Machine Learning
LABORATORY: CNN In Class

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Objectives:

- Students will implement 2D convolution and pooling operations from scratch (no PyTorch/TensorFlow high-level API like nn.Conv2d, F.max_pool2d, etc.) using only NumPy.
- Understand padding and stride behavior. Apply vertical and horizontal edge detection. Visualize results in black & white

Part 1. Instruction

- In this assignment, you will implement a basic Convolutional Neural Network operation pipeline using NumPy only — without using any deep learning libraries like PyTorch, TensorFlow, or OpenCV's built-in convolution functions.
- You will manually implement a general 2D convolution function that supports:
  - Padding (to preserve spatial dimensions)
  - Stride (to downsample the output)
- Then, you will apply vertical and horizontal edge detection filters to a grayscale input image and visualize the effects of:
  - Padding (padding=1)
  - Strided convolution (stride=2)
- Specifically, your tasks are to:
  - Load and normalize a grayscale image (e.g., checkerboard.png) for testing edge detection.
  - Implement the general convolution operation

$$C(j,k) = \sum_{l} \sum_{m} I(j+l, k+m)K(l,m)$$

$$\boldsymbol{I(j+l,k+m) = Image\ region}$$

$$\boldsymbol{K(l,m) = Kernel\ (Filter)}$$

$$\boldsymbol{C(j,k) = output\ at\ position\ (j,k)}$$

  - Apply the vertical edge detection kernel and horizontal edge detection kernel from Slide 6 to detect pattern structures in the image.
  - Apply convolution again using stride=2 to observe how spatial resolution changes (see Slide 8).
  - Visualize the output as black-and-white (binary) images using thresholding.
- At the end of the lab, please answer the two short questions to demonstrate your understanding of padding and stride.

Part 2. Code Template

Step	Procedure

1	`import numpy as np`
	`import cv2`
	`import matplotlib.pyplot as plt`
	
	`# Step 1: Load a grayscale image and normalize`
	# ➤ Slide 5: Understanding image representation
	`image = cv2.imread('original.png', cv2.IMREAD_GRAYSCALE)`
	`image = image.astype(np.float32) / 255.0   # Normalize to range [0, 1]`

2	`# Step 2: General Convolution Function`
	# ➤ Slide 8: C(j, k) = sum_l sum_m I(j + l, k + m) * K(l, m)
	`def convolve2d(image, kernel, padding=0, stride=1):`
	`    # TODO 1: Flip kernel for convolution`
	`    # TODO 2: Apply zero-padding if padding > 0`
	`    # TODO 3: Calculate output height and width`
	`    # TODO 4: Slide the kernel across the image with stride`
	`    # TODO 5: At each position, compute the sum of element-wise multiplication`
	`    return np.zeros((1, 1))  # Placeholder, replace with real output`

3	`# Step 3: Define edge detection filters`
	# ➤ Slide 6: Vertical & Horizontal edge filters
	`vertical_filter = np.array([`
	`    [x, x, x],`
	`    [x, x, x],`
	`    [x, x, x]`
	`], dtype=np.float32)`
	
	`horizontal_filter = np.array([`
	`    [x, x, x],`
	`    [ x,  x,  x],`
	`    [ x,  x,  x]`
	`], dtype=np.float32)`

4	`# Step 4: Convolve image with filters (padding=1, stride=1)`
	# ➤ Slide 7: Padding helps preserve image size
	`# TODO: vertical_edges = convolve2d(image, vertical_filter, padding=1)`
	`# TODO: horizontal_edges = convolve2d(image, horizontal_filter, padding=1)`
	
	`# Try strided convolutions (padding=1, stride=2)`
	# ➤ Slide 8: Stride reduces spatial resolution
	`# TODO: vertical_stride = convolve2d(image, vertical_filter, padding=1, stride=2)`
	`# TODO: horizontal_stride = convolve2d(image, horizontal_filter, padding=1, stride=2)`

5	`# Step 5: Visualization and Binarization function for black-and-white display`
	`def binarize(img, threshold=0.5):`
	`    img = img - np.min(img)`
	`    if np.max(img) != 0:`
	`        img = img / np.max(img)`
	`    return (img > threshold).astype(np.float32)`

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# Visualization
# TODO: Use matplotlib to show:
# - Original image
# - Vertical edges (pad=1)
# - Horizontal edges (pad=1)
# - Vertical edges (stride=2)
# - Horizontal edges (stride=2)
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#Example Output: (References Only)
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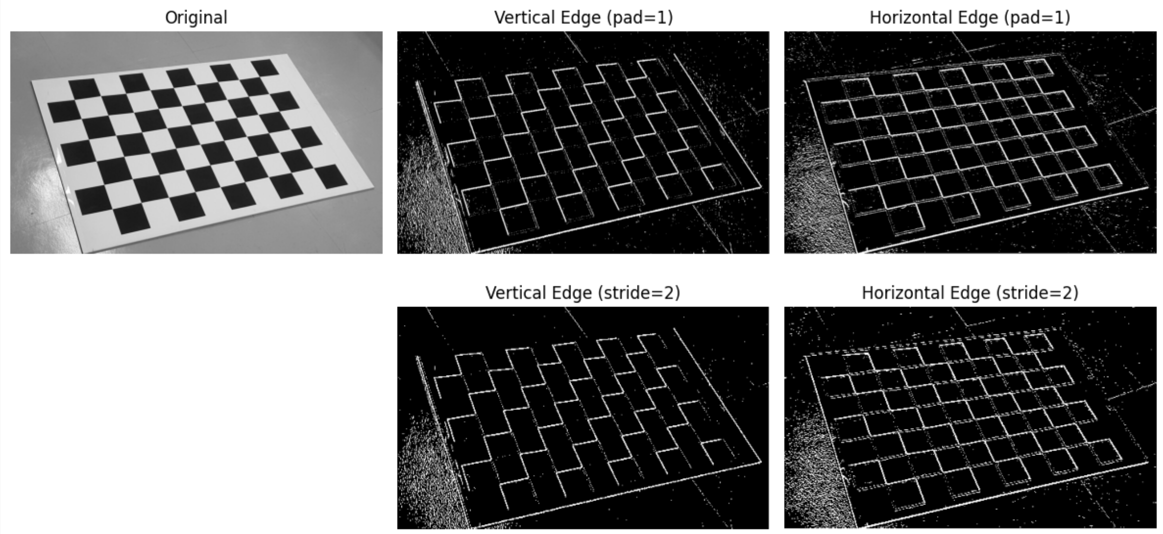


Grading Assignment & Submission (30% Max)

Implementation:

1. (10%) Correctly implement the convolve2d() function, including kernel flipping, padding, and stride
2. (5%) Correctly apply vertical and horizontal edge detection filters.
3. (5%) Apply binary thresholding to convert outputs to black-and-white images, and clearly visualize them using matplotlib. Show all five views: original, vertical (pad=1), horizontal (pad=1), vertical (stride=2), and horizontal (stride=2).

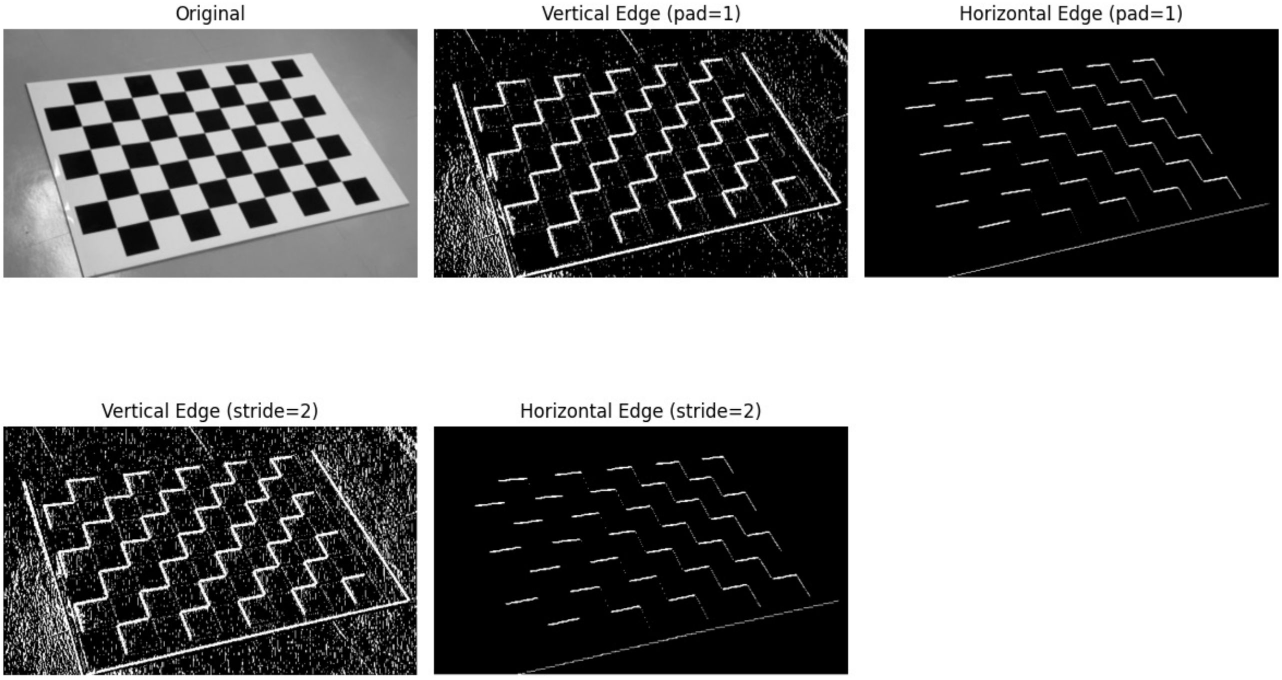
Question:

4. (5%) What types of patterns are detected by the vertical edge filter in an image? How is this different from the horizontal edge filter?
5. (5%) What is the effect of padding on the output image when applying convolution? Why is padding used?

Submission :

1. Report: Provide your screenshots of your results in the last pages of this PDF File.
2. Code: Submit your complete Python script in either .py or .ipynb format.
3. Upload both your report and code to the E3 system (**Labs6 In Class Assignment**). Name your files correctly:
   a. Report: StudentID_Lab6_InClass.pdf
   b. Code: StudentID_Lab6_InClass.py or StudentID_Lab6_InClass.ipynb
4. Deadline: 16:20 PM
5. Plagiarism is **strictly prohibited**. Submitting copied work from other students will result in penalties.

Results and Discussion:



4. What types of patterns are detected by the vertical edge filter in an image? How is this different from the horizontal edge filter?

The vertical edge filter computes the difference between pixels on its right and left, i.e. it approximates the horizontal gradient $\partial I/\partial x$. As a result, it "lights up" (produces bright responses for) any vertical boundary in the image where there is a sudden change in intensity across columns. In your checkerboard example, every vertical side of a square appears as a bright line in the "Vertical Edge (pad=1)" output.

horizontal edge filter computes the difference between pixels above and below, i.e. it approximates the vertical gradient $\partial I/\partial y$. It therefore highlights horizontal boundaries (edges running left-to-right), which you can see as bright streaks along each horizontal row in the "Horizontal Edge (pad=1)" result.

5. What is the effect of padding on the output image when applying convolution? Why is padding used?

Padding adds a one-pixel border of zeros (for padding=1) around the original image before convolution. This has two main effects:

1. Size preservation: Without padding, each convolution reduces the output dimensions by kernel_size−1 (so a 3×3 kernel shrinks a 100×100 image to 98×98). With padding=1, the output remains 100×100, matching the input.
2. Edge coverage: It allows the filter to center on every original pixel—including those at the very border—so that edge patterns at the image's perimeter are detected. In your output figures, you can observe that borders of the checkerboard still produce edge responses; without padding, those border edges would be lost or only partially detected.