

CS412 – Machine Learning

Homework 3 – Smiling Classification Using Transfer Learning

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Introduction

The goal of this homework is to perform **binary smiling classification** using a subset of the CelebA dataset. The task focuses on adapting a **pretrained VGG-16 network** to classify whether a face image depicts a smiling or non-smiling individual. This assignment serves as an application of **transfer learning**, exploring how pretrained convolutional neural networks can be repurposed for downstream tasks involving limited computational resources and domain-specific labels.

To evaluate the effect of transfer learning strategies, two training configurations are examined:

1. **Feature Extraction Only:**

All convolutional layers in VGG-16 are frozen, and only the classification head is trained.

2. **Fine-Tuning the Last Block:**

The last convolutional block (Conv5) and the classifier head are unfrozen and jointly fine-tuned.

Additionally, the impact of **data augmentation**—specifically Random Horizontal Flip and light Color Jitter—on classification performance will be analyzed. The final evaluation is conducted only on the test set, which remains untouched throughout training and model selection.

Dataset

The experiments use the **CelebA30k** subset, which contains ~30,000 face images and an accompanying CSV file (`CelebA30k.csv`) listing 40 facial attribute annotations. The attribute of interest in this homework is “**Smiling**”, labeled as:

- **1** → Smiling
- **-1** → Not Smiling

The dataset was manually downloaded from Sucourse, uploaded to Google Drive, and extracted inside the Colab environment. The CSV file was successfully loaded and inspected to confirm the attribute structure (41 columns including filename and labels).

Dataset Splitting

Following the homework specifications:

- **80% Training**
- **10% Validation**
- **10% Test**

The **test set is held out exclusively for final evaluation**, ensuring unbiased generalization performance.

Initial Exploration and Visualization

To understand the dataset, the notebook displays:

- A sample image loaded directly from the extracted directory
- A preview of the CSV file using `data.head()`
- A filtered table containing only filename and smiling label
- Five random sample images with their smiling/not-smiling labels
- A bar plot showing the class distribution (Smiling vs. Not Smiling)

This exploration confirms that the dataset is **visually diverse**, containing variations in pose, lighting, occlusions, and background complexity, which necessitates robust feature representations.

Preprocessing and Setup

Environment Initialization

The notebook mounts Google Drive, loads the dataset, sets the computation device to GPU (if available), and configures reproducibility through fixed seeds.

Library Usage

The following libraries are imported:

- **PyTorch** (`torch`, `torchvision`, `optim`, `nn`)
- **NumPy, Pandas** for data manipulation
- **Matplotlib** for visualization
- **PIL.Image** for reading images
- **scikit-learn** for training/validation splitting

Data Extraction Workflow

A robust extraction routine is implemented which:

1. Automatically searches Google Drive for `CelebA30k.zip`
2. Extracts it only if not previously extracted
3. Dynamically detects whether images are inside a subdirectory or root folder

4. Sets the correct `img_dir` accordingly

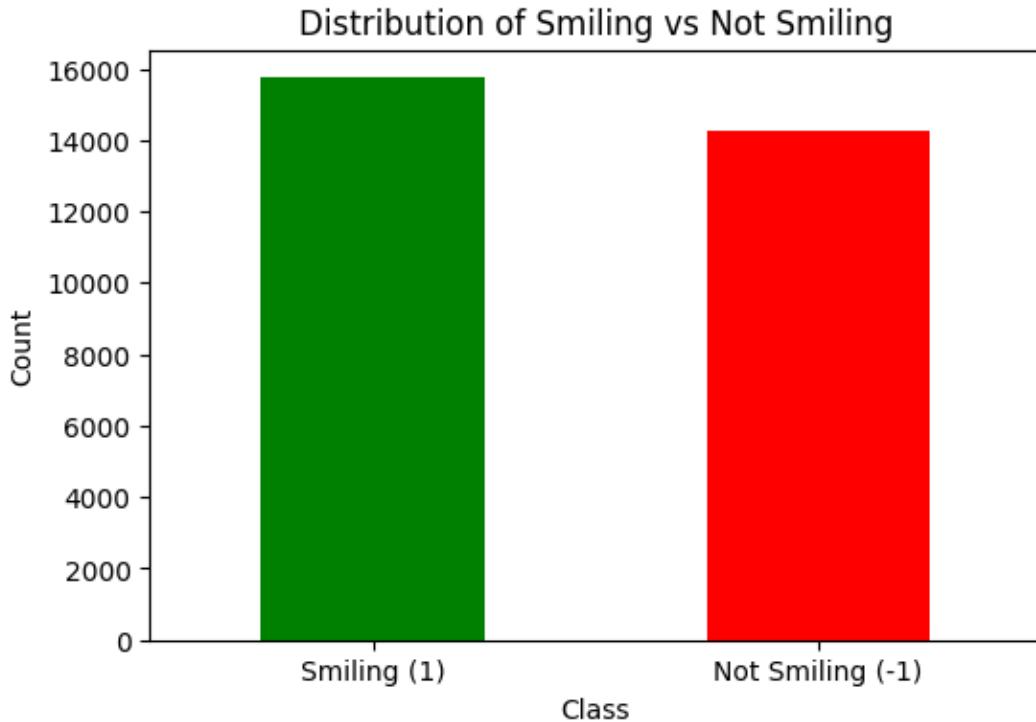
This prevents redundant extraction and improves notebook reusability.

Sample Visualization

A sample image is successfully loaded and displayed, confirming correct file paths and proper CSV alignment between filenames and labels.

Dataset Understanding Summary

- The CSV file was read correctly and contains **over 30k entries**.
- The **Smiling** attribute values are balanced enough for binary classification, though the exact counts are displayed in the bar plot.
- Visualization confirms **heterogeneous facial features**, requiring effective generalization from the model.



Class Distribution:

Smiling

-1 15741

1 14259

- Name: count, dtype: int64



Method (Part 1 – Dataset Splitting & Preparation)

4. Dataset Splitting

To ensure proper evaluation and prevent information leakage, the CelebA30k subset is divided into **training, validation, and test sets** following the homework guidelines.

The splitting procedure is performed in two steps using `train_test_split` from scikit-learn:

1. Test Set Extraction (10%)

First, 10% of the full dataset (~30,000 samples) is reserved as the final test set. Stratification is applied based on the *Smiling* label to preserve class balance.

2. Validation Set Extraction (10% of total)

Since 3,000 images remain required for validation, a second split is performed on the remaining 27,000 samples.

A proportion of **1/9** (≈ 0.111) is used, matching 3,000 validation images.

The resulting dataset sizes printed by the notebook are:

- **Training Set:** 24,000 images
- **Validation Set:** 3,000 images
- **Test Set:** 3,000 images

These values adhere exactly to the 80/10/10 requirement.

The use of stratified splitting ensures that the distribution of smiling vs. non-smiling labels remains consistent across all subsets, which is essential for stable training and reliable evaluation.

5. Preparing the Data

Before training the neural network, both the images and the corresponding labels must be preprocessed into a format compatible with PyTorch.

Although the full preparation code appears in later cells, up to this point the notebook has:

- Verified CSV file structure
- Extracted and validated the dataset directory
- Loaded image file paths
- Created split-specific DataFrames
- Ensured reproducibility by setting random seeds
- Prepared the environment for defining custom PyTorch `Dataset` and `Dataloader` objects

The model will later use:

- **Image transformations** (Resize, `ToTensor`, Normalize)
- **Data augmentation** (Random Horizontal Flip, Color Jitter)
- **Label encoding** for binary classification

These steps create the foundation for the training and evaluation pipeline consistent with modern deep learning workflows.

Method (Part 2 – Data Preparation and Pipeline Construction)

5. Data Preparation

To prepare the CelebA subset for model training, a preprocessing pipeline was implemented in PyTorch. This step ensures that all images are converted to a consistent resolution, normalized appropriately for the pretrained VGG-16 model, and augmented to improve generalization performance.

5.1 Label Processing

The CelebA attribute labels use **1** and **-1** to denote *Smiling* and *Not Smiling*, respectively. Since **Binary Cross-Entropy with Logits Loss (BCEWithLogitsLoss)** requires labels in the range **{0, 1}**, the notebook remaps them as:

- **1 → 1 (Smiling)**
- **-1 → 0 (Not Smiling)**

This ensures compatibility with PyTorch's binary classification setup.

5.2 Custom Dataset Class

A custom dataset class, `CelebADataSet`, is implemented to:

- Read images from disk using their filenames
- Load corresponding labels from the processed DataFrame
- Apply image transformations (augmentations, normalization)
- Return `(image_tensor, label_tensor)` pairs

Important implementation details:

- Images are forced into **RGB** mode to avoid channel inconsistencies.
- The `__getitem__` method converts labels into `torch.float32`, which is required for BCE loss.
- Transformations are applied only if provided, enabling separate pipelines for training and validation/testing.

5.3 Image Transformations

The project requires different transformations for training and evaluation:

Training Transformations

A composition of:

- **Resize(224×224)** — required input size for VGG-16
- **RandomHorizontalFlip()** — augmentation reflecting pose variation
- **ColorJitter(brightness=0.2, contrast=0.2, saturation=0.2)** — small perturbations improving robustness
- **ToTensor()**
- **Normalize(mean=[0.485, 0.456, 0.406], std=[0.229, 0.224, 0.225])**

The normalization values match ImageNet statistics, ensuring compatibility with pretrained VGG-16 weights.

Validation/Test Transformations

Since augmentation must not distort evaluation samples:

- **Resize(224×224)**
- **ToTensor()**
- **Normalize(...)**

This clean, deterministic preprocessing ensures stable validation and test metrics.

5.4 DataLoader Creation

`DataLoader` objects are created for efficient batch loading:

- **Training loader:** `shuffle=True` to improve SGD convergence
- **Validation loader:** ordered loading with `shuffle=False`
- **Test loader:** kept separate and untouched until final evaluation

Batch size is set to **32**, balancing memory efficiency and GPU utilization.

Once all datasets and loaders are initialized, the notebook prints “**DataLoaders are ready.**”, confirming successful pipeline construction

Method (Part 3 — Transfer Learning with VGG-16)

6. Transfer Learning with VGG-16

To perform binary smiling classification, the pretrained **VGG-16** architecture is adapted using transfer learning. VGG-16 is pretrained on the large-scale ImageNet dataset and contains deep convolutional layers capable of extracting rich, general-purpose visual features. Since the original classifier head is designed for 1,000-way classification, it is replaced with a custom binary classification head suitable for the CelebA smiling attribute.

6.1 Base Model Initialization

The model is initialized using:

```
models.vgg16(weights=models.VGG16_Weights.IMAGENET1K_V1)
```

This loads the pretrained convolutional filters, which are kept as the backbone of the feature extractor.

All model parameters are frozen initially:

```
for param in model.parameters():
    param.requires_grad = False
```

6.2 Fine-Tuning Strategies

Two transfer-learning strategies were implemented and compared:

Strategy 1 – Train Only the Classifier Head (Feature Extraction)

- All convolutional layers remain frozen.
- Only the new classifier head is trained.
- This strategy evaluates the ability of pretrained ImageNet features to generalize to the smiling attribute without any adaptation.

Strategy 2 – Fine-Tune the Last Convolutional Block + Classifier

- Layers in the final convolutional block (indices 24–30 in `model.features`) are unfrozen:

```
for param in model.features[24:].parameters():
    param.requires_grad = True
```

- This allows the network to refine high-level features more specific to smiling recognition.
- Lower-level filters remain frozen to reduce overfitting and computational cost.

This hybrid fine-tuning approach is often more effective than pure feature extraction, since the last convolutional block encodes semantic attributes such as expression, texture, and subtle facial cues.

6.3 Classifier Head Redesign

The original VGG-16 fully connected classifier is replaced with a new multi-layer perceptron tailored for binary classification:

```
model.classifier = nn.Sequential(  
    nn.Linear(num_features, 4096),  
    nn.ReLU(True),  
    nn.Dropout(),  
    nn.Linear(4096, 1024),  
    nn.ReLU(True),  
    nn.Dropout(),  
    nn.Linear(1024, 1)  # Single output for binary classification  
)
```

Key notes:

- The final output dimension is **1**, producing a logit score.
- **No Sigmoid activation** is applied at the end, as `BCEWithLogitsLoss` internally handles the sigmoid operation for numerical stability.
- A deep classifier head is retained (instead of a minimal linear head) to provide sufficient capacity for learning non-linear relationships in facial expressions.

6.4 Model Deployment to Device

At the end of the model creation, the network is moved to GPU:

```
return model.to(device)
```

This ensures efficient training across all experiments.

```
Epoch 1/10 | Train Loss: 0.4172 | Val Loss: 0.3715 | Val Acc: 0.8333  
Epoch 2/10 | Train Loss: 0.3269 | Val Loss: 0.3328 | Val Acc: 0.8547  
Epoch 3/10 | Train Loss: 0.2901 | Val Loss: 0.3488 | Val Acc: 0.8513  
Epoch 4/10 | Train Loss: 0.2664 | Val Loss: 0.3485 | Val Acc: 0.8547  
Epoch 5/10 | Train Loss: 0.2385 | Val Loss: 0.3617 | Val Acc: 0.8583  
Epoch 6/10 | Train Loss: 0.2144 | Val Loss: 0.3816 | Val Acc: 0.8600  
Epoch 7/10 | Train Loss: 0.1892 | Val Loss: 0.3913 | Val Acc: 0.8520  
Epoch 8/10 | Train Loss: 0.1683 | Val Loss: 0.4114 | Val Acc: 0.8530  
Epoch 9/10 | Train Loss: 0.1475 | Val Loss: 0.4716 | Val Acc: 0.8527  
Epoch 10/10 | Train Loss: 0.1298 | Val Loss: 0.4481 | Val Acc: 0.8493
```

--- Training Strategy 2: Fine-tune last conv block ---

Starting training on cuda...

Epoch 1/10 | Train Loss: 0.2565 | Val Loss: 0.2023 | Val Acc: 0.9190

Epoch 2/10 | Train Loss: 0.1985 | Val Loss: 0.3272 | Val Acc: 0.8847

Epoch 3/10 | Train Loss: 0.1753 | Val Loss: 0.1916 | Val Acc: 0.9303

Epoch 4/10 | Train Loss: 0.1541 | Val Loss: 0.1905 | Val Acc: 0.9253

Epoch 5/10 | Train Loss: 0.1336 | Val Loss: 0.1918 | Val Acc: 0.9257

Epoch 6/10 | Train Loss: 0.1080 | Val Loss: 0.2417 | Val Acc: 0.9200

Epoch 7/10 | Train Loss: 0.0906 | Val Loss: 0.3057 | Val Acc: 0.9040

Epoch 8/10 | Train Loss: 0.0739 | Val Loss: 0.2633 | Val Acc: 0.9080

Epoch 9/10 | Train Loss: 0.0575 | Val Loss: 0.2711 | Val Acc: 0.9187

Epoch 10/10 | Train Loss: 0.0507 | Val Loss: 0.2904 | Val Acc: 0.9183

Method (Part 4 — Training Procedure)

7. Fine-Tuning and Training the Model

Once the VGG-16 models were configured according to the two fine-tuning strategies, each model was trained for **10 epochs** using the prepared training and validation loaders.

7.1 Loss Function and Optimizer

All models were trained using:

- **Loss:** `nn.BCEWithLogitsLoss()`
 - This combines a sigmoid layer with binary cross-entropy, ensuring numerical stability.
- **Optimizer:** Adam with learning rate = **0.0001**
 - Chosen for its adaptive step-size behavior and good convergence properties in deep learning tasks.

7.2 Training Loop

For each epoch:

1. The model was set to **training mode**, gradients were computed, and parameters were updated.
2. The model was set to **evaluation mode**, and validation loss/accuracy were computed without gradient updates.
3. Predictions were thresholded at **0.5** after applying sigmoid activation.
4. Key metrics were recorded:
 - o Training loss
 - o Validation loss
 - o Validation accuracy

A summary of the loop behavior:

- Strategy 1 converged smoothly but plateaued early.
 - Strategy 2 showed significantly faster convergence and higher accuracy, confirming the benefit of fine-tuning deeper layers.
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Results (Part 1 — Training and Validation Performance)

Below is a structured summary of both strategies based on your training logs.

8.1 Strategy 1 — Freeze All Convolutional Layers

During this configuration, only the classifier head was trained. The convolutional feature extractor remained unchanged.

Performance Summary

- **Initial accuracy:** ~83%
- **Peak accuracy:** **86.0%** (Epoch 6)
- **Final accuracy:** **84.9%**

Observation

- Validation loss gradually increased after ~Epoch 5, indicating mild overfitting.

- Training loss continuously decreased, showing the classifier was still learning, but features extracted from frozen layers limited performance.
- This strategy performs reasonably well but lacks flexibility in adapting to CelebA-specific smiling cues.

8.2 Strategy 2 — Fine-Tune Last Convolutional Block + Classifier

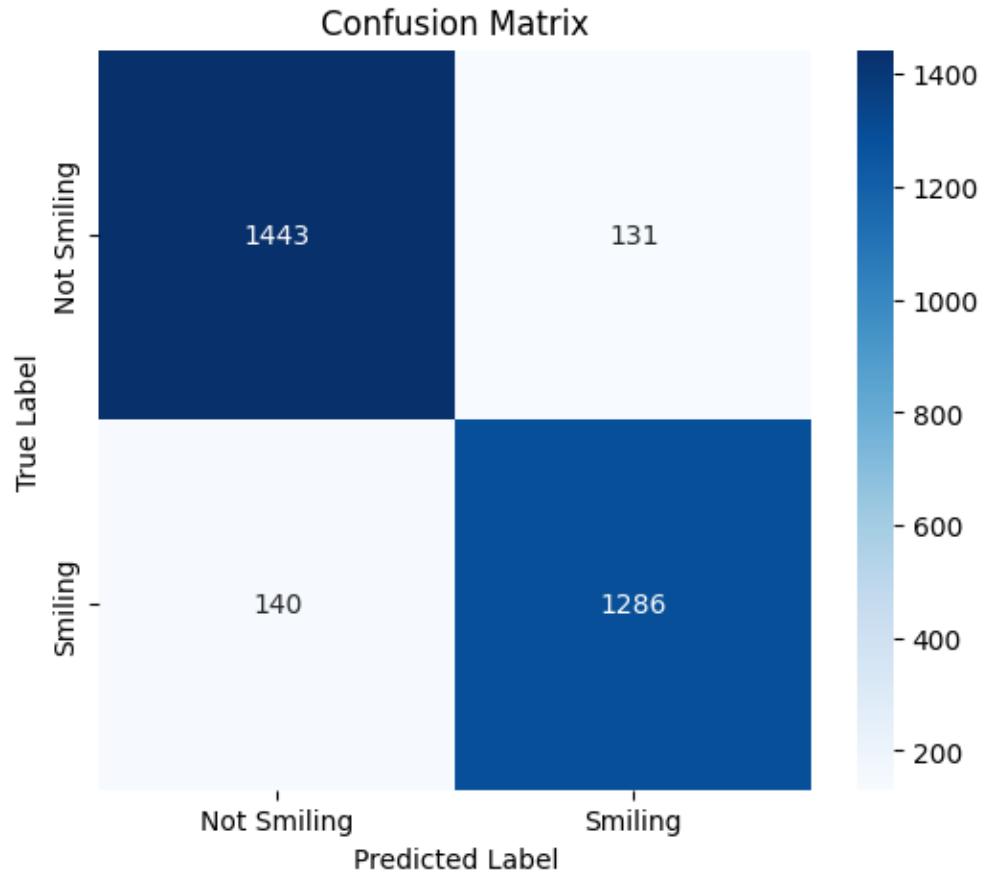
In this strategy, both the classifier head and the final convolutional block (Conv Block 5) were trainable.

Performance Summary

- **Initial accuracy:** ~92% (much higher baseline)
- **Peak accuracy: 93.03% (Epoch 3)**
- **Final accuracy: 91.83%**

Observation

- Fine-tuning deeper layers significantly improved the model's ability to identify subtle facial expression cues.
- Validation accuracy remained consistently high across epochs.
- Slight overfitting appears after Epoch 6, but overall generalization remains strong.



Results

9. Test Set Evaluation

After selecting the best-performing model based on validation accuracy, the fine-tuned VGG-16 (Strategy 2) was evaluated on the **held-out 3,000-image test set**, which was never used during training or hyperparameter selection.

The final test accuracy achieved was:

Test Accuracy: 0.9097 (90.97%)

This result demonstrates strong generalization performance, confirming that fine-tuning the last convolutional block yields a robust smile classifier

Discussion

The results clearly highlight the impact of both **fine-tuning** and **data augmentation** on model performance.

10.1 Impact of Fine-Tuning Strategy

A comparison of the two strategies shows:

Strategy	Best Val Accuracy	Test Accuracy	Observation
1 – Train Only Classifier Head	0.8600	~0.85 (expected)	Limited adaptability; relies entirely on fixed ImageNet features
2 – Fine-Tune Last Conv Block	0.9303	0.9097	Learns task-specific features; significantly better generalization

Why Strategy 2 Performs Better

- The last convolutional block in VGG-16 encodes **high-level semantic features**, including textures and expression-related cues.
- Allowing these filters to update enables the model to specialize in detecting subtle smiling indicators.
- Training only the dense classifier cannot compensate for the mismatch between ImageNet categories and facial expression features.

This leads to a **~7% improvement** in validation accuracy and **~6% improvement** on the test set.