

CS230: Deep Learning

Winter Quarter 2021

Stanford University

Midterm Examination

180 minutes

	Problem	Full Points	Your Score
1	Multiple Choice	16	
2	Short Answers	16	
3	Convolutional Architectures	20	
4	Augmenting with Noise	13	
5	Binary Classification	10	
6	Backpropagation	20	
7	Numpy Coding	20 (+10)	
Total		115 (+10)	

The exam contains 31 pages including this cover page.

- If you wish to complete the midterm in \LaTeX , please download the project source's ZIP file here. (The Stanford Box link, just in case you face issues with the hyperlink: <https://stanford.box.com/s/9dhx0l4jaqmk3o1fk3egfuisbvbvx69k1>)
- This exam is open book, but collaboration with anyone else, either in person or online, is strictly forbidden pursuant to The Stanford Honor Code.
- In all cases, and especially if you're stuck or unsure of your answers, **explain your work, including showing your calculations and derivations!** We'll give partial credit for good explanations of what you were trying to do.

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I attest that I have not given or received aid in this examination, and that I have done my share and taken an active part in seeing to it that others as well as myself uphold the spirit and letter of the Honor Code.

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Question 1 (Multiple Choice Questions, 16 points)

For each of the following questions, circle the letter of your choice. Each question has AT LEAST one correct option unless explicitly mentioned. No explanation is required.

- (a) **(2 points)** Your model for classifying different dog species is getting a high training set error. Which of the followings are promising things to try to improve your classifier?
- (i) Use a bigger neural network
 - (ii) Get more training data
 - (iii) Increase the regularization parameter lambda
 - (iv) Increase the parameter `keep_prob` in dropout layer (assume the classifier has dropout layers)

Solution: (i), (iv).

- (b) **(2 points)** Which of the followings are true about Batch Normalization?
- (i) Batch Norm layers are skipped at test time because a single test example cannot be normalized.
 - (ii) Its learnable parameters can only be learned using gradient descent or mini-batch gradient descent, but not other optimization algorithms.
 - (iii) It helps speed up learning in the network.
 - (iv) It introduces noise to a hidden layer's activation, because the mean and the standard deviation are estimated with a mini-batch of data.

Solution: (iii), (iv).

- (c) **(2 points)** If your input image is $64 \times 64 \times 16$, how many parameters are there in a single 1×1 convolution filter, including bias?
- (i) 2
 - (ii) 17
 - (iii) 4097
 - (iv) 1

Solution: (ii).

The filter contains 16 parameters in the weight and 1 in the bias.

- (d) **(2 points)** Which *one* of the following statements on initialization is *false*?

- (i) The variances of layer outputs remain unchanged during training when Xavier initialization is used.
- (ii) Initializing all weights to a positive constant value isn't sufficient to break learning symmetry during training.
- (iii) Different activation functions may benefit from different types of initializations.
- (iv) It's possible to break symmetry by initializing weights to be sampled uniformly from the set $\{-1, 1\}$.

Solution: (i)

Xavier initialization guarantees the variances are standardized at the start, but this can change over the course of training

- (e) **(2 points)** The shape of your input image is (n_h, n_w, n_c) ; the convolution layer uses a 1-by-1 filter with stride = 1 and padding = 0. Which of the following statements are correct?
- (i) You can reduce n_c by using 1x1 convolution. However, you cannot change n_h, n_w .
 - (ii) You can use a standard maxpooling to reduce n_h, n_w , but not n_c .
 - (iii) You can use a 1x1 convolution to reduce n_h, n_w, n_c .
 - (iv) You can use maxpooling to reduce n_h, n_w, n_c .

Solution: (i), (ii).

Maxpooling operates on the height and width dimensions of an image. Convolution reduces the input channels.

- (f) **(2 points)** Which of the following statements on regularization are true?
- (i) Using L-2 regularization enforces a Laplacian prior on your network weights.
 - (ii) Batch normalization can have an implicit regularizing effect, especially with smaller minibatches.
 - (iii) Layernorm's regularization effect increases with larger batch sizes.
 - (iv) Your choice of regularization factor can cause your model to underfit.

Solution: (ii), (iv).

(i): L-2 regularization enforces a Gaussian prior on weights
(ii): Smaller minibatches result in noisier estimates of the minibatch mean and variance - this has been empirically shown to improve generalization in some cases
(iii): Layer normalization doesn't depend on minibatch size and hasn't been shown to theoretically or empirically aid generalization
(iv): Setting an extremely large factor pushes learned weights close to zero

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- (g) **(2 points)** What is the benefit of using Momentum optimization?
- (i) Simple update rule with minimal hyperparameters
 - (ii) Helps get weights out of local minima
 - (iii) Effectively scales the learning rate to act the same amount across all dimensions
 - (iv) Combines the benefits of multiple optimization methods

Solution: (ii).

The choices describe SGD, Momentum, RMSProp, and Adam, respectively.

- (h) **(2 points)** Which of the below can you implement to solve the exploding gradient problem?
- (i) Use SGD optimization
 - (ii) Oversample minority classes
 - (iii) Increase the batch size
 - (iv) Impose gradient clipping

Solution: (iv).

Gradient clipping is an easy way to keep gradient values well-behaved. The other options do not help the problem at all.

Question 2 (Short Answers, 16 points)

The questions in this section can be answered in 2-4 sentences. Please be concise in your responses.

- (a) **(2 points)** Why is scaling (γ) and shifting (β) often applied after the standard normalization in the batch normalization layer?

Solution: Simply normalizing the inputs of a layer may change what the layer can represent. For instance, normalizing the inputs of a sigmoid function would constrain them to the linear regime of the nonlinearity. Inserting learnable transformation in the batch norm layer restores the representation power of the network.

- (b) **(2 points)** You are solving a biometric authentication task (modeled as binary classification) that uses fingerprint data to help users log into their devices. You train a classification model for user A until it achieves $> 95\%$ accuracy on a held-back development set (for same user). However, upon deployment you get complaints the model fails to correctly authenticate user A about half the time (50% misclassification rate). List one factor you think could have contributed to the *mismatch* in misclassification rates between the dev set and deployment, and how you'd go about fixing this issue.

Solution: The model does really well on the dev set, but fails upon deployment (can be thought of as test set). This reduces to a distribution discrepancy between the test and dev distributions. There are multiple factors that could contribute to this, but a couple of important (and popular) ones are:

- **Class imbalance in dev set:** Model could deterministically predict the same label all the time, yet achieve 95% dev accuracy if 95% of the dev set samples belonged to that label. This could be solved by using a balanced dev set, or using an alternate evaluation metric such as F1 score.
- **Distribution shift between dev and deployment:** Key change in biometric attribute being monitored. Eg.- user started wearing mask when logging

in (facial recognition), alteration to fingerprint (fingerprint recognition), etc..
Solution would be to retrain model with data from new conditions.

Grading was based on:

- reference to the distribution discrepancy between dev and test
- identifying a possible solution

Since the problem asked for only **one** factor, students had submitting multiple solutions were graded on their *first* answer. Partial credit was awarded in cases where multiple factors (and solutions) were listed, but the correct answer was not the topmost one.

(c) **(2 points)** A convolutional neural network has 4 consecutive layers as follows:

3x3 conv (stride 2) - 2x2 Pool - 3x3 conv (stride 2) - 2x2 Pool

How large is the support (the set of image pixels which activate) of a neuron in the 4th non-image layer of this network?

Solution: $1 \times 1 \leftarrow 2 \times 2 \leftarrow 5 \times 5 \leftarrow 10 \times 10 \leftarrow 21 \times 21$. The support is $21 \times 21 = 441$ pixels.

(d) **(2 points)** Is it always a good strategy to train with large batch size? Why or why not?

Solution: No. First of all, you could easily run out of memory on your GPU. Second, training with large batch size could lead to high test error (<https://mobile.twitter.com/ylecun/status/989610208497360896?lang=en>). Third, training with large batch size could potentially make the training diverging.

(e) **(2 points)** What is the purpose of using 1x1 convolution?

Solution: 1x1 convolution reduces the size of feature maps before sending them to layers with more expensive filters (3x3, 5x5). Using 1x1 convolution, we can stack more layers and allocate them on the training device. Check the inception paper for more details.

- (f) **(2 points)** Why is the sigmoid activation function susceptible to the vanishing gradient problem?

Solution: As the input into the sigmoid becomes either too small or too large, the sigmoid output begins over-saturating and the gradient in those regimes approach 0.

- (g) **(2 points)** Say you are trying to solve a binary classification problem where the positive class is very underrepresented (e.g. 9 negatives for every positive). Describe precisely a technique which you can use during training which helps alleviate the class imbalance problem. Would you apply this technique at test time? Why or why not?

Solution: You can oversample the positive class 9x so that the classes "look even" during training. You would not apply this technique at test time, as it gives an inaccurate model performance metric on the dev/test set.

- (h) **(2 points)** Let p be the **probability of keeping** neurons in a dropout layer. We have seen that in forward passes, we often scale activations by dividing them by p during training time.

You accidentally train a model with dropout layers *without* dividing the activations by p . How would you resolve this issue at test time? Please justify your answer mathematically.

Solution:

- Dropout switched off at test time - expected activation thus larger than train by factor $\frac{1}{p}$; fix by multiplying outputs of each layer by p
- Some mathematical expression involving an expectation over activations, and how the scaling factor helps rescale the expected value.

Question 3 (Convolutional Architectures, 20 points)

Consider a convolutional neural network block whose input size is $64 \times 64 \times 8$. The block consists of the following layers:

- A convolutional layer 32 filters with height and width 3 and 0 padding which has both a weight and a bias (i.e. CONV3-32)
- A 2×2 max-pooling layer with stride 2 and 0 padding (i.e. POOL-2)
- A batch normalization layer (i.e. BATCHNORM)

Compute the output activation volume dimensions and number of parameters of the layers. You can write the activation shapes in the format (H, W, C) where H, W, C are the *height*, *width*, and *channel* dimensions, respectively.

- i. **(2 points)** What is the output activation volume dimensions and number of parameters for CONV3-32?

Solution: Activation volume dimensions: $62 \times 62 \times 32$
 Number of parameters: $(3 * 3 * 8 + 1) * 32 = 2336$

- ii. **(2 points)** What is the output activation volume dimensions and number of parameters for POOL2?

Solution: Activation volume dimensions: $31 \times 31 \times 32$
 Number of parameters: 0

- iii. **(2 points)** What is the output activation volume dimensions and number of parameters for BATCHNORM?

Solution: Activation volume dimensions: $31 \times 31 \times 32$
 Number of parameters: $2 * 32$

Now you will design a very small convolutional neural network for the task of digit predict: given a 16×16 image (with 3 channels i.e. RGB), you want to predict the digit shown in the image. Therefore, this is a 10-class classification problem.

Your network will have 4 layers, given in order: a convolutional layer, a max-pooling layer, a flatten layer, and a fully-connected layer.

Design the neural network to solve this problem. Of course, there are many, many solutions to this question. To narrow the solution space, here are some restrictions:

- Your convolutional layer must have a stride of 1 and have 4 filters. Because of memory limits, this layer's **activation volume** should not have no more than 576 total elements in the tensor per input image (e.g. a $2 \times 2 \times 8$ tensor has $2 * 2 * 8 = 32$ total elements in it).
- Your max-pooling layer must have the same stride as pool size e.g. a 2×2 pooling layer must have a stride of 2.
- Again because of memory limits, your final fully-connected layer will not have a bias term, and its total number of **parameters** cannot exceed 1440.

The rest is up to you. Answer the following questions to incrementally build out your small CNN architecture.

- iv. **(4 points)** What are the hyperparameters of the convolutional layer you propose (i.e. filter size, padding)? Also, what are the activation volume dimensions for this layer?

Solution: POSSIBLE SOLUTION

Filter size: 5; padding: 0 (stride: 1; filters: 4)

Activation volume dimensions: $12 \times 12 \times 4$

2 points for correct AVD given hyperparams, 2 points for making sure that dims are $\leq 12 \times 12$

- v. **(4 points)** What are the hyperparameters of the max-pooling layer you propose (i.e. pool size)? Also, what are the activation volume dimensions for this layer?

Solution: POSSIBLE SOLUTION

Pool size and stride: 2 (padding: 0)

Activation volume dimensions: $6 \times 6 \times 4$

2 points for correct AVD given hyperparams, 2 points for making sure that dims are $\leq 6 \times 6$

- vi. **(2 points)** What are the activation volume dimensions of the final fully-connected layer?

Solution: ONLY SOLUTION(S)

Activation volume dimensions: 1×10 or just 10

- vii. **(4 points)** You start training your model and notice underfitting, so you decide to add data augmentation as part of your preprocessing pipeline. Given that you are working with images of handwritten digits, for each data augmentation technique, state whether or not the technique is appropriate for the task. If not, explain why not.

(a) Scaling slightly

Solution: Is appropriate

(b) Flipping vertically or horizontally

Solution: Is not appropriate; e.g. 7 is vertically flipped and is unreadable

(c) Rotating by 90 or 180 degrees

Solution: Is not appropriate; e.g. 6 turns into 9

(d) Shearing slightly

Solution: Is appropriate

Question 4 (Augmenting with Noise, 13 points)

You are tasked with solving a fitting a linear regression model on a set of m datapoints where each feature has some dimensionality d . Your dataset can be described as the set:

$$\{x^{(i)}, y^{(i)}\}_{i=1}^m, \text{ where } x^{(i)} \in \mathbb{R}^d$$

For all parts of this problem, assume m is very large (you can consider the limit $m \rightarrow \infty$). You initially decide to optimize the loss objective:

$$J = \frac{1}{m} \sum_{i=1}^m (y^{(i)} - x^{(i)T} \theta)^2$$

using Batch Gradient Descent. Here, $\theta \in \mathbb{R}^d$ is your weight vector. Assume you are ignoring a bias term for this problem.

- i. **(3 points)** Write each update of the *batch* gradient descent, $\frac{\partial J}{\partial \theta}$ in **vectorized** form. Your solution should be a **single** vector (no summation terms) in terms of the matrix \mathbf{X} and vectors \mathbf{Y} and θ , where

$$\mathbf{X} = \begin{bmatrix} x^{(1)T} \\ \vdots \\ x^{(m)T} \end{bmatrix} \text{ and } Y = \begin{bmatrix} y^{(1)} \\ \vdots \\ y^{(m)} \end{bmatrix}$$

Solution:

- Final solution is

$$\frac{\partial J}{\partial \theta} = \frac{2}{m} \mathbf{X}^T (\mathbf{X} \theta - Y)$$

Dimensions (\mathbb{R}^d) should match precisely for full points

- Two common approaches are “derive, then vectorize” and “vectorize, then

derive”. Both get full credit. With the first approach:

$$\begin{aligned}\frac{\partial J}{\partial \theta} &= \frac{2}{m} \sum_i (x^{(i)T} \theta - y^{(i)}) x^{(i)} \quad (\text{derivative step}) \\ &= \frac{\partial J}{\partial \theta} = \frac{2}{m} \mathbf{X}^T (\mathbf{X} \theta - Y) \quad (\text{vectorization step})\end{aligned}$$

A coworker suggests you augment your dataset by adding Gaussian noise to your features. Specifically, you would be adding *zero-mean, Gaussian* noise of *known variance* σ^2 from the distribution

$$\mathcal{N}(0, \sigma^2 I)$$

where $I \in \mathbb{R}^{d \times d}$, $\sigma \in \mathbb{R}$

This modifies your original objective to:

$$J_* = \frac{1}{m} \sum_{i=1}^m (y^{(i)} - (x^{(i)} + \delta^{(i)})^T \theta)^2$$

where $\delta^{(i)}$ are **i.i.d.** noise vectors, $\delta^{(i)} \in \mathbb{R}^d$ and $\delta^{(i)} \sim \mathcal{N}(0, \sigma^2 I)$.

- ii. **(6 points)** Express the **expectation** of the modified objective J_* over the gaussian noise, $\mathbb{E}_{\delta \sim \mathcal{N}}[J_*]$, as a function of the original objective J added to a term *independent* of your data. Your answer should be in the form

$$\mathbb{E}_{\delta \sim \mathcal{N}}[J_*] = J + C$$

where C is independent of points in $\{x^{(i)}, y^{(i)}\}_{i=1}^m$.

Hint:

- For a Gaussian random vector δ with mean zero, covariance matrix $\sigma^2 I$,

$$\mathbb{E}_{\delta \sim \mathcal{N}}[\delta \delta^T] = \sigma^2 I$$

and

$$\mathbb{E}_{\delta \sim \mathcal{N}}[\delta] = \mathbf{0}$$

As a consequence, $\mathbb{E}_{\delta \sim \mathcal{N}}[(\delta^T v)^2] = \sigma^2 v^T v$ for a constant vector v

Solution:

$$\begin{aligned}
 J_* &= \frac{1}{m} \sum_{i=1}^m (y^{(i)} - (x^{(i)} + \delta^{(i)})^T \theta)^2 \\
 &= \frac{1}{m} \sum_{i=1}^m ((y^{(i)} - x^{(i)T} \theta) - \delta^{(i)T} \theta)^2 \\
 &= \frac{1}{m} \sum_{i=1}^m ((y^{(i)} - x^{(i)T} \theta)^2 - 2(y^{(i)} - x^{(i)T} \theta)(\delta^{(i)T} \theta) + (\delta^{(i)T} \theta)^2) \\
 &= J + \frac{1}{m} \sum_{i=1}^m (-2(y^{(i)} - x^{(i)T} \theta)(\delta^{(i)T} \theta) + (\delta^{(i)T} \theta)^2)
 \end{aligned}$$

$$\mathbb{E}_{\delta \sim \mathcal{N}}[J_*] = J + \mathbb{E}_{\delta \sim \mathcal{N}} \left[\frac{1}{m} \sum_{i=1}^m (-2(y^{(i)} - x^{(i)T} \theta)(\delta^{(i)T} \theta) + (\delta^{(i)T} \theta)^2) \right]$$

From **Linearity of Expectation**, we can take the expectation individually for each sample:

$$\mathbb{E}_{\delta \sim \mathcal{N}}[-2(y^{(i)} - x^{(i)T} \theta)\delta^{(i)T} \theta] = -2(y^{(i)} - x^{(i)T} \theta)\mathbb{E}[\delta^{(i)T} \theta] = \mathbf{0}$$

$$\mathbb{E}_{\delta \sim \mathcal{N}}[(\delta^{(i)T} \theta)^2] = \sigma^2 \|\theta\|_2^2 \text{ (follows directly from hints)}$$

Thus, we get:

$$\mathbb{E}_{\delta \sim \mathcal{N}}[J_*] = J + \sigma^2 \|\theta\|_2^2$$

- iii. **(2 points)** In expectation, what effect would the addition of the noise have on model overfitting/underfitting? Explain why.

Solution: In expectation, the new objective would help regularize the model, due to the L2 regularization term.

- iv. **(2 points)** Consider the limits $\sigma \rightarrow 0$ and $\sigma \rightarrow \infty$. What impact would these extremes in the value of σ have on model training (relative to no noise added)? Explain why.

Solution:

- $\sigma \rightarrow 0$: Less regularizing/no effect
- $\sigma \rightarrow \infty$: All weights get pushed to zero / model underfits

Question 5 (Binary Classification, 10 points)

You are building a classification model to distinguish between labels from a *synthetically* generated dataset. More specifically, you are given a dataset,

$$\{x^{(i)}, y^{(i)}\}_{i=1}^m, \text{ where } x^{(i)} \in \mathbb{R}^2, y^{(i)} \in \{0, 1\}$$

The data is generated with the scheme:

$$X|Y = 0 \sim \mathcal{N}(2, 2)$$

$$X|Y = 1 \sim \mathcal{N}(0, 3)$$

You can assume the dataset is perfectly balanced between the two classes.

1. **(2 points)** As a baseline, you decide to use a logistic regression model to fit the data. Since the data is synthesized easily, you can assume you have infinitely many samples (i.e. $m \rightarrow \infty$). Can your logistic regression model achieve 100% training accuracy? Explain your answer.

Solution: No. The standard deviations of the two distributions are large enough that a significant proportion of the samples won't be separable by a linear decision boundary (the type drawn by logistic regression).

2. **(8 points)** After training on a large training set of size M , your logistic regressor achieves a training accuracy of T . Can the following techniques, *applied individually*, improve over this *training accuracy*? Please justify your answer in a single sentence.

Solution: The key here is to realize the logistic regression model is a linear classifier and suffers from *high bias*. Since we assume the model has been trained to convergence, the only techniques that can help are ones that increase variance of the model. We need not worry about overfitting since we care only about improving the training performance.

- (a) Adding a regularizing term to the binary cross entropy loss function for the logistic regressor

Solution: No, regularization wouldn't help fit the training set better

- (b) Standardizing all training samples to have *mean zero* and *unit variance*

Solution: No; no impact on model variance, only helps speed up training in this case

- (c) Using a 5-hidden layer feedforward network *without* non-linearities in place of logistic regression

Solution: This can be mathematically reduced to a single layer where the weights are a product of the weight matrices from the original network; the decision boundary would still be linear.

- (d) Using a 2-hidden layer feedforward network *with* ReLU in place of logistic regression

Solution: Yes. Non-linearities in the hidden layers can help the model learn a more non-linear boundary separating the two distributions. Correct solutions commonly referred to reduced bias/higher variance, the non-linear boundary, increased model complexity, or some association between the ReLU and increased performance. Solutions referring to “ReLU speeding up training” were partially penalized since more efficient training doesn't impact the final training error (but rather how quickly we attain that error).

Caveat: this answer is difficult to empirically verify. Theoretically, an infinite-width hidden layer with non-linearity can help approximate any non-linear boundary (see Universal Approximation Theorem for reference). However, this could require the hidden layer to be infeasibly large, given the distributions being separated are Gaussians (with infinite support). The UAT is beyond the scope of the class, hence any reference to a non-linear decision boundary would suffice. In some cases, solutions that answered ‘no’ on this part received partial credit, so long as they were accompanied by a discussion on the nature of distributions being separated.

Question 6 (Backpropagation, 20 points)

The softmax function has the desirable property that it outputs a probability distribution, and is often used as activation function in many classification neural networks.

Consider a 2-layer neural network for K -class classification using softmax activation and cross-entropy loss, as defined below:

$$\begin{aligned}\mathbf{z}^{[1]} &= W^{[1]}\mathbf{x} + \mathbf{b}^{[1]} \\ \mathbf{a}^{[1]} &= \text{LeakyReLU}(\mathbf{z}^{[1]}, \alpha = 0.01) \\ \mathbf{z}^{[2]} &= W^{[2]}\mathbf{a}^{[1]} + \mathbf{b}^{[2]} \\ \hat{\mathbf{y}} &= \text{softmax}(\mathbf{z}^{[2]}) \\ L &= - \sum_{i=1}^K \mathbf{y}_i \log(\hat{\mathbf{y}}_i)\end{aligned}$$

where the model is given input \mathbf{x} of shape $D_x \times 1$, and one-hot encoded label $\mathbf{y} \in \{0, 1\}^K$. Assume that the hidden layer has D_a nodes, i.e. $\mathbf{z}^{[1]}$ is a vector of size $D_a \times 1$. Recall the softmax function is computed as follows:

$$\hat{\mathbf{y}} = \left[\frac{\exp(\mathbf{z}_1^{[2]})}{Z}, \dots, \frac{\exp(\mathbf{z}_K^{[2]})}{Z} \right]$$

where $Z = \sum_{j=1}^K \exp(\mathbf{z}_j^{[2]})$

- (i) **(2 points)** What are the shapes of $W^{[2]}, b^{[2]}$? If we were vectorizing across m examples, i.e. using a batch of samples $X \in \mathcal{R}^{D_x \times m}$ as input, what would be the shape of the output of the hidden layer?

Solution: $W^{[2]} \in \mathcal{R}^{K \times D_a}, b^{[2]} \in \mathcal{R}^{K \times 1}$.

The output has size $D_a \times m$.

- (ii) **(2 points)** What is $\partial \hat{\mathbf{y}}_k / \partial z_k^{[2]}$? Simplify your answer in terms of element(s) of $\hat{\mathbf{y}}$.

Solution:

$$\frac{\partial \hat{\mathbf{y}}_k}{\partial z_k^{[2]}} = \frac{\exp(z_k^{[2]})Z - \exp(z_k^{[2]})^2}{Z^2} = \hat{\mathbf{y}}_k(1 - \hat{\mathbf{y}}_k)$$

- (iii) **(2 points)** What is $\partial \hat{\mathbf{y}}_k / \partial z_i^{[2]}$, for $i \neq k$? Simplify your answer in terms of element(s) of $\hat{\mathbf{y}}$.

Solution:

$$\frac{\partial \hat{\mathbf{y}}_k}{\partial z_i^{[2]}} = -\frac{\exp(z_k^{[2]})\exp(z_i^{[2]})}{Z^2} = -\hat{\mathbf{y}}_k \hat{\mathbf{y}}_i$$

- (iv) **(3 points)** Assume that the label \mathbf{y} has 1 at its k^{th} entry, and 0 elsewhere. What is $\partial L / \partial z_i^{[2]}$? Simplify your answer in terms of $\hat{\mathbf{y}}_i$. Hint: Consider both cases where $i = k$ and $i \neq k$.

Solution:

$$L = -\log(\hat{\mathbf{y}}_k)$$

When $i = k$,

$$\frac{\partial L}{\partial z_i^{[2]}} = \frac{\partial L}{\partial \hat{\mathbf{y}}_k} \frac{\partial \hat{\mathbf{y}}_k}{\partial z_i^{[2]}} = -\frac{1}{\hat{\mathbf{y}}_i} \hat{\mathbf{y}}_i(1 - \hat{\mathbf{y}}_i) = \hat{\mathbf{y}}_i - 1$$

When $i \neq k$,

$$\frac{\partial L}{\partial z_i^{[2]}} = \frac{\partial L}{\partial \hat{\mathbf{y}}_k} \frac{\partial \hat{\mathbf{y}}_k}{\partial z_i^{[2]}} = \frac{1}{\hat{\mathbf{y}}_k} \hat{\mathbf{y}}_k \hat{\mathbf{y}}_i = \hat{\mathbf{y}}_i$$

- (v) **(1 points)** What is $\partial z^{[2]} / \partial a^{[1]}$? Refer to this result as δ_1 .

Solution: $\delta_1 = W^{[2]}$

- (vi) **(2 points)** What is $\partial a^{[1]}/\partial z^{[1]}$? Refer to this result as δ_2 . Feel free to use curly brace notation.

Solution:

$$\delta_2 = \begin{cases} 1, & \text{if } z_i^{[1]} \geq 0 \\ 0.01, & \text{otherwise} \end{cases}$$

- (vii) **(6 points)** Denote $\partial L/\partial z^{[2]}$ with δ_0 . What is $\partial L/\partial W^{[1]}$ and $\partial L/\partial b^{[1]}$? You can reuse notations from previous parts. Hint: Be careful with the shapes.

Solution: Using chain rule for partial derivatives, we get:
(Note the element-wise product)

$$\partial L/\partial W^{[1]} = \delta_1^T * \delta_0 \circ \delta_2 * \mathbf{x}^T$$

$$\partial J/\partial b^{[1]} = \delta_1^T * \delta_0 \circ \delta_2$$

- (viii) **(2 points)** To avoid running into issues with numerical stability, one trick may be used when implementing the softmax function. Let $m = \max_{i=1}^K z_i$ be the max of z_i , then

$$\hat{\mathbf{y}}_i = \frac{\exp(\mathbf{z}_i^{[2]} - m)}{\sum_{j=1}^K \exp(\mathbf{z}_j^{[2]} - m)}$$

What is the numerical problem with the initial softmax computation? Why the modified formula would help resolving that problem?

Solution: A big $\mathbf{z}_i^{[2]}$ will lead to overflow. All very small $\mathbf{z}_i^{[2]}$ will lead to division-by-zero error.

The modified formula ensures the maximum exponential result is 1, and the denominator is always greater than 1.

Question 7 (Numpy Coding , 20 points (+10 bonus points))

Stanford Medical School reaches out to you for your help to analyze an MRI dataset. Since the dataset contains 3-D images, you decide to build a model with 3-D convolution (Conv3D). However, you soon find that your most powerful weapon, NumPy, does not have a good Conv3D implementation. Instead of waiting for NumPy's developers to respond to your feature request, you figure that you would just implement one yourself.

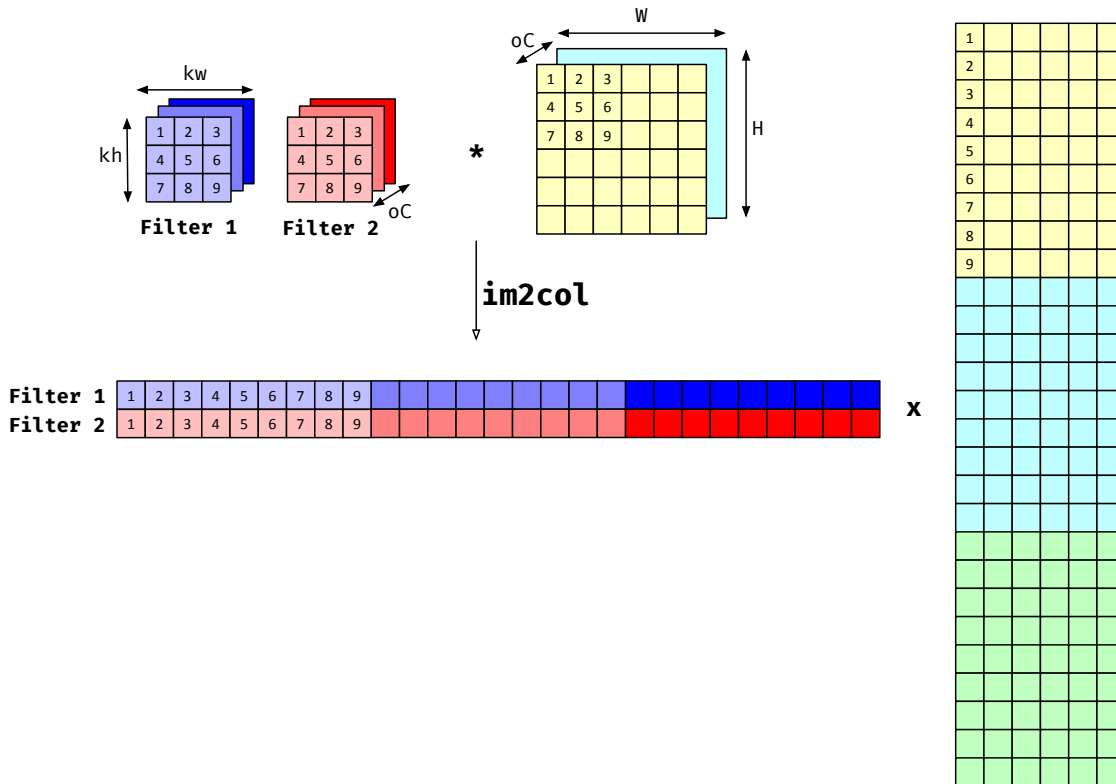
You are given two NumPy ndarrays: an image array $\in \mathbb{R}^{N,iC,H,W,D}$ and a filter tensor $\in \mathbb{R}^{oC,iC,kw,kh,kd}$, with the following specifications:

- N: Number of images within a batch.
- iC, oC: Numbers of input and output channels, respectively.
- H, W, D: Height, width, and depth of an MRI frame.
- kw, kh, kd: Sizes of a filter's height, width, and depth dimension.

A Conv3D is very similar to a Conv2D, with the only difference being that Conv3D also performs convolution (also known as correlation before the era of deep learning) on a third dimension, D. In your case, you choose to start with the simplest Conv3D settings: there's no padding or dilation, and the stride size is set to 1. To speed up the kernel execution, you should first transform the two ndarrays into two matrices. Then, you would do a matrix multiplication, a highly optimized NumPy subroutine, to generate the final result.

Pseudocode:

1. **Transform N-D data into 2-D.** The idea here is that NumPy is not great with pure Python loops. However, we can reformat data into matrices to utilize NumPy's fast matrix multiplication support. To do so, we need to extend a trick called image-to-column (im2col) so that it can handle a 3-D image. What is im2col? Roughly speaking, it divides an image into kw-by-kh sub-images, Then, im2col flattens the sub-images into columns and stacks them together. At the same time, the filters are also flattened into a matrix. By multiplying the filter matrix with the stacked columns of an image, we effectively perform a convolution:



Obviously, this approach only works for 2-D images for now. Hence, at this step, your goal is to extend `im2col` to work on 3-D images.

2. **Data reformatting.** After doing `im2col` followed by a matrix multiplication, you need to reformat the data so that it is still in the shape of (N, oC, oW, oH, oD) , where oW, oH, oD are the width, height, and depth of the output tensor.

Implementing Conv3D

We ask that you write down a `Conv3D` implemented using Python for-loops. Obviously, this approach will not run efficiently, but it gives you a baseline you can improve on. We have extra bonus points for you if you could figure out how to replace the loops with NumPy subroutines! For all of the subproblems in this section, you can assume that you have access to the stride parameter.

7.1 Implement get_tiled_dim (5 points) First, you need to calculate the output dimensions of Conv3D. Please implement `get_tiled_dim`. The input arguments are `img_dim`, the size of an image dimension, and `kern_dim`, the size of a dimension of the kernel.

```
import numpy as np
def get_tiled_dim(img_dim: int, kern_dim: int) -> int:
    """
    :param img_dim: The size of an image dimension.
    :param kern_dim: The size of a kernel dimension.
    :return: The size of the output dimension.
    """
```

Solution:

```
import numpy as np
def get_tiled_dim(img_dim: int, kern_dim: int) -> int:
    """
    :param img_dim: The size of an image dimension.
    :param kern_dim: The size of a kernel dimension.
    :return: The size of the output dimension.

    return (img_dim - kern_dim) // stride + 1
```

7.2 Conv3D in loop-form (15 points) Then, you need to implement the actual Conv3D using NumPy matrix multiplication and Python loops. Hint: use the `get_tiled_dim` function to calculate the output dimensions.

```
import numpy as np

def conv3d_naive(image: np.ndarray, weight: np.ndarray) -> np.ndarray:
    """
    :param image: Images with depth information of size
                  N by iC by D by H by W.
    :param weight: Filters of size oC by iC by kw by kh by kd.
    :return: The result of running Conv3D
    """
```

Solution:

```

import numpy as np

def conv3d_naive(image: np.ndarray, weight: np.ndarray) -> np.ndarray:
    """
    :param image: Images with depth information of size
                  N by iC by D by H by W.
    :param weight: Filters of size oC by iC by kw by kh by kd.
    :return: The result of running Conv3D
    """

    def get_tiled_dim(img_dim: int, kern_dim: int) -> int:
        return (img_dim - kern_dim) // stride + 1

    new_h, new_w, new_d = [
        get_tiled_dim(a, b) for (a, b) in zip([H, W, D], [kw, kh, kd])
    ]

    flattened_weight = weight.reshape((oC, iC * kh * kw * kd))
    new_image = np.zeros([new_h * new_w * new_d * N, iC * kh * kw * kd])

    for i_h in range(new_h):
        _i_h = i_h * stride
        __i_h = _i_h + kh
        for i_w in range(new_w):
            _i_w = i_w * stride
            __i_w = _i_w + kw
            for i_d in range(new_d):
                _i_d = i_d * stride
                __i_d = _i_d + kd
                tile = image[:, :, _i_h:__i_h, _i_w:__i_w, _i_d:__i_d].
                    reshape((N, iC * kh * kw * kd))
                ir_new_image = (i_h * new_w * new_d + i_w * new_d + i_d)*N
                new_image[ir_new_image : ir_new_image + N, :] = tile

    result = np.transpose(
        (flattened_weight @ new_image.T).reshape(
            (oC, new_h, new_w, new_d, N)), (4, 0, 1, 2, 3)
    )
    return result

```

7.3 Conv3D using fast NumPy subroutines (Bonus, 10 points) Since Python is an interpreted language, Python loops can be very slow. Luckily, NumPy provides subroutines that allow us to manipulate large tensor data efficiently. Can you implement a Conv3D without any loops involved? Hint: you can take a look at `np.lib.stride_tricks.sliding_window_view`.

```
import numpy as np

def conv3d_no_loop(image: np.ndarray, weight: np.ndarray) -> np.ndarray:
    """
    :param image: Images with depth information of size
                  N by iC by D by H by W.
    :param weight: Filters of size oC by iC by kw by kh by kd.
    :return: The result of running Conv3D
    """
```

Solution:

```

import numpy as np

def conv3d_no_loop(image: np.ndarray, weight: np.ndarray) -> np.ndarray:
    """
    :param image: Images with depth information of size
                  N by iC by D by H by W.
    :param weight: Filters of size oC by iC by kw by kh by kd.
    :return: The result of running Conv3D
    """

    def get_tiled_dim(img_dim: int, kern_dim: int) -> int:
        return (img_dim - kern_dim) // stride + 1

    new_h, new_w, new_d = [
        get_tiled_dim(a, b) for (a, b) in zip([H, W, D], [kw, kh, kd])
    ]

    flattened_weight = weight.reshape((oC, iC * kh * kw * kd))
    strided_sub_images = np.lib.stride_tricks.sliding_window_view(
        image, (kh, kw, kd), (2, 3, 4)
    ) # N, iC, new_h, new_w, new_d, kh, kw, kd
    flattened_image = np.transpose(
        strided_sub_images, (0, 2, 3, 4, 1, 5, 6, 7)
    ).reshape(
        (N * new_h * new_w * new_d, iC * kh * kw * kd)
    ) # N, new_h, new_w, new_d, iC, kh, kw, kd
    result = np.transpose(
        (flattened_weight @ flattened_image.T).reshape(
            (oC, N, new_h, new_w, new_d)), (1, 0, 2, 3, 4)
        )

    return result

```

END OF PAPER