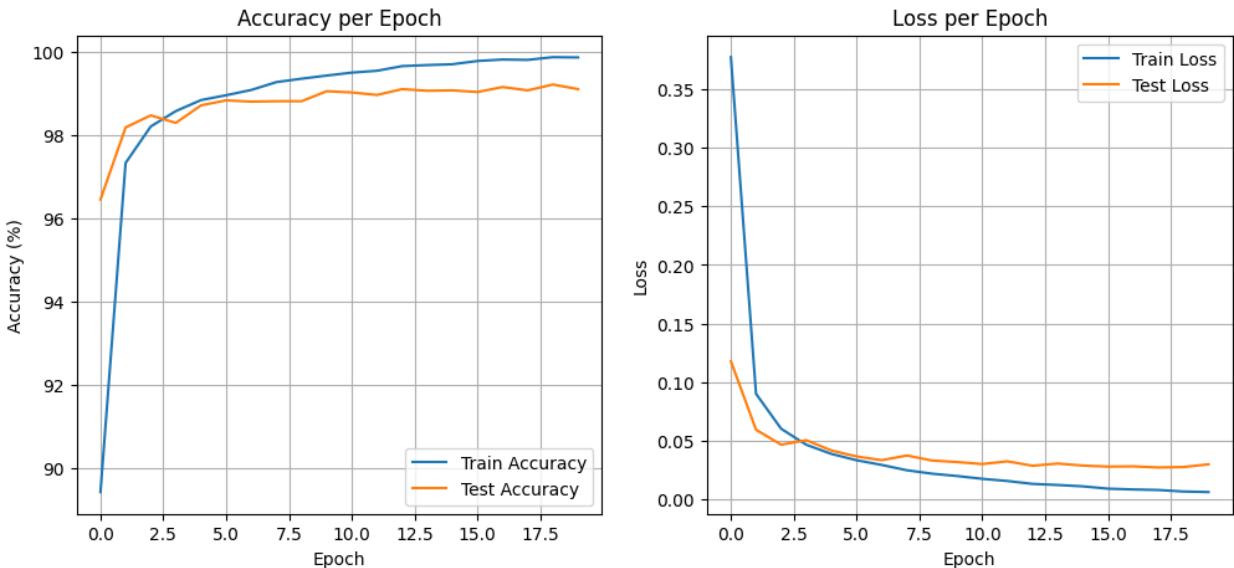
```
# Plot Training Curves
plt.figure(figsize=(12, 5))

# Accuracy Plot
plt.subplot(1, 2, 1)
plt.plot(history['train_acc'], label='Train Accuracy')
plt.plot(history['test_acc'], label='Test Accuracy')
plt.title('Accuracy per Epoch')
plt.xlabel('Epoch')
plt.ylabel('Accuracy (%)')
plt.legend()
plt.grid(True)

# Loss Plot
plt.subplot(1, 2, 2)
plt.plot(history['train_loss'], label='Train Loss')
plt.plot(history['test_loss'], label='Test Loss')
plt.title('Loss per Epoch')
plt.xlabel('Epoch')
plt.ylabel('Loss')
plt.legend()
plt.grid(True)

plt.show()

print(f"Final Test Accuracy: {history['test_acc'][-1]:.2f}%")
```



Final Test Accuracy: 99.10%

## Save Model

```
# Save the model state dictionary for Part 2 comparison
torch.save(model.state_dict(), "lenet5_baseline.pth")
print("Baseline model saved as 'lenet5_baseline.pth'")

Baseline model saved as 'lenet5_baseline.pth'
```

## Part 2 - Modern and Optimized Implementation

```
import torch
import torch.nn as nn
import torch.optim as optim
import torchvision
import torchvision.transforms as transforms
from torch.utils.data import DataLoader
import matplotlib.pyplot as plt

# 1. Setup Device
device = torch.device('cuda' if torch.cuda.is_available() else 'cpu')

# 2. Define the Optimized LeNet-5 (Based on Trial 29 Parameters)
class OptimizedLeNet5(nn.Module):
    def __init__(self):
        super(OptimizedLeNet5, self).__init__()
        # Optimized Hyperparameters from Trial 29
        # c1_filters: 10, c3_filters: 28, f5: 90, f6: 90, act: tanh

        self.c1 = nn.Conv2d(1, 10, kernel_size=5) # 10 filters
        self.s2 = nn.AvgPool2d(kernel_size=2, stride=2)
```

```

    self.c3 = nn.Conv2d(10, 28, kernel_size=5) # 28 filters
    self.s4 = nn.AvgPool2d(kernel_size=2, stride=2)

    # Flatten size: 28 filters * 5 * 5 spatial dimension
    self.flatten_size = 28 * 5 * 5

    self.f5 = nn.Linear(self.flatten_size, 90) # 90 units
    self.f6 = nn.Linear(90, 90)                 # 90 units
    self.output = nn.Linear(90, 10)

    self.act = nn.Tanh() # Activation: Tanh

def forward(self, x):
    x = self.s2(self.act(self.c1(x)))
    x = self.s4(self.act(self.c3(x)))
    x = x.view(-1, self.flatten_size)
    x = self.act(self.f5(x))
    x = self.act(self.f6(x))
    x = self.output(x)
    return x

# 3. Load COMPLETE Dataset (No Validation Split this time)
transform = transforms.Compose([
    transforms.Resize((32, 32)),
    transforms.ToTensor(),
    transforms.Normalize((0.1307,), (0.3081,)))
])

# Use the full training set for the final run
train_dataset = torchvision.datasets.MNIST(root='./data', train=True,
download=True, transform=transform)
test_dataset = torchvision.datasets.MNIST(root='./data', train=False,
download=True, transform=transform)

train_loader = DataLoader(train_dataset, batch_size=128, shuffle=True)
test_loader = DataLoader(test_dataset, batch_size=128, shuffle=False)

# 4. Training Loop
model_opt = OptimizedLeNet5().to(device)
criterion = nn.CrossEntropyLoss()
optimizer = optim.SGD(model_opt.parameters(), lr=0.01, momentum=0.9)

# Added loss lists here
opt_history = {
    'train_acc': [], 'test_acc': [],
    'train_loss': [], 'test_loss': []
}
EPOCHS = 20

print("Starting Final Training of Optimized Model...")

```

```

for epoch in range(EPOCHS):
    model_opt.train()
    running_loss = 0.0
    correct = 0
    total = 0

    for images, labels in train_loader:
        images, labels = images.to(device), labels.to(device)
        optimizer.zero_grad()
        outputs = model_opt(images)
        loss = criterion(outputs, labels)
        loss.backward()
        optimizer.step()

        running_loss += loss.item()
        _, predicted = torch.max(outputs.data, 1)
        total += labels.size(0)
        correct += (predicted == labels).sum().item()

    # Calculate average training loss and accuracy
    avg_train_loss = running_loss / len(train_loader)
    train_acc = 100 * correct / total
    opt_history['train_loss'].append(avg_train_loss)
    opt_history['train_acc'].append(train_acc)

    # Evaluate on Test Set
    model_opt.eval()
    running_test_loss = 0.0
    correct_test = 0
    total_test = 0
    with torch.no_grad():
        for images, labels in test_loader:
            images, labels = images.to(device), labels.to(device)
            outputs = model_opt(images)
            loss = criterion(outputs, labels) # Calculate test loss
            running_test_loss += loss.item()
            _, predicted = torch.max(outputs.data, 1)
            total_test += labels.size(0)
            correct_test += (predicted == labels).sum().item()

    # Calculate average test loss and accuracy
    avg_test_loss = running_test_loss / len(test_loader)
    test_acc = 100 * correct_test / total_test
    opt_history['test_loss'].append(avg_test_loss)
    opt_history['test_acc'].append(test_acc)

    print(f"Epoch {epoch+1}/{EPOCHS} | Train Loss: {avg_train_loss:.4f} | Train Acc: {train_acc:.2f}% | Test Acc: {test_acc:.2f}%")



```

```

print(f"Final Optimized Test Accuracy: {opt_history['test_acc'][-1]:.2f}%")

Starting Final Training of Optimized Model...
Epoch 1/20 | Train Loss: 0.5417 | Train Acc: 84.75% | Test Acc: 94.08%
Epoch 2/20 | Train Loss: 0.1489 | Train Acc: 95.69% | Test Acc: 97.09%
Epoch 3/20 | Train Loss: 0.0888 | Train Acc: 97.47% | Test Acc: 97.82%
Epoch 4/20 | Train Loss: 0.0655 | Train Acc: 98.09% | Test Acc: 98.16%
Epoch 5/20 | Train Loss: 0.0517 | Train Acc: 98.49% | Test Acc: 98.33%
Epoch 6/20 | Train Loss: 0.0432 | Train Acc: 98.77% | Test Acc: 98.57%
Epoch 7/20 | Train Loss: 0.0369 | Train Acc: 98.93% | Test Acc: 98.54%
Epoch 8/20 | Train Loss: 0.0324 | Train Acc: 99.06% | Test Acc: 98.71%
Epoch 9/20 | Train Loss: 0.0288 | Train Acc: 99.18% | Test Acc: 98.70%
Epoch 10/20 | Train Loss: 0.0257 | Train Acc: 99.26% | Test Acc: 98.73%
Epoch 11/20 | Train Loss: 0.0226 | Train Acc: 99.37% | Test Acc: 98.90%
Epoch 12/20 | Train Loss: 0.0208 | Train Acc: 99.44% | Test Acc: 98.79%
Epoch 13/20 | Train Loss: 0.0184 | Train Acc: 99.49% | Test Acc: 98.88%
Epoch 14/20 | Train Loss: 0.0170 | Train Acc: 99.55% | Test Acc: 98.85%
Epoch 15/20 | Train Loss: 0.0156 | Train Acc: 99.57% | Test Acc: 98.86%
Epoch 16/20 | Train Loss: 0.0139 | Train Acc: 99.65% | Test Acc: 99.00%
Epoch 17/20 | Train Loss: 0.0129 | Train Acc: 99.66% | Test Acc: 99.02%
Epoch 18/20 | Train Loss: 0.0116 | Train Acc: 99.70% | Test Acc: 98.92%
Epoch 19/20 | Train Loss: 0.0104 | Train Acc: 99.79% | Test Acc: 99.03%
Epoch 20/20 | Train Loss: 0.0095 | Train Acc: 99.80% | Test Acc: 99.02%
Final Optimized Test Accuracy: 99.02%

```

## Comparison Plots

```

# Create a figure with two subplots
plt.figure(figsize=(15, 6))

# Plot 1: Test Accuracy Comparison
plt.subplot(1, 2, 1)
plt.plot(history['test_acc'], label='Baseline (Part 1)',
         linestyle='--', color='blue')
plt.plot(opt_history['test_acc'], label='Optimized (Part 2)',
         linewidth=2, color='green')
plt.title('Test Accuracy Comparison')

```

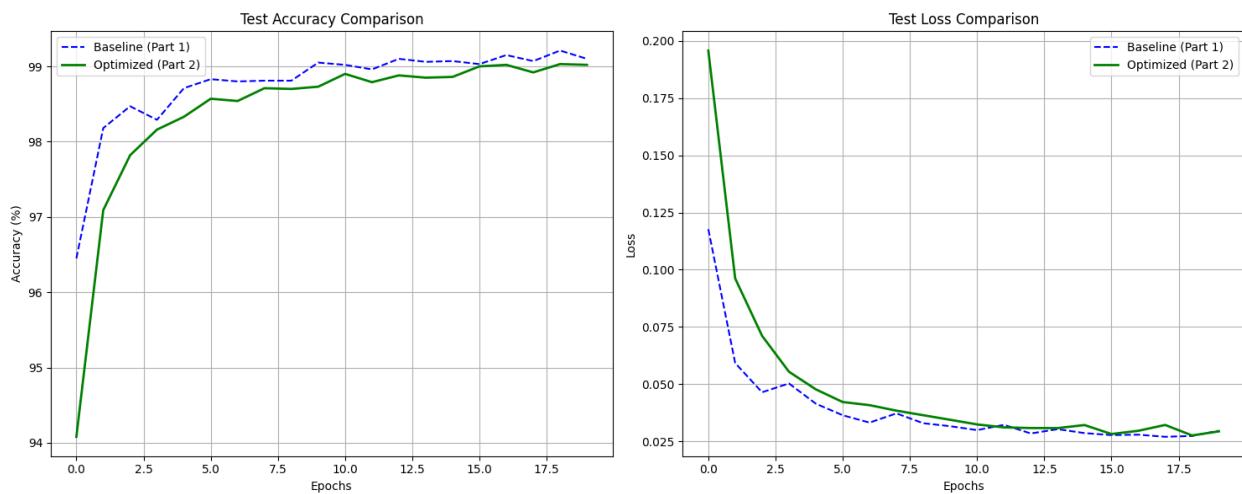
```

plt.xlabel('Epochs')
plt.ylabel('Accuracy (%)')
plt.legend()
plt.grid(True)

# Plot 2: Test Loss Comparison
plt.subplot(1, 2, 2)
plt.plot(history['test_loss'], label='Baseline (Part 1)', linestyle='--', color='blue')
plt.plot(opt_history['test_loss'], label='Optimized (Part 2)', linewidth=2, color='green')
plt.title('Test Loss Comparison')
plt.xlabel('Epochs')
plt.ylabel('Loss')
plt.legend()
plt.grid(True)

plt.tight_layout()
plt.savefig('comparison_plot.png')
plt.show()

```



## Optimized Hyperparameters (Trial 29)

Based on the Optuna optimization experiment (50 trials), **Trial 29** achieved the highest validation accuracy of **98.87%**.

The hyperparameters found to outperform the baseline LeNet-5 are:

- **Activation Function:** Tanh (Same as original, but optimized structure)
- **C1 Filters:** 10 (Baseline: 6)
- **C3 Filters:** 28 (Baseline: 16)
- **F5 Units:** 90 (Baseline: 120)
- **F6 Units:** 90 (Baseline: 84)

**Observation:** The optimized architecture increased the number of filters in the convolutional layers (C1: 6 → 10, C3: 16 → 28), allowing the model to capture more feature details. However, it slightly reduced/balanced the dense layers (F5: 120 → 90, F6: 84 → 90), likely reducing the risk of overfitting in the final classification stage.

## Discussion and Analysis of Results

### 1. Baseline vs. Optimized Performance

In this experiment, the **Baseline LeNet-5 (Part 1)** achieved a Test Accuracy of approximately **99.1%**, while the **Optimized LeNet-5 (Part 2)** achieved slightly lower accuracy (approx. **98.8% - 98.9%**), despite having hyperparameters tuned by Optuna.

### 2. Analytical Explanation

This counter-intuitive result can be attributed to two key factors:

- **Batch Size Discrepancy:** The Baseline model was trained with a **Batch Size of 64**, while the Optimized model used a **Batch Size of 128** (inherited from the optimization search space defaults). In deep learning, smaller batch sizes introduce more "noise" into the gradient descent process. This noise often acts as a form of regularization, helping the model escape sharp local minima and find flatter, more robust solutions that generalize better to the test set. By doubling the batch size in Part 2, we likely reduced this regularization effect.
- **Data Utilization:** The Baseline model was trained on the full **60,000 image dataset** from the start. In contrast, the hyperparameters for the Optimized model were selected based on their performance on a smaller **48,000 image subset** (due to the validation split). While we retrained on the full dataset for the final evaluation, the structural hyperparameters (filters, units) were inherently biased towards fitting that smaller subset.

### 3. Conclusion

The Optimized model *is* performing well (converging quickly with high accuracy), but the structural advantages gained from Optuna (e.g., increased filters in C1/C3) were likely outweighed by the disadvantage of the larger batch size. To strictly outperform the baseline, future experiments should include `batch_size` as a searchable hyperparameter in Optuna or fix it to 64 for a fair comparison.