
SESSION // 04

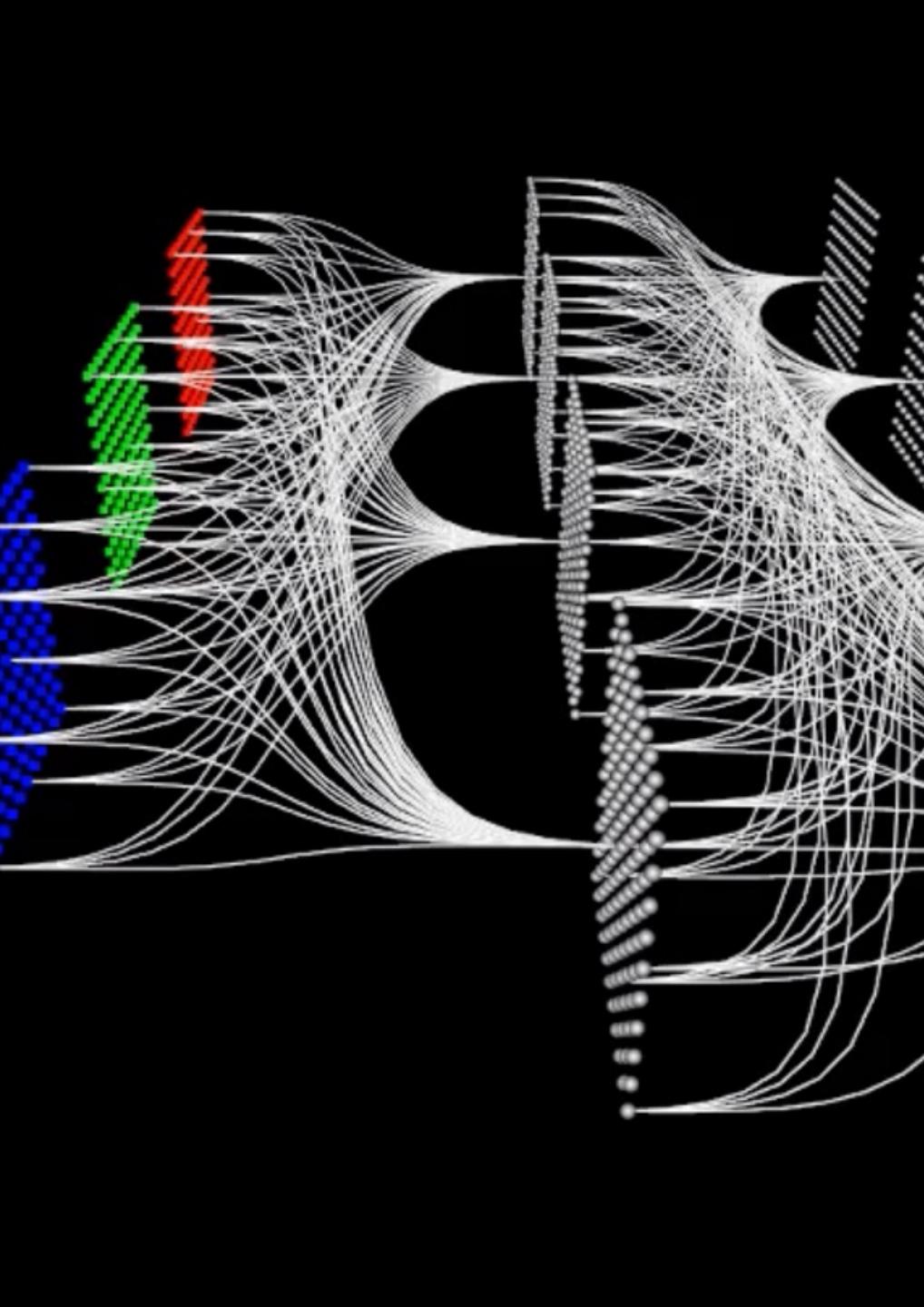
CONVOLUTIONAL NEURAL NETWORKS

**FACULTY OF
SCIENCE AND ENGINEERING**

+++

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AGENDA

Introduction to Convolutional Neural Networks (CNNs)

- Understanding what makes CNNs unique for image processing

The Convolution Operation

- Mathematical foundations of convolution
- Key parameters: kernel size, stride, padding, dilation

Filters in CNNs

- Understanding what filters detect in images
- Different types of filters for edge detection, sharpening, etc.

Image Data Preparation

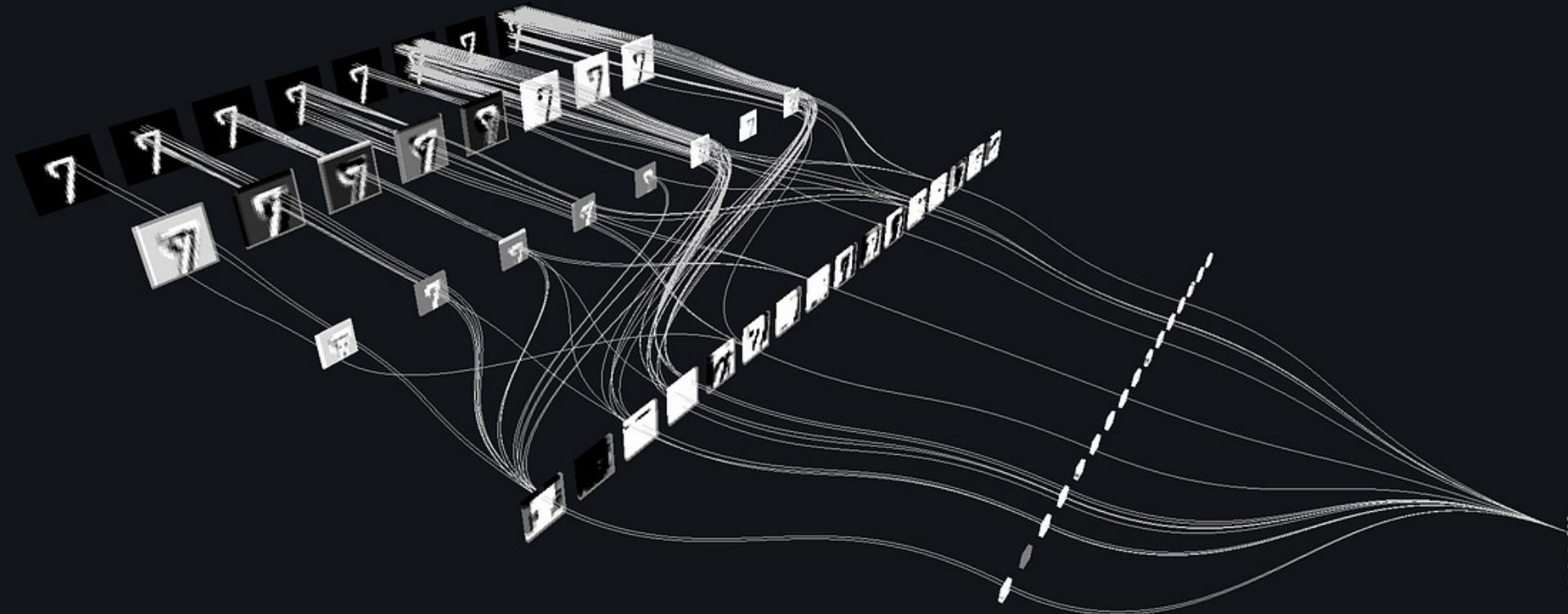
Data Loading for Deep Learning

Simple CNN Implementation

Advanced CNN Components

Case Study: Crack Detection in Historical Buildings

Popular CNN Architectures



CNN

Convolutional Neural Networks (CNNs) are specialized neural networks designed for processing structured grid-like data, such as images

- Inspired by visual cortex organization
- Revolutionized computer vision

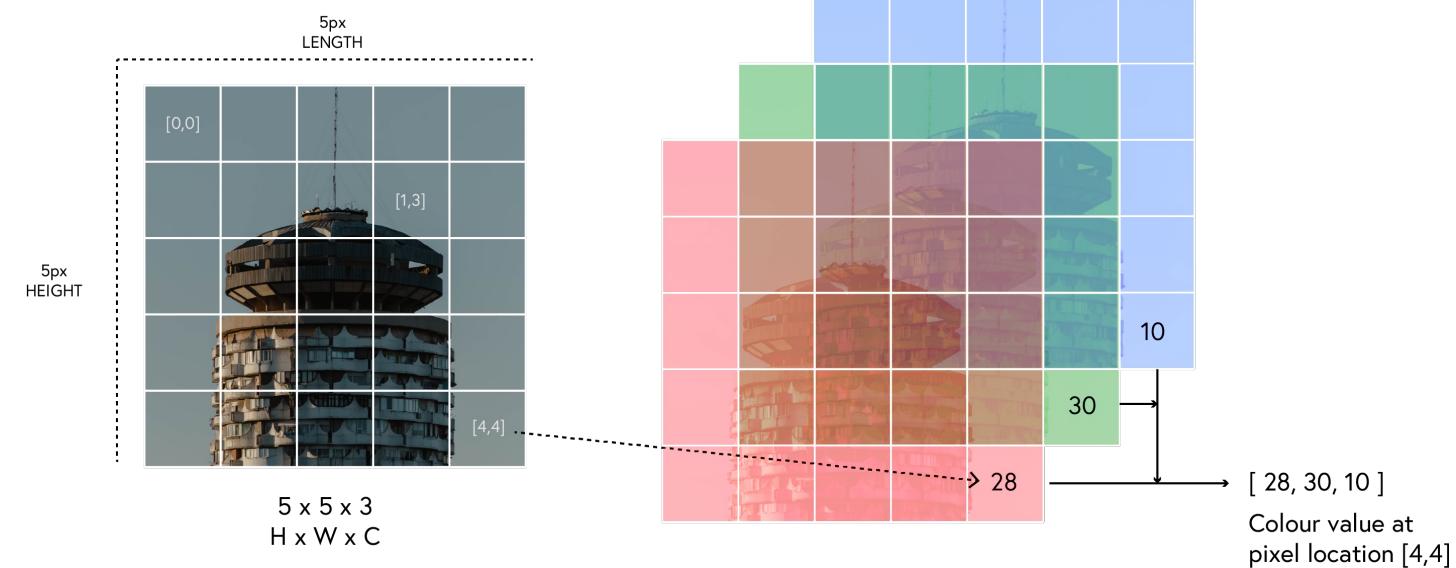
WHY STANDARD NEURAL NETWORKS STRUGGLE WITH IMAGES

Spatial Relationships: Standard networks don't account for spatial relationships between pixels

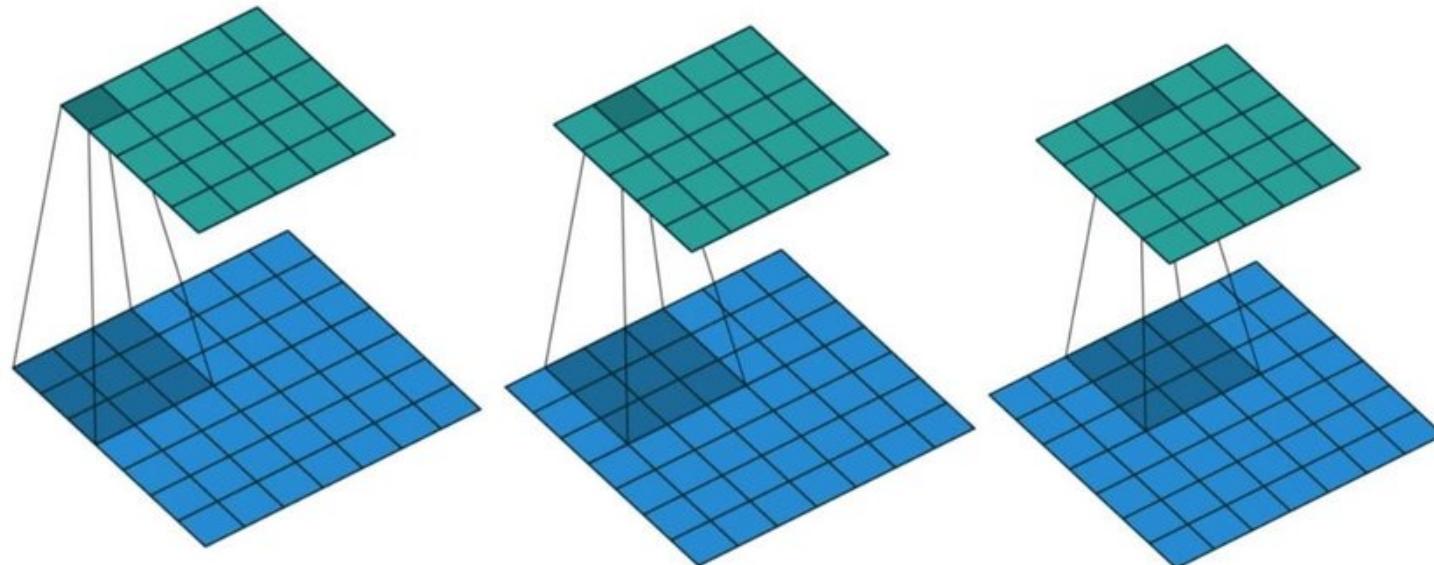
Parameter Explosion: A $224 \times 224 \times 3$ image would require over 150,000 weights per neuron

Translation Invariance: Objects can appear anywhere in an image but have the same meaning

Feature Hierarchy: Images contain low-level features that compose into higher-level features



CONVOLUTION



Definition: A mathematical operation that slides a filter over an input, performing element-wise multiplication and summation

KEY PARAMETERS IN CONVOLUTION

- **Kernel Size:** The dimensions of the filter
- **Stride:** How many pixels the filter shifts
- **Padding:** Adding extra pixels around the border
- **Dilation:** Spacing between kernel elements

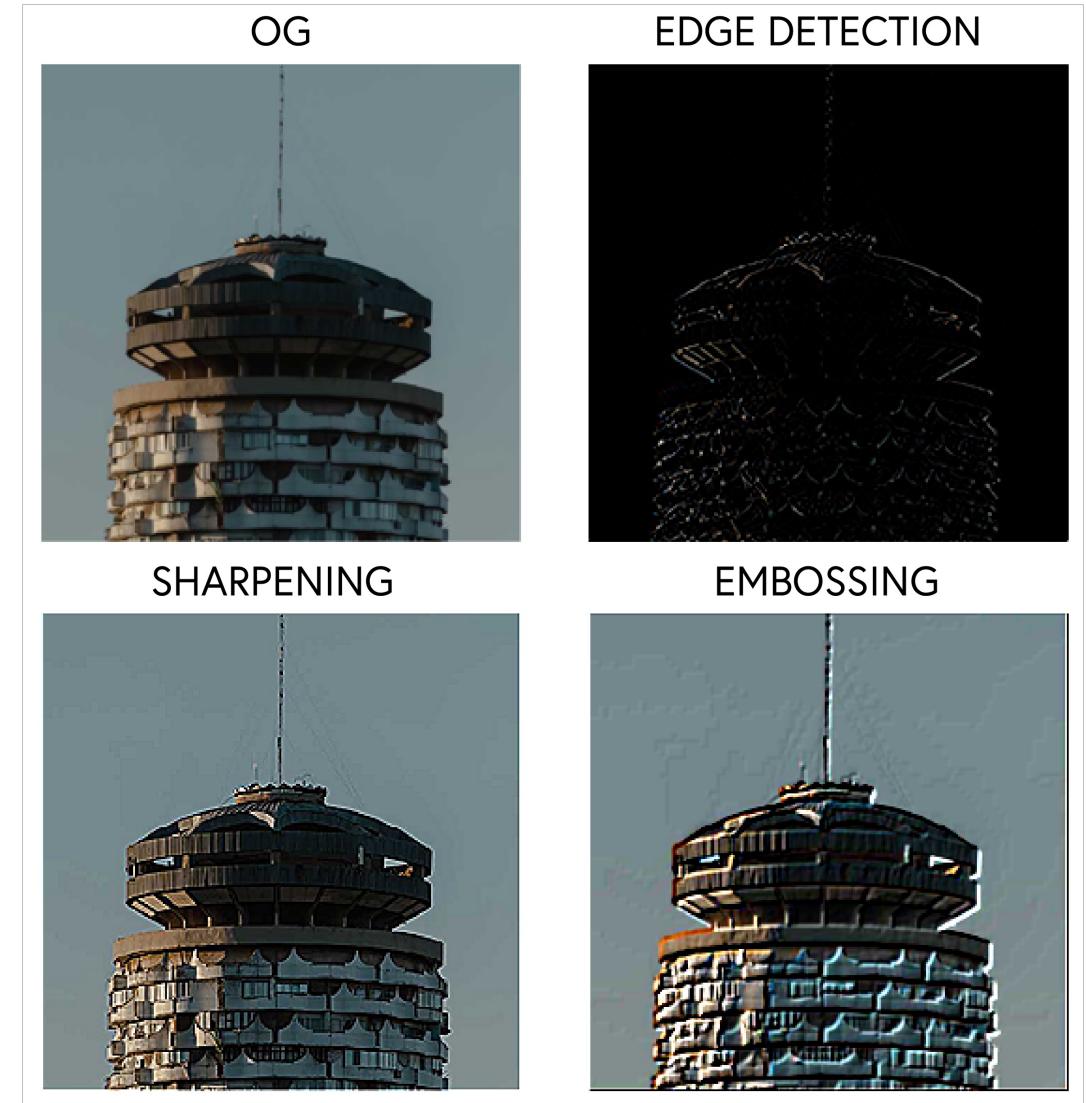


```
conv_layer = torch.nn.Conv2d(in_channels,  
                           out_channels,  
                           kernel_size,  
                           bias,  
                           padding,  
                           groups)
```

FILTERS IN CNNS

Filters are small matrices that detect specific patterns in images

- Different filters detect different features (edges, textures, etc.)
- Weights in filters are learned during training

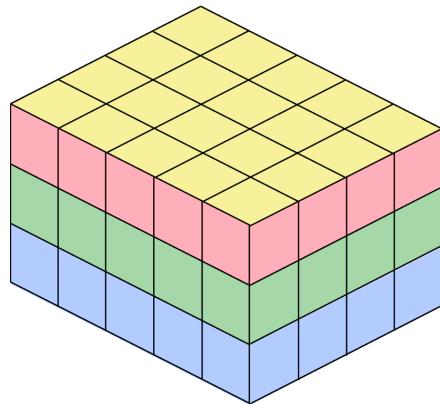


PREPARING IMAGES

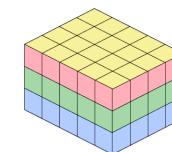
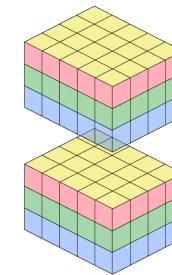
Need to convert images into proper format for
CNNs

- **PyTorch expects 4D tensors:** (batch_size, channels, height, width)
- **Data augmentation** techniques increase training set diversity

[3 x 5 x 4]



BATCHES x CHANNELS x HEIGHT x WIDTH
[N x 3 x 5 x 4]



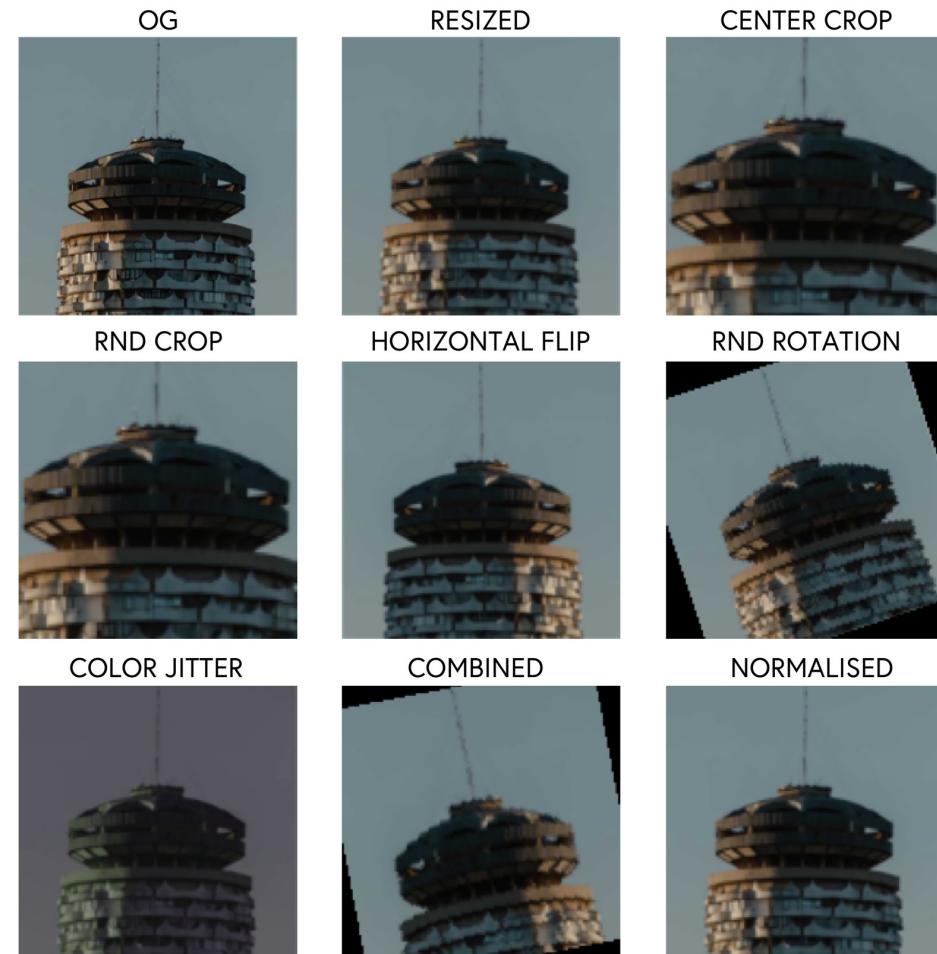
[B x C x H x W]
 [B x H x W x C]

IMAGE TRANSFORMATIONS AND AUGMENTATION

Artificially expanding dataset by applying transformations

Benefits:

- Prevents overfitting
- Improves model generalization
- Handles varied real-world conditions
- Addresses class imbalance



AUGMENTATION TECHNIQUES

- Geometric: Flips, rotations, scaling, cropping
- Color: Brightness, contrast, saturation adjustments
- Noise: Adding random noise for robustness
- Occlusion: Random erasing to simulate partial obscuring

Combining multiple augmentations:

- Domain-specific augmentations (e.g., for medical images)
- Online vs. offline augmentation

```
from torchvision import transforms

train_transforms = transforms.Compose([
    transforms.Resize((64, 64)),
    transforms.RandomHorizontalFlip(),
    transforms.RandomRotation(15),
    transforms.ColorJitter(brightness=0.2, contrast=0.2),
    transforms.ToTensor(),
    transforms.Normalize([0.485, 0.456, 0.406],
                      [0.229, 0.224, 0.225])
])
```

DATASET ORGANISATION

```
datasets/
└── raw/          # Original unprocessed data
   ├── processed/ # Preprocessed data ready for training
   └── project_datasets/
       └── crack_detection/
           ├── train/
           │   ├── crack/
           │   └── no_crack/
           ├── validation/
           │   ├── crack/
           │   └── no_crack/
           └── test/
               ├── crack/
               └── no_crack/
   └── future_project/
       ...
...
```

For CNN projects, proper dataset organization is crucial. A well-structured dataset allows for:

- Data Splitting Strategies
- Train/Validation/Test Split
- Stratified Splitting: Ensures class distribution is maintained across splits
- Cross-Validation: For smaller datasets or when maximum data usage is needed

IMAGEFOLDER: SMART DATASET MANAGEMENT

```
from torchvision.datasets import ImageFolder
from torchvision import transforms

# Define transformations
transform = transforms.Compose([
    transforms.Resize((224, 224)),
    transforms.ToTensor(),
    transforms.Normalize([0.485, 0.456, 0.406], [0.229, 0.224, 0.225])
])

# Automatically load images and assign labels based on folder structure
train_dataset = ImageFolder(root="datasets/crack_detection/train",
                            transform=transform)

# Access class information
print(f"Classes: {train_dataset.classes}")           # ['crack', 'no_crack']
print(f"Class to index: {train_dataset.class_to_idx}") # {'crack': 0, 'no_crack': 1}
```

EFFICIENT BATCH PROCESSING

```
from torch.utils.data import DataLoader

# Create efficient data loading pipeline
train_loader = DataLoader(
    train_dataset,
    batch_size=32,          # Number of samples per batch
    shuffle=True,            # Shuffle data at each epoch
    num_workers=4,           # Parallel data loading processes
    pin_memory=True,         # Speed up data transfer to GPU
    drop_last=False          # Keep incomplete final batch
)

# Inspect a batch
for images, labels in train_loader:
    print(f"Batch shape: {images.shape}") # torch.Size([32, 3, 224, 224])
    print(f"Labels: {labels}")           # tensor([0, 1, 0, 1, ...])
    break
```

THE HISTORICAL CRACK DATASET: PRESERVING OUR HERITAGE

Dataset Overview

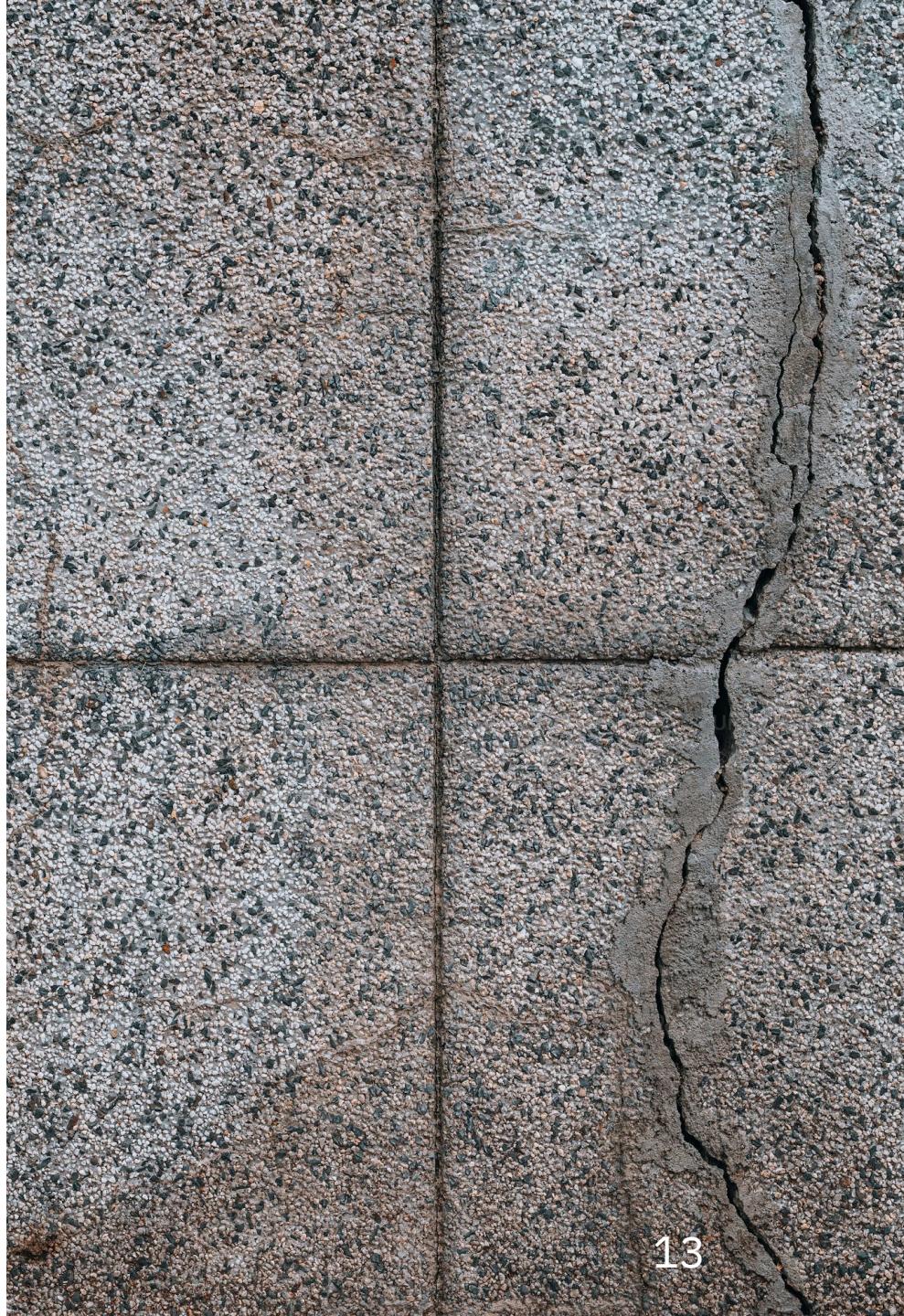
- 757 crack images / 3,139 non-crack images
- First dataset specifically for historical building monitoring
- Captures unique patterns in traditional materials

Why It Matters

- Manual inspection is time-consuming, costly, and error-prone
- Historical buildings require specialized monitoring approaches
- Early crack detection can prevent catastrophic structural failure
- AI solutions can scale inspection across multiple heritage sites

Technical Applications

- Automated drone surveys for continuous monitoring
- Mobile applications for conservation specialists
- Detection of early-stage deterioration before visible to human eye



SIMPLE CNN

CNN Components:

- Conv2D
- ReLU
- Fully connected layers
- Information flow through the network
- Parameter sharing and local connectivity

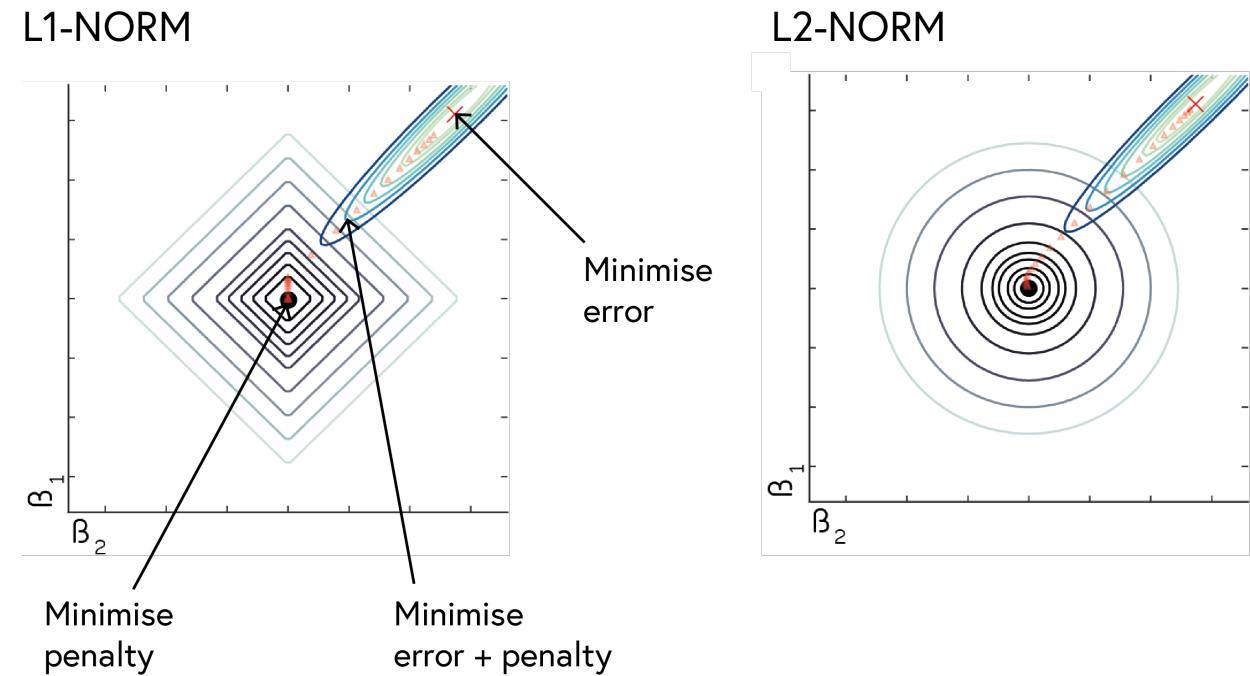
```
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class simpleCNN(torch.nn.Module):
    def __init__(self, n_classes):
        super(simpleCNN, self).__init__()
        self.conv1 = torch.nn.Conv2d(3, 16, kernel_size=3,
                                stride=1, padding=1)
        self.fc1 = torch.nn.Linear(16 * 64 * 64, 16)
        self.fc2 = torch.nn.Linear(16, n_classes)

    def forward(self, x):
        x = torch.nn.functional.relu(self.conv1(x))
        x = x.view(-1, 16 * 64 * 64)
        x = torch.nn.functional.relu(self.fc1(x))
        x = self.fc2(x)
        return x
```

REGULARISATION TECHNIQUES

- **Dropout:** Prevents co-adaptation of neurons
- **Batch normalization:** Stabilises and accelerates training
- **Weight decay:** Penalises large weights
- **Early stopping:** Prevents overfitting

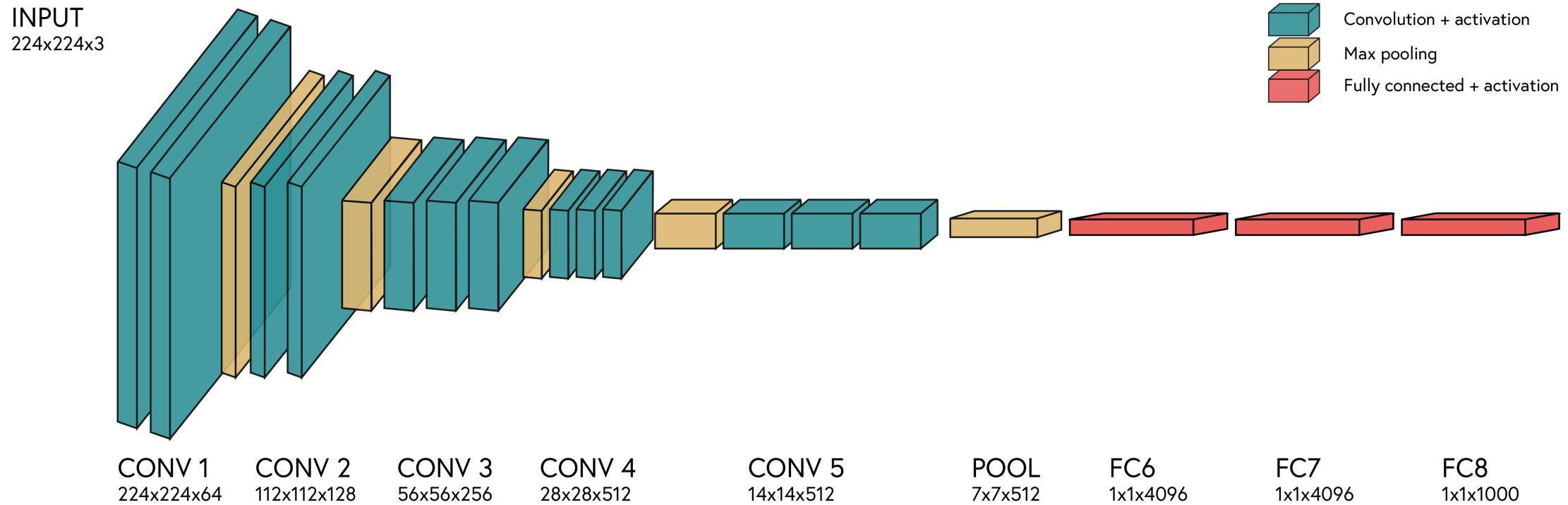


VGG16

Developed by Visual Geometry Group (Oxford, 2014)

Revolutionary simple yet effective design principles:

- Very deep network (16 weight layers)
- Small 3×3 convolution filters throughout
- Consistent doubling of filter count ($64 \rightarrow 128 \rightarrow 256 \rightarrow 512$)
- Max pooling for dimension reduction



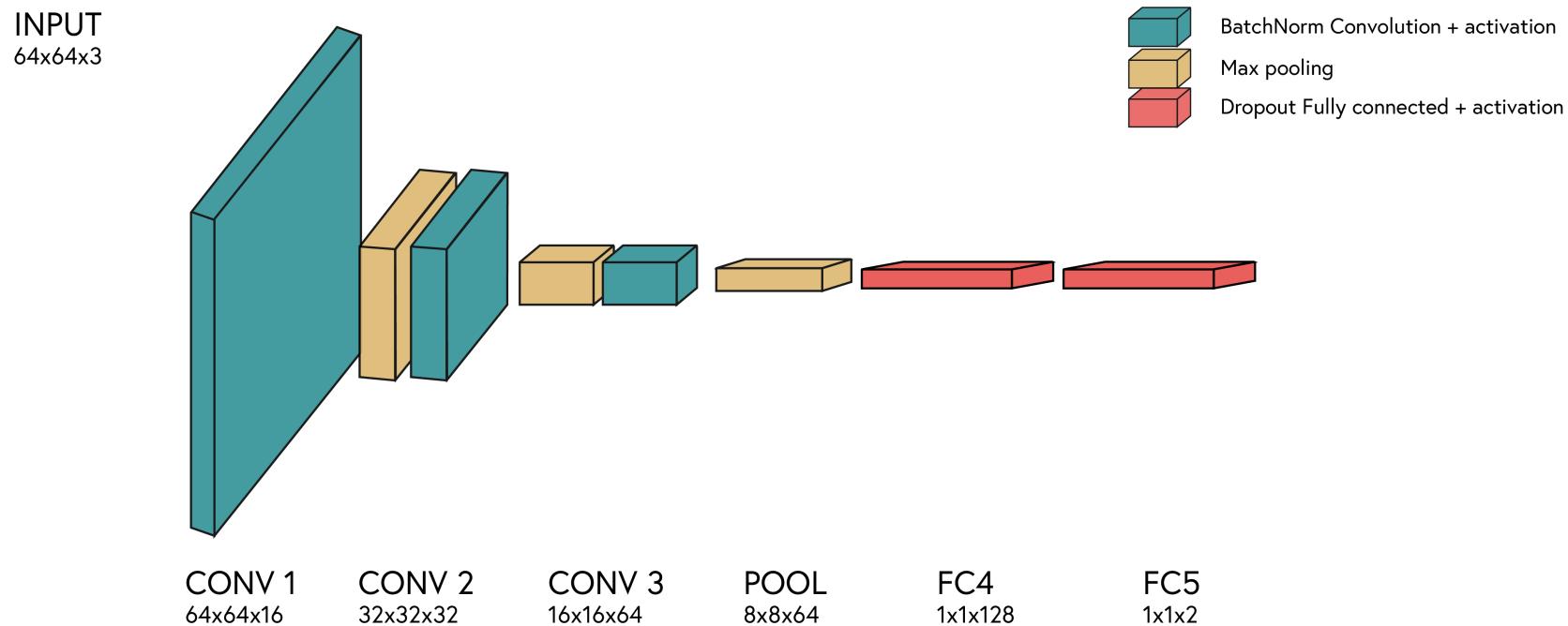
TINY VGG

Simplified version of VGG with 3 convolutional blocks

- Input → Conv → BatchNorm → ReLU → Pool → (repeat 3x) → FC → Output

Regularization:

- BatchNorm + Dropout ($p=0.1$) to prevent overfitting
- Progressive Feature Maps: $3 \rightarrow 16 \rightarrow 32 \rightarrow 64$ channels
- Dimensionality Reduction: Using pooling to reduce spatial dimensions
- Consistent Pattern: Conv → BatchNorm → ReLU → Pool at each level





BEST PRACTICES FOR CNNS

- Start with simple architectures and gradually increase complexity
- Use appropriate regularization techniques
- Apply proper data augmentation
- Monitor training with validation metrics
- Practice transfer learning when possible