

EE239A_Problem_Set_1_YAMAN_YUCEL

October 18, 2023

1 ECE 239AS: Problem Set #1

This problem set will revisit the imaging pipeline, denoising, and HDR imaging from the corresponding lectures and textbook sections. The goal is to develop a working understanding of the digital image formation model that is central to most modern day imaging devices. This will be important in later course material when we discuss extreme imaging systems that. With that goal in mind, the organization of this notebook is split into three problems:

1. Imaging Pipeline
2. Denoising
3. High Dynamic Range Imaging

These three steps are a key part of the digital photography pipeline.

1.1 How to Implement

Sections of code you need to write are marked with:

**** STUDENT CODE HERE **** and have function names beginning with “student_”. After the key student functions, we will include a call to a function named “check_code_correctness” which will evaluate your output against an output from the TAs.

NOTE: This will only check for correctness if you use the exact algorithm we do. We **highly encourage** you to explore new algorithms not covered in class, but these cannot be sanity checked by our code.

```
[1]: !pip install rawpy
      !pip install imageio
      !pip install gdown
```

Collecting rawpy

Downloading

rawpy-0.18.1-cp310-cp310-manylinux_2_17_x86_64.manylinux2014_x86_64.whl (1.9 MB)
1.9/1.9 MB

10.0 MB/s eta 0:00:00

Requirement already satisfied: numpy in /usr/local/lib/python3.10/dist-packages (from rawpy) (1.23.5)

Installing collected packages: rawpy

Successfully installed rawpy-0.18.1

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Requirement already satisfied: numpy in /usr/local/lib/python3.10/dist-packages (from imageio) (1.23.5)

Requirement already satisfied: pillow>=8.3.2 in /usr/local/lib/python3.10/dist-packages (from imageio) (9.4.0)

Requirement already satisfied: gdown in /usr/local/lib/python3.10/dist-packages (4.6.6)

Requirement already satisfied: filelock in /usr/local/lib/python3.10/dist-packages (from gdown) (3.12.4)

Requirement already satisfied: requests[socks] in /usr/local/lib/python3.10/dist-packages (from gdown) (2.31.0)

Requirement already satisfied: six in /usr/local/lib/python3.10/dist-packages (from gdown) (1.16.0)

Requirement already satisfied: tqdm in /usr/local/lib/python3.10/dist-packages (from gdown) (4.66.1)

Requirement already satisfied: beautifulsoup4 in /usr/local/lib/python3.10/dist-packages (from gdown) (4.11.2)

Requirement already satisfied: soupsieve>1.2 in /usr/local/lib/python3.10/dist-packages (from beautifulsoup4->gdown) (2.5)

Requirement already satisfied: charset-normalizer<4,>=2 in /usr/local/lib/python3.10/dist-packages (from requests[socks]->gdown) (3.3.0)

Requirement already satisfied: idna<4,>=2.5 in /usr/local/lib/python3.10/dist-packages (from requests[socks]->gdown) (3.4)

Requirement already satisfied: urllib3<3,>=1.21.1 in /usr/local/lib/python3.10/dist-packages (from requests[socks]->gdown) (2.0.6)

Requirement already satisfied: certifi>=2017.4.17 in /usr/local/lib/python3.10/dist-packages (from requests[socks]->gdown) (2023.7.22)

Requirement already satisfied: PySocks!=1.5.7,>=1.5.6 in /usr/local/lib/python3.10/dist-packages (from requests[socks]->gdown) (1.7.1)

```
[2]: # Imports
import numpy as np
from PIL import Image
import matplotlib.pyplot as plt
import rawpy
import json
import scipy
import imageio.v3 as iio
%matplotlib inline
```

```
[3]: def check_code_correctness(test_function, test_in, test_out):
    """Checks if the given function behaves as expected"""

    Args:
    test_function: Function to test
    test_in: The sample input to test on
    test_out: The expected output of the function given the specified input
```

```

Returns:
    True if the function behaves as expected, False otherwise (wrong answer,
    ↪ or error)
    """

    try:
        student_out = test_function(test_in)
    except NotImplementedError as err:
        print("Please implement and remove \'raise NotImplementedError\' ")
        return False
    except RuntimeError as err:
        print("Please make sure you have the right dimensions and type")
        return False
    except:
        print("An exception occurred: could not compute output")
        return False

    try:
        if not( np.allclose( student_out, test_out) ):
            print("Test failed, student output does not match test output")
            return False
    except TypeError as err:
        print("Please make sure your function outputs the correct type")
        return False
    except:
        print("An exception occurred: could not check output")
        return False

    return True

```

```

[4]: # Get relevant data -- see references below for sources
!wget http://storage.googleapis.com/gresearch/refraw360/raw.zip
!unzip raw.zip

!wget https://www.pauldebevec.com/Research/HDR/SourceImages/
    ↪ Memorial_SourceImages.zip
!mkdir hdr
!unzip Memorial_SourceImages.zip -d hdr

!gdown https://drive.google.com/uc?id=1bGF1FUdeVThzXSLQn0J3PVUxtpt4tRua
!unzip sol.zip

```

--2023-10-19 02:56:37--

http://storage.googleapis.com/gresearch/refraw360/raw.zip

Resolving storage.googleapis.com (storage.googleapis.com)... 172.253.117.207,
142.250.99.207, 142.250.107.207, ...

Connecting to storage.googleapis.com
(storage.googleapis.com)|172.253.117.207|:80... connected.
HTTP request sent, awaiting response... 200 OK
Length: 20483316803 (19G) [application/zip]
Saving to: 'raw.zip'

raw.zip 100%[=====>] 19.08G 172MB/s in 2m 26s

2023-10-19 02:59:04 (133 MB/s) - 'raw.zip' saved [20483316803/20483316803]

Archive: raw.zip

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[illegible]

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inflating: rawnerf/testscenes/pianotest/raw/test/IMG_6656.json
inflating: rawnerf/testscenes/pianotest/raw/test/IMG_6666.dng
creating: rawnerf/testscenes/pianotest/raw/test/slow/
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6716.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6757.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6723.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6753.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6711.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6742.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6681.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6722.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6715.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6706.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6703.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6717.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6722.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6742.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6755.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6681.dng

inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6713.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6728.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6697.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6695.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6679.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6762.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6683.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6745.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6670.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6765.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6750.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6672.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6746.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6672.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6757.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6686.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6725.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6688.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6712.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6691.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6747.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6740.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6696.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6702.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6671.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6765.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6667.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6749.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6761.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6668.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6713.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6767.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6677.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6730.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6673.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6736.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6732.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6674.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6725.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6684.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6740.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6706.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6762.dng
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6674.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6708.json
inflating: rawnerf/testscenes/pianotest/raw/test/slow/IMG_6750.dng
inflating: rawnerf/testscenes/pianotest/raw/test/IMG_6656.dng
inflating: rawnerf/testscenes/pianotest/poses_bounds.npy


```

    creating: rawnerf/testscenes/pianotest/sparse/
    creating: rawnerf/testscenes/pianotest/sparse/0/
  inflating: rawnerf/testscenes/pianotest/sparse/0/points3D.bin
  inflating: rawnerf/testscenes/pianotest/sparse/0/images.bin
  inflating: rawnerf/testscenes/pianotest/sparse/0/cameras.bin
  inflating: rawnerf/testscenes/pianotest/sparse/0/project.ini
  inflating: rawnerf/testscenes/pianotest/colmap_output.txt
  inflating: rawnerf/testscenes/pianotest/database.db
--2023-10-19 03:04:08--
https://www.pauldebevec.com/Research/HDR/SourceImages/Memorial_SourceImages.zip
Resolving www.pauldebevec.com (www.pauldebevec.com)... 173.254.30.120
Connecting to www.pauldebevec.com (www.pauldebevec.com)|173.254.30.120|:443...
connected.
HTTP request sent, awaiting response... 200 OK
Length: 9227471 (8.8M) [application/zip]
Saving to: 'Memorial_SourceImages.zip'

```

```
Memorial_SourceImag 100%[=====]    8.80M  22.3MB/s    in 0.4s
```

```
2023-10-19 03:04:09 (22.3 MB/s) - 'Memorial_SourceImages.zip' saved
[9227471/9227471]
```

```

Archive:  Memorial_SourceImages.zip
  inflating: hdr/memorial0063.png
  inflating: hdr/memorial0064.png
  inflating: hdr/memorial0065.png
  inflating: hdr/memorial0066.png
  inflating: hdr/memorial0067.png
  inflating: hdr/memorial0068.png
  inflating: hdr/memorial0069.png
  inflating: hdr/memorial0070.png
  inflating: hdr/memorial0071.png
  inflating: hdr/memorial0072.png
  inflating: hdr/memorial0073.png
  inflating: hdr/memorial0074.png
  inflating: hdr/memorial0075.png
  inflating: hdr/memorial0076.png
  inflating: hdr/memorial.hdr_image_list.txt
  inflating: hdr/memorial.hdr
  inflating: hdr/README.txt
  inflating: hdr/memorial0061.png
  inflating: hdr/memorial0062.png

```

```
Downloading...
```

```
From: https://drive.google.com/uc?id=1bGF1FUdeVThzXSLQn0J3PVUxtpt4tRua
```

```
To: /content/sol.zip
```

```
100% 707M/707M [00:08<00:00, 85.5MB/s]
```

```
Archive:  sol.zip
```

```
    creating: sol/
```

```

inflating: sol/hdr.npy
inflating: __MACOSX/sol/._hdr.npy
inflating: sol/demosaick.npy
inflating: __MACOSX/sol/._demosaick.npy
inflating: sol/white_balance.npy
inflating: __MACOSX/sol/._white_balance.npy
inflating: sol/processed.npy
inflating: __MACOSX/sol/._processed.npy
inflating: sol/house_img.jpeg
inflating: __MACOSX/sol/._house_img.jpeg
inflating: sol/color_transform.npy
inflating: __MACOSX/sol/._color_transform.npy

```

1.2 Problem 1: Imaging Pipeline

Textbook Section: 2.2.4

In this problem, we will re-create part of the imaging pipeline, specifically demosaicking, white balancing, color transforms, and gamma encoding. By the end, you will be able to take in RAW images and output processed images. For each of the steps, we will suggest an implementation technique based on what was covered in Lecture 2.

We load one specific image at first for code correctness checks, but feel free to try new images from the dataset or images you capture yourself!

```

[5]: dng_file = "/content/rawnerf/scenes/windowlegovary/raw/IMG_6796.dng"
    meta_file = "/content/rawnerf/scenes/windowlegovary/raw/IMG_6796.json"

    dng = rawpy.imread(dng_file)
    with open(meta_file, "r") as json_file:
        meta = json.load(json_file)
    raw_img = dng.raw_image # raw is now a numpy array

    # Convert to between 0-1
    blacklevel = np.array(meta[0]['BlackLevel']).reshape(1, 1)
    whitelevel = np.array(meta[0]['WhiteLevel']).reshape(1, 1)
    raw_img = (raw_img - blacklevel) / (whitelevel - blacklevel)

```

Let's visualize the input (RAW images) and expected output (Processed images):

Lets start with the first step: demosaicking. The function should take in a mosaicked image in the bayer pattern and return a RGB image. We discussed one way to do this in class: bilinear interpolation. This technique gets values for a pixel by averaging the values of its neighbors. However, the positions of a pixels neighbors are not the same for different channels. We've put the

2x2 pattern (RGGB in this case) for the raw image below. Let's start by visualizing the expected output:

```
[6]: def student_demosaicking(bayer_img_input):  
    """Converts Bayer data into a full RGB image.  
  
    Input data should be ndarray of shape [height, width] with 2x2 mosaic_  
↪pattern:  
  
    -----  
    |red  |green|  
    -----  
    |green|blue |  
    -----  
  
    Args:  
        bayer_img: [H, W] numpy array. Contains values in the bayer pattern  
  
    Returns:  
        rgb_img: [H,W,3] numpy array.  
  
    Potential Implementation:  
  
    [Lecture 2] A potential implementation is bilinear interpolation  
    where each pixel value is averaged from its four neighbors. Where those_  
↪neighbors  
    are located will vary based on the color you are trying to interpolate. Our_  
↪code will  
    sanity check bilinear interpolation.  
    """  
    blue = np.zeros(raw_img.shape)  
    red = np.zeros(raw_img.shape)  
    green = np.zeros(raw_img.shape)  
  
    red[0::2,0::2] = raw_img[0::2, 0::2]  
    blue[1::2,1::2] = raw_img[1::2,1::2]  
    green[0::2,1::2] = raw_img[0::2,1::2]  
    green[1::2,0::2] = raw_img[1::2,0::2]  
  
    kernel_RB = np.array([[0.25,0.5,0.25],[0.5,1,0.5],[0.25,0.5,0.25]])  
    kernel_G = np.array([[0,0.25,0],[0.25,1,0.25],[0,0.25,0]])  
  
    red_conv = scipy.signal.convolve2d(red, kernel_RB, boundary='wrap',  
↪mode='same')
```

```

    green_conv = scipy.signal.convolve2d(green, kernel_G, boundary='wrap',
↪mode='same')
    blue_conv = scipy.signal.convolve2d(blue, kernel_RB, boundary='wrap',
↪mode='same')

    RGB_image = np.stack((red_conv, green_conv, blue_conv), axis=-1)

    return RGB_image

```

```

[7]: check_code_correctness(student_demosaicking, raw_img, np.load('/content/sol/
↪demosaick.npy'))

```

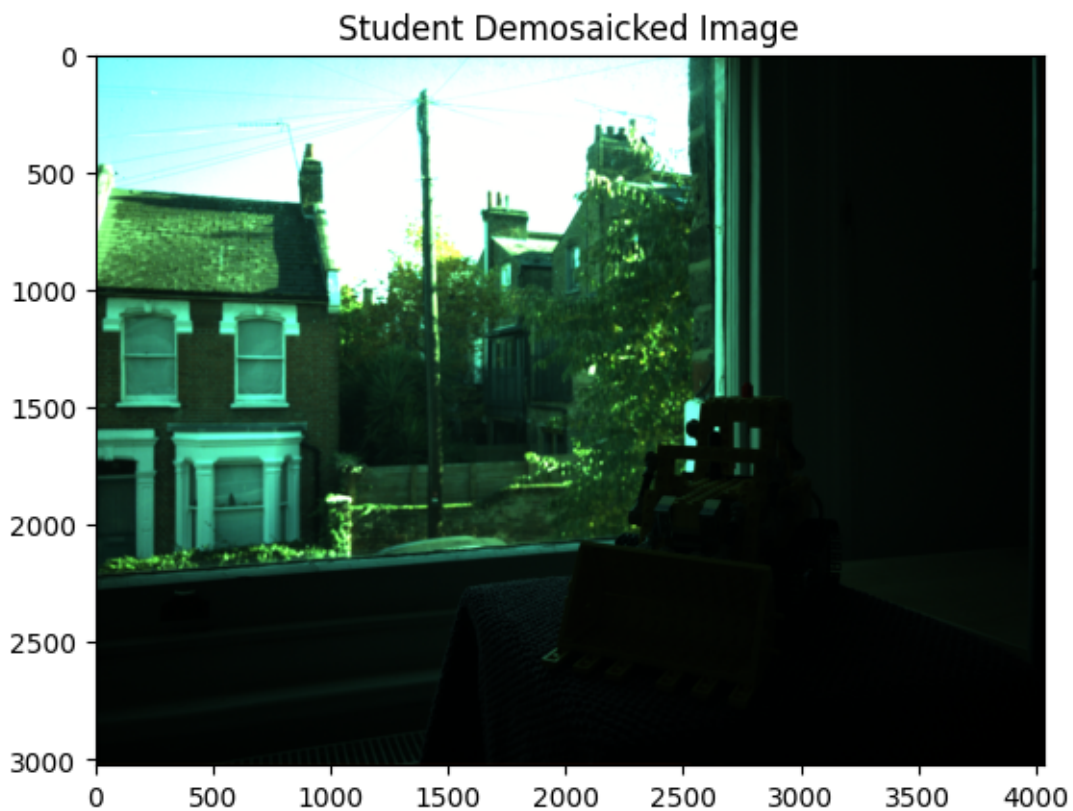
[7]: True

```

[8]: demosaicked_img = student_demosaicking(raw_img)
    demosaicked_img = np.where(demosaicked_img>1.0, 1.0, demosaicked_img)
    plt.imshow(demosaicked_img)
    plt.title("Student Demosaicked Image")
    plt.show()

```

WARNING:matplotlib.image:Clipping input data to the valid range for imshow with RGB data ([0..1] for floats or [0..255] for integers).



The next step is white balancing. A simple implementation is the gray-world assumption. This is what we will sanity check with the code correctness function. Once again, let's start by visualizing the expected output:

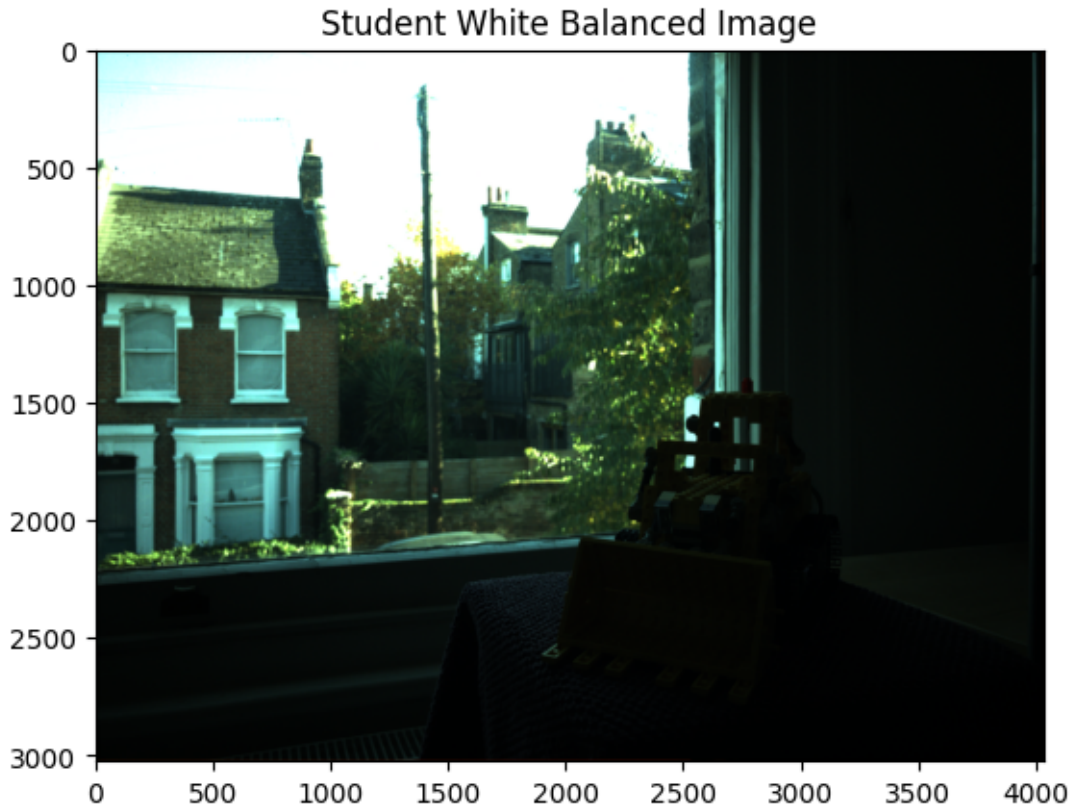
```
[9]: def student_white_balancing(demosaicked_image):  
    """White balances an image.  
  
    Args:  
        demosaicked_image: [H,W,3] numpy array containing RGB values  
  
    Returns:  
  
        white_balanced_img: [H,W,3] numpy array  
  
    Potential Implementation:  
  
    [Lecture 2] Two common implementations are the gray-world assumption or the  
    white-world assumption. Both can be implemented using a matrix_  
    ↪multiplication.  
    Our code will sanity check the gray-world assumption.  
    """  
    R_avg = np.mean(demosaicked_image[:, :, 0])  
    G_avg = np.mean(demosaicked_image[:, :, 1])  
    B_avg = np.mean(demosaicked_image[:, :, 2])  
    matrix = np.array([[G_avg/R_avg, 0, 0],  
                      [0, 1, 0],  
                      [0, 0, G_avg/B_avg]])  
  
    image_resaped = demosaicked_image.reshape(-1, 3)  
    result = np.dot(matrix, image_resaped.T).T  
    white_balanced_img = result.reshape(demosaicked_image.shape)  
  
    return white_balanced_img
```

```
[10]: check_code_correctness(student_white_balancing, demosaicked_img, np.load('/  
    ↪content/sol/white_balance.npy'))
```

[10]: True

```
[11]: white_balanced_img = student_white_balancing(demosaicked_img)  
plt.imshow(white_balanced_img)  
plt.title("Student White Balanced Image")  
plt.show()
```

WARNING:matplotlib.image:Clipping input data to the valid range for imshow with RGB data ([0..1] for floats or [0..255] for integers).



Next, we have to convert to RGB space. We will provide the individual matrices to convert between spaces, but you will have to choose how to apply them. Let's start by visualizing the expected output image.

```
[12]: xyz2cam = np.array([float(x) for x in meta[0]["ColorMatrix2"].split(" ")]).  
      ↪ reshape(3,3) # load from the picture metadata  
  
# Color conversion from reference illuminant XYZ to RGB color space.  
# See http://www.brucelindbloom.com/index.html?Eqn\_RGB\_XYZ\_Matrix.html.  
rgb2xyz = np.array([[0.4887180, 0.3106803, 0.2006017],  
                    [0.1762044, 0.8129847, 0.0108109],  
                    [0.0000000, 0.0102048, 0.9897952]])
```

We've given you two matrices here: one converts from xyz color space to camera color space. The other converts from RGB color space to xyz color space. How can we combine these into a matrix that converts from camera space to RGB space?

```
[13]: def student_color_transform(white_balanced_image):
    """Color transform from camera space to rgb

    Args:
        white_balanced_image: [H,W,3] numpy array in camera color space

    Returns:

        rgb_image: [H,W,3] numpy array in RGB color space

    Potential Implementation:

    How would you combine the provided matrices to get the image into RGB space?
    """

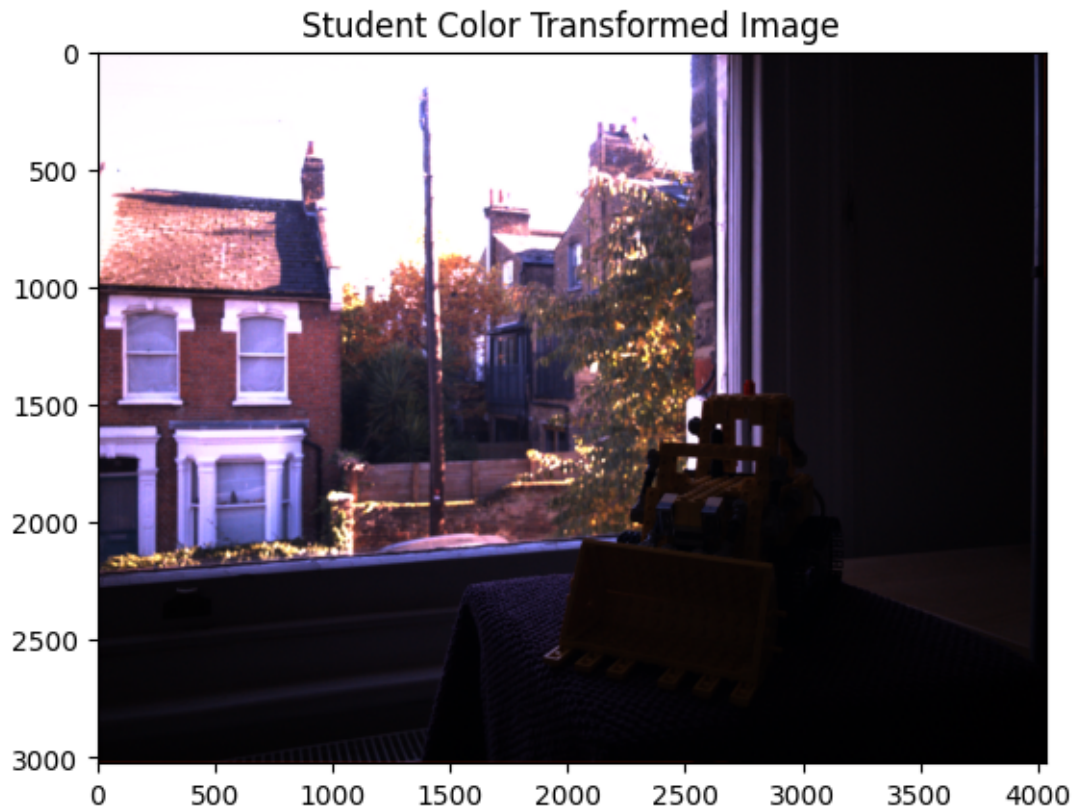
    matrix = np.matmul(xyz2cam,rgb2xyz)
    inv_matrix = np.linalg.inv(matrix)
    image_reshaped = white_balanced_image.reshape(-1, 3)
    result = np.matmul(inv_matrix,image_reshaped.T).T
    rgb_image = result.reshape(white_balanced_image.shape)
    return rgb_image
```

```
[14]: check_code_correctness(student_color_transform, white_balanced_img, np.load('/
↳content/sol/color_transform.npy'))
```

[14]: True

```
[15]: rgb_img = student_color_transform(white_balanced_img)
plt.imshow(rgb_img)
plt.title("Student Color Transformed Image")
plt.show()
```

WARNING:matplotlib.image:Clipping input data to the valid range for imshow with RGB data ([0..1] for floats or [0..255] for integers).



The last step is gamma encoding. The expected output:

```
[16]: def student_gamma_encode(color_transformed_image):
    """Gamma encodes an image.

    Args:
        color_transformed_image: [H,W,3] numpy array containing RGB values

    Returns:

        gamma_encoded_img: [H,W,3] numpy array

    Potential Implementation:

    [Lecture 2] For this section, you will need a value for the power. As
    discussed
    in class, a good value is  $\lambda = 1 / 2.2$ . Try experimenting with
    different values.
    Our code will sanity check with the suggested lambda.
```



```

"""
'''
gamma_decoded_img = np.where(gamma_decoded_img>1.0, 1.0, gamma_decoded_img)
gamma_decoded_img = np.where(gamma_decoded_img<0.0, 0.0, gamma_decoded_img)
gamma_decoded_img = np.power(color_transformed_image, 1.0 / 2.2)
'''

color_transformed_image = np.where(color_transformed_image>1.0, 1.0,
↳color_transformed_image)
color_transformed_image = np.where(color_transformed_image<0.0, 0.0,
↳color_transformed_image)
gamma_decoded_img = np.power(color_transformed_image, 1.0 / 2.2)

return gamma_decoded_img

```

```

[17]: check_code_correctness(student_gamma_encode, rgb_img, np.load('/content/sol/
↳processed.npy'))

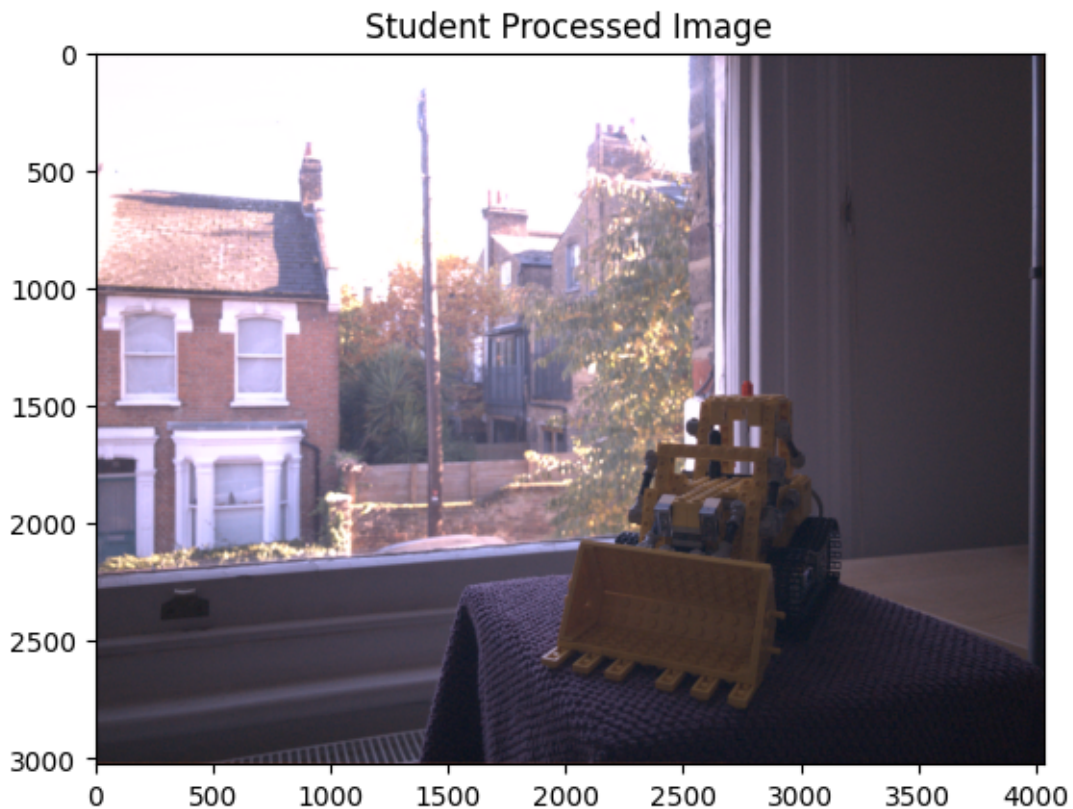
```

[17]: True

```

[18]: processed_image = student_gamma_encode(rgb_img)
plt.imshow(processed_image)
plt.title("Student Processed Image")
plt.show()

```



If you tried any new techniques, briefly explain them here:

1.3 Problem 2: Denoising

In class, we discussed how the imaging pipeline is not perfect: there are multiple sources of noise including Dark Current, ADC noise, and read noise. In this problem, we will follow the steps in Lecture 3 to estimate these various types of noise. We'll start by estimating the dark current then estimate gain and the ADC noise.

We'll set the parameters of the noise ourselves and then try to estimate them and see how close we get. Let's start by setting up some helper functions:

The input of this section is parameters for various types of noise and our expected outputs are to estimate these parameters with high accuracy.

```
[19]: # Set parameters:
      qe = 1 # Quantam efficiency
      D = 0.05 # Dark Current
      sigma_read = 0.03 # Std Dev. of read noise
      sigma_adc = 0.03 # Std Dev of ADC noise
      g = 1 # Gain
      #exposure is qe

[20]: def N_photon_detections(t, alpha, flux):
      return np.random.poisson(t * alpha * flux)

      def N_phantom_detections(t, D):
          return np.random.poisson(t * D)

      # Total number of detections
      # t - exposure time, D - dark current
      def N_detections(t, alpha, flux, D):
          return np.random.poisson(t*(alpha * flux + D),size = flux.shape)

      def n_read(sigma_read):
          return np.random.normal(scale=sigma_read)

      def n_adc(sigma_adc):
          return np.random.normal(scale=sigma_adc)
```

To estimate scene flux, we can load a grayscale image and then use the values as flux. Flux should be a [H,W] array. Try implementing an image with 0 flux, or various levels of gray flux. We'll need them in the estimation process.

```
[21]: # Returns flux from input image
def image_flux(img_path):
    gray_img = np.array(Image.open(img_path).convert("L"))
    flux = (255 - gray_img) / 255
    return flux

# Returns image with 0 flux everywhere
def zero_flux(size):
    flux = np.zeros(size)
    return flux

# Returns image with gray_level flux everywhere
def gray_level_flux(size, gray_level):
    flux = gray_level * np.ones(size)
    return flux
```

Now, let's implement functions to calculate image values and statistics. We've implemented another function as well named "set_vals". It takes in values for D, quantum efficiency, sigma read, and sigma adc and set the global values for these variables. Any values that are not explicitly set are kept the same. You will need to call this function later.

```
[22]: def set_vals(D_val=None, sigma_read_val=None, sigma_adc_val=None, qe_val=None,
    ↪g_val=None):
    if D_val is not None:
        global D
        D = D_val
    if qe_val is not None:
        global qe
        qe = qe_val
    if sigma_read_val is not None:
        global sigma_read
        sigma_read = sigma_read_val
    if sigma_adc_val is not None:
        global sigma_adc
        sigma_adc = sigma_adc_val
    if g_val is not None:
        global g
        g = g_val

# Get an image reading given the exposure and flux of the scene
def student_get_I(t, flux):
    I = N_detections(t,qe,flux,D) * g + n_read(sigma_read) * g +
    ↪n_adc(sigma_adc)
    return I

# Estimate mean of image reading given exposure and flux
def student_get_E_I(t, flux):
```

```

    E_I = t * (qe * flux + D) * g
    return E_I

# Estimate variance of image reading given exposure and flux
def student_get_var_I(t, flux):
    var_I = t * (qe * flux + D) * (g**2) + (sigma_read**2) * (g**2) +
    ↪(sigma_adc**2)
    return var_I

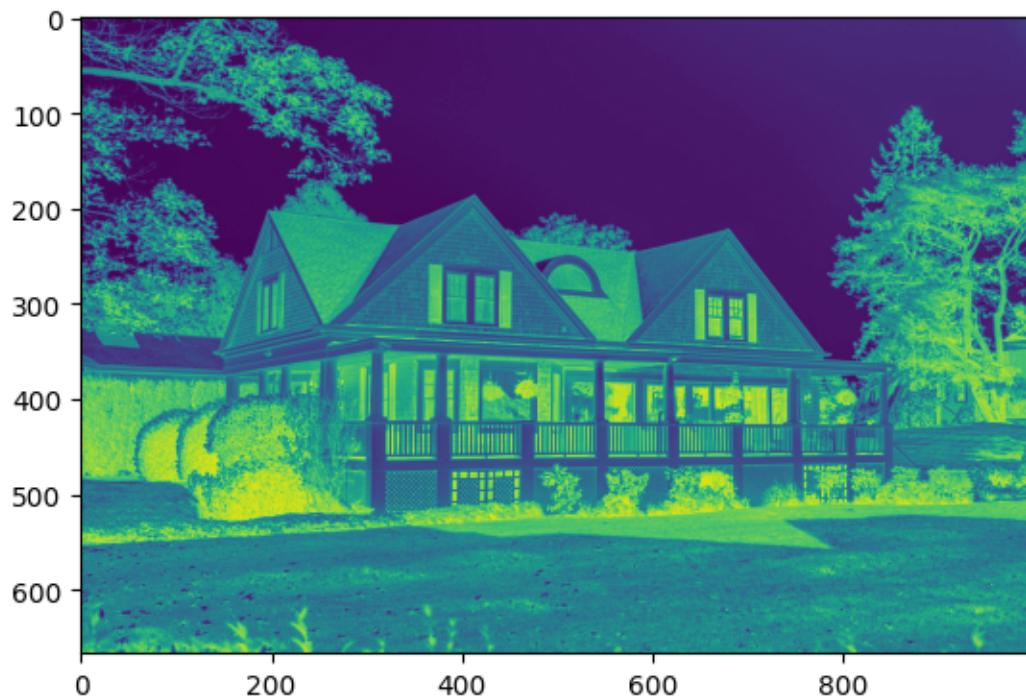
```

Lets see how our images “I” look:

```

[23]: I_hat = student_get_I(10000, image_flux('/content/sol/house_img.jpeg')) # Try
    ↪playing with the time to see how it looks
plt.imshow(I_hat)
plt.show()

```



Now that we have these helper functions, lets start by estimating dark current. We ideally want to get multiple samples that we can average. The N variable denotes how many samples we should average to get our final number.

```

[24]: def student_estimate_dark_current(size, N=100):

    t = 1e20
    I_values = np.array([student_get_I(t, zero_flux(size)) for _ in range(N)])

```

```

I_sum = np.sum(I_values, axis=0)

E_I_est = I_sum / N
D = E_I_est / (t * g)

return D

```

Let's test this out. Remember the expected value is 0.05.

```

[25]: print(student_estimate_dark_current((256,256))[0,0]) # should be 0.05 #[0,0]
      ↪ delete

```

0.050000000000108884

```

[26]: correct = True
      for D_val in [0.01,0.02,0.05,0.06]:
          set_vals(D_val=D_val)
          est_D = student_estimate_dark_current((256,256))
          correct = correct and np.allclose([est_D], [D_val])
      if correct:
          print("All tests passed")
      else:
          print("Error!")

```

All tests passed

Now let's estimate n_{read} and n_{adc} . As we discussed in Lecture 5, we can do this through a multi-step process: 1. Compute mean and variance for various gray levels (the number of levels is set by N_{levels}) 2. Fit a line to the data and use it to estimate g and n_{add} 3. Use the estimated values of g and n_{add} to estimate n_{read} and n_{adc} .

How do we do step 3? We can leverage the following relationship:

$$n_{\text{add}} = \mathcal{N}(0, \sqrt{\sigma_{\text{read}}^2 \cdot g^2 + \sigma_{\text{adc}}^2})$$

```

[27]: #n_add^2 = g^2 * sigma_read^2 + sigma_adc^2
      def student_estimate_read_adc(size, N_levels=10, N=10):
          """
          Estimates n_read and n_adc.

          Potential Implementation based on Lecture 5:
          1. Compute mean and variance for various gray levels (with dark current_
          ↪ correction)
          2. Fit a line to the data and estimate parameters

          Returns:
              n_read: estimated n_read
              n_adc: estimated n_adc

```

```

"""
set_vals(D_val=0)

max_flux = 1
max_g = 10
t = 1

n_g_level = 10
gain_levels = np.linspace(1,max_g,n_g_level)
gray_levels = np.linspace(0,max_flux,N_levels)

g_est_list = []
n_add_est_list = []

for i in range(len(gain_levels)):
    E_list = []
    var_list = []

    set_vals(g_val=gain_levels[i])

    for j in range(len(gray_levels)):
        gray_flux = gray_level_flux(size,gray_levels[j])

        E_list.append(np.mean(student_get_E_I(t,gray_flux)))
        var_list.append(np.mean(student_get_var_I(t,gray_flux)))

    est_g, est_var_add = np.polyfit(np.array(E_list),np.array(var_list),1)
    n_add_est_list.append(est_var_add)
    g_squared = gain_levels**2
    est_var_read,est_var_adc = np.polyfit(g_squared,np.array(n_add_est_list),1)
    return np.sqrt(est_var_read),np.sqrt(est_var_adc)

```

```

[30]: set_vals(sigma_adc_val=0.01, sigma_read_val=0.01)
      student_estimate_read_adc((512,512))

```

```

[30]: (0.009999999999999819, 0.01000000000000007865)

```

```

[31]: correct = True
      set_vals(D_val=0) # We've estimated it now and can subtract from input images
      for n_adc, n_read in zip([0.01,0.02,0.05,0.06], [0.01, 0.05, 0.02, 0.01]):
          set_vals(sigma_adc_val=n_adc, sigma_read_val=n_read)
          est_n_read, est_n_adc = student_estimate_read_adc((256,256))
          correct = correct and np.allclose([est_n_read, est_n_adc], [n_read, n_adc])
      if correct:
          print("All tests passed")
      else:
          print("Error!")

```

All tests passed

If all tests are passing, congrats! You implemented a system to estimate the various noises in the imaging pipeline.

1.4 Problem 3: HDR Imaging

In this problem, we will implement exposure bracketing for HDR reconstruction. We have access to a set of images taken at various exposure levels and we want to output a single HDR picture that better represents the scene.

Let's start by visualizing the expected output and input:

Lets load images in and reading exposure levels. We've written a function below that loads in the shutter speed, f-stop, and gain of the images.

```
[32]: data_file = "/content/hdr/memorial.hdr_image_list.txt"
num_imgs = 0
ldr_imgs = []

with open(data_file, "r") as img_list:
    for line in img_list:
        if line[0] == "#":
            continue
        vals = line.split()
        if len(vals) == 1:
            num_imgs = int(vals[0])
        else:
            fname, inv_shutter_speed, f_stop, gain, nd_filters = vals
            inv_shutter_speed = float(inv_shutter_speed)
            f_stop = int(f_stop)
            gain = int(gain)
            I = np.array(Image.open('/content/hdr/'+fname.replace('.ppm', '.
↳png'))))
            ldr_imgs.append((I, inv_shutter_speed, f_stop, gain)) # Which one
↳of these measures exposure time?
```

```
[33]: # Visualize the first 5 images
fig, ax = plt.subplots(1,16)
for i in range(16):
    ax[i].imshow(ldr_imgs[i][0])
plt.title("Sample Input Images")
plt.show()
```



Now that we have the images, let's put them together following the exposure bracketing technique discussed in class. In this technique, we take pixel values from images with varying exposure, weight them by both pixel values and exposure values (see Lecture 5 for details) and then combine them to get an HDR image.

A key question you will have to answer is how to convert the data we have into exposure values we can use for weighting. As a hint, exposure values are generally integer numbers with 0 being the “middle”.

```
[34]: def student_hdr_reconstruct(imgs):

    n_images = len(imgs)
    inv_shutter_speed_list = np.array([1 / img[1] for img in imgs])
    weight_shutter = 1/(np.abs(np.log2(inv_shutter_speed_list)) + 1)
    pixel_sum = np.zeros(imgs[0][0].shape)
    weight_sum = np.zeros(imgs[0][0].shape)

    for i in range(n_images):
        img = imgs[i][0] / 255

        mask1 = np.all(img > 0.05,axis = 2)
        mask2 = np.all(img < 0.95, axis = 2)

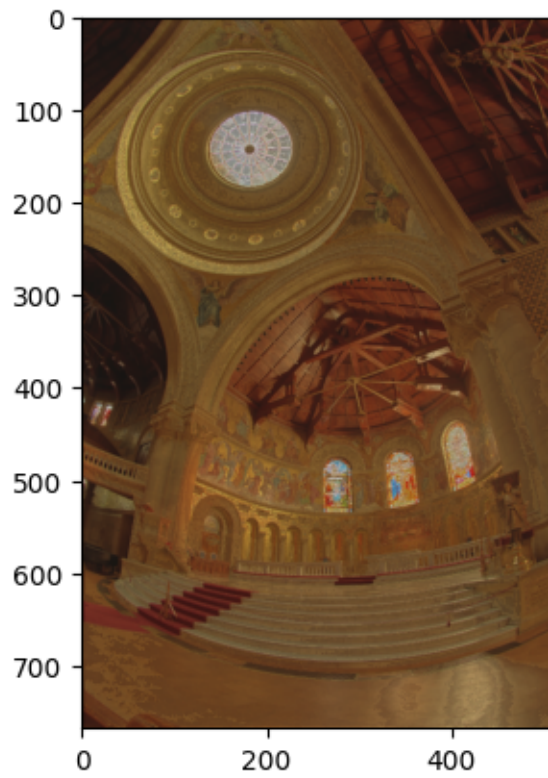
        mask1_repeat = np.repeat(mask1[...,np.newaxis],3,axis = 2).astype(int)
        mask2_repeat = np.repeat(mask2[...,np.newaxis],3,axis = 2).astype(int)

        masked_img = img * mask1_repeat * mask2_repeat

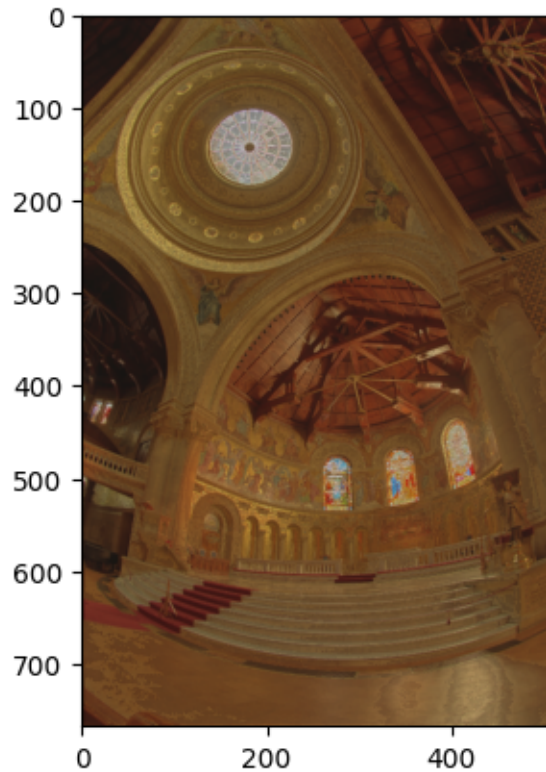
        weight_new = masked_img * weight_shutter[i]
        pixel_sum += masked_img * (weight_new)
        weight_sum += weight_new

    hdr_img = pixel_sum / weight_sum
    return hdr_img
```

```
[35]: #MY RESULT
hdr_img = student_hdr_reconstruct(ldr_imgs)
plt.imshow(hdr_img)
plt.show()
```

```
[36]: sol = np.load('/content/sol/hdr.npy')  
      plt.imshow(sol)  
      plt.show()
```



```
[37]: check_code_correctness(student_hdr_reconstruct, ldr_imgs, np.load('/content/sol/
      ↪hdr.npy'))
```

[37]: True

If you used techniques not discussed in class, please briefly summarize them here: Please check the above explanation.

1.5 References

Many of the materials used here were compiled from various different academic papers and datasets:

Raw Dataset:

NeRF in the Dark: High Dynamic Range View Synthesis from Noisy Raw Images, Ben Mildenhall and Peter Hedman and Ricardo Martin-Brualla and Pratul P. Srinivasan and Jonathan T. Barron, CVPR (2022)

HDR dataset:

Recovering High Dynamic Range Radiance Maps from Photographs., Paul E. Debevec and Jitendra Malik, SIGGRAPH 97, August 1997

Further Reading:

[38]: *# I have also included previous versions of codes that are inefficient.*

```
[39]: #CODE WITHOUT PADDING, EDGES ARE NOT SAME WITH THE SOLUTION, CHECK SOLUTION
      ↪BELOW.
      '''
      def student_demosaicking(bayer_image):
          """Converts Bayer data into a full RGB image.

          Input data should be ndarray of shape [height, width] with 2x2 mosaic
          ↪pattern:

              -----
              |red  |green|
              -----
              |green|blue |
              -----

          Args:
              bayer_img: [H, W] numpy array. Contains values in the bayer pattern

          Returns:
              rgb_img: [H,W,3] numpy array.

          Potential Implementation:

          [Lecture 2] A potential implementation is bilinear interpolation
          where each pixel value is averaged from its four neighbors. Where those
          ↪neighbors
          are located will vary based on the color you are trying to interpolate. Our
          ↪code will
          sanity check bilinear interpolation.
          """

      H,W = bayer_image.shape[0],bayer_image.shape[1]
      rgb_img = np.zeros((H, W, 3))
      for i in range(0,H):
          for j in range(0,W):
              #RED
              if(i % 2 == 0):
                  if(j % 2 == 0):
                      rgb_img[i,j,0] = bayer_image[i,j]
                  else:
                      if(j == W - 1):
                          rgb_img[i,j,0] = bayer_image[i,j-1]
                      else:
```

```

        rgb_img[i,j,0] = (bayer_image[i,j-1] + bayer_image[i,j+1])/ 2
    else:
        if(i == H - 1):
            if(j == W - 1):
                rgb_img[i,j,0] = bayer_image[i-1,j-1]
            else:
                if(j % 2 == 0):
                    rgb_img[i,j,0] = bayer_image[i-1,j]
                else:
                    rgb_img[i,j,0] = (bayer_image[i-1,j-1] + bayer_image[i-1,j+1])/2
        else:
            if(j%2 == 0):
                rgb_img[i,j,0] = (bayer_image[i-1,j] + bayer_image[i+1,j])/2
            else:
                if(j == W - 1):
                    rgb_img[i,j,0] = (bayer_image[i-1,j-1] + bayer_image[i+1,j-1])/2
                else:
                    rgb_img[i,j,0] = (bayer_image[i-1,j-1] + bayer_image[i-1,j+1] +
↪ bayer_image[i+1,j-1] + bayer_image[i+1,j+1])/4
    #GREEN
    if(i%2 == 0):
        if(i == 0):
            if(j %2 == 0):
                if(j == 0):
                    rgb_img[i,j,1] = (bayer_image[i+1,j] + bayer_image[i,j+1])/2
                else:
                    rgb_img[i,j,1] = (bayer_image[i,j-1] + bayer_image[i+1,j] +
↪ bayer_image[i,j+1])/3
            else:
                rgb_img[i,j,1] = bayer_image[i,j]
        else:
            if(j%2 == 0):
                if(j == 0):
                    rgb_img[i,j,1] = (bayer_image[i-1,j] + bayer_image[i+1,j] +
↪ bayer_image[i,j+1])/3
            else:
                rgb_img[i,j,1] = (bayer_image[i-1,j] + bayer_image[i+1,j] +
↪ bayer_image[i,j+1] + bayer_image[i,j-1])/4
            else:
                rgb_img[i,j,1] = bayer_image[i,j]
    else:
        if( i == H - 1):
            if(j%2 == 0):
                rgb_img[i,j,1] = bayer_image[i,j]
            else:
                if(j == W - 1):
                    rgb_img[i,j,1] = (bayer_image[i-1,j] + bayer_image[i,j-1])/2

```

```

        else:
            rgb_img[i, j, 1] =  $\lfloor$ 
↪ (bayer_image[i, j-1] + bayer_image[i-1, j] + bayer_image[i, j+1]) / 3
        else:
            if(j%2 == 0):
                rgb_img[i, j, 1] = bayer_image[i, j]
            else:
                if(j == W - 1):
                    rgb_img[i, j, 1] = (bayer_image[i-1, j] + bayer_image[i+1, j] +  $\lfloor$ 
↪ bayer_image[i, j-1]) / 3
                else:
                    rgb_img[i, j, 1] = (bayer_image[i-1, j] + bayer_image[i+1, j] +  $\lfloor$ 
↪ bayer_image[i, j+1] + bayer_image[i, j-1]) / 4
        #BLUE
        if(i%2 == 0):
            if(i == 0):
                if(j%2 == 0):
                    if(j == 0):
                        rgb_img[i, j, 2] = bayer_image[i+1, j+1]
                    else:
                        rgb_img[i, j, 2] = (bayer_image[i+1, j+1] + bayer_image[i+1, j-1]) / 2
                else:
                    rgb_img[i, j, 2] = bayer_image[i+1, j]
            else:
                if(j%2 == 0):
                    if(j == 0):
                        rgb_img[i, j, 2] = (bayer_image[i-1, j+1] + bayer_image[i+1, j+1]) / 2
                    else:
                        rgb_img[i, j, 2] =  $\lfloor$ 
↪ (bayer_image[i-1, j-1] + bayer_image[i-1, j+1] + bayer_image[i+1, j-1] + bayer_image[i+1, j+1]) /
↪ 4
                else:
                    rgb_img[i, j, 2] = (bayer_image[i-1, j] + bayer_image[i+1, j]) / 2
        else:
            if(j%2 == 0):
                if(j == 0):
                    rgb_img[i, j, 2] = bayer_image[i, j+1]
                else:
                    rgb_img[i, j, 2] = (bayer_image[i, j-1] + bayer_image[i, j+1]) / 2
            else:
                rgb_img[i, j, 2] = bayer_image[i, j]

    return rgb_img
'''

```

[39]: `'\ndef student_demosaicking(bayer_image):\n """Converts Bayer data into a full RGB image.\n\n Input data should be ndarray of shape [height, width]`

```

with 2x2 mosaic pattern:\n          -----\n          |red |green|\n
-----\n          |green|blue |\n          -----\n\n      Args:\n
bayer_img: [H, W] numpy array. Contains values in the bayer pattern\n\n
Returns:\n      rgb_img: [H,W,3] numpy array.\n\n\n      Potential
Implementation:\n\n      [Lecture 2] A potential implementation is bilinear
interpolation\n      where each pixel value is averaged from its four neighbors.
Where those neighbors\n      are located will vary based on the color you are
trying to interpolate. Our code will\n      sanity check bilinear interpolation.\n
"""\n      H,W = bayer_image.shape[0],bayer_image.shape[1]\n      rgb_img =
np.zeros((H, W, 3))\n      for i in range(0,H):\n          for j in range(0,W):\n
#RED\n          if(i % 2 == 0):\n              if(j % 2 == 0):\n
rgb_img[i,j,0] = bayer_image[i,j]\n              else:\n                  if(j == W - 1
):\n                      rgb_img[i,j,0] = bayer_image[i,j-1]\n                      else:\n
rgb_img[i,j,0] = (bayer_image[i,j-1] + bayer_image[i,j+1])/ 2\n                      else:\n
if(i == H - 1):\n                  if(j == W - 1):\n                      rgb_img[i,j,0] =
bayer_image[i-1,j-1]\n                      else:\n                          if(j % 2 == 0):\n
rgb_img[i,j,0] = bayer_image[i-1,j]\n                          else:\n
rgb_img[i,j,0] = (bayer_image[i-1,j-1] + bayer_image[i-1,j+1])/2\n
else:\n                  if(j%2 == 0):\n                      rgb_img[i,j,0] =
(bayer_image[i-1,j] + bayer_image[i+1,j])/2\n                      else:\n
if(j == W - 1):\n                      rgb_img[i,j,0] = (bayer_image[i-1,j-1] +
bayer_image[i+1,j-1])/2\n                      else:\n                          rgb_img[i,j,0] =
(bayer_image[i-1,j-1] +bayer_image[i-1,j+1]+ bayer_image[i+1,j-1] +
bayer_image[i+1,j+1])/4\n                      #GREEN\n                      if(i%2 == 0):\n
if(i == 0):\n                          if(j %2 == 0):\n                              if(j == 0):\n
rgb_img[i,j,1] = (bayer_image[i+1,j] + bayer_image[i,j+1])/2\n
else:\n                          rgb_img[i,j,1] = (bayer_image[i,j-1] + bayer_image[i+1,j]
+ bayer_image[i,j+1])/3\n                          else:\n                              rgb_img[i,j,1] =
bayer_image[i,j]\n                              else:\n                                  if(j%2 == 0):\n
if(j == 0):\n                          rgb_img[i,j,1] = (bayer_image[i-1,j] +
bayer_image[i+1,j] + bayer_image[i,j+1])/3\n                          else:\n
rgb_img[i,j,1] = (bayer_image[i-1,j] + bayer_image[i+1,j] + bayer_image[i,j+1]+
bayer_image[i,j-1])/4\n                          else:\n                              rgb_img[i,j,1] =
bayer_image[i,j]\n                              else:\n                                  if( i == H - 1):\n
if(j%2 == 0):\n                          rgb_img[i,j,1] = bayer_image[i,j]\n                          else:\n
if(j == W - 1):\n                          rgb_img[i,j,1] = (bayer_image[i-1,j] +
bayer_image[i,j-1])/2\n                          else:\n                              rgb_img[i,j,1] =
(bayer_image[i,j-1]+bayer_image[i-1,j]+bayer_image[i,j+1])/3\n                          else:\n
if(j%2 == 0):\n                          rgb_img[i,j,1] = bayer_image[i,j]\n
else:\n                          if(j == W - 1):\n                              rgb_img[i,j,1] =
(bayer_image[i-1,j] + bayer_image[i+1,j] + bayer_image[i,j-1])/3\n
else:\n                          rgb_img[i,j,1] = (bayer_image[i-1,j] + bayer_image[i+1,j]
+ bayer_image[i,j+1]+ bayer_image[i,j-1])/4\n                          #BLUE\n                          if(i%2 ==
0):\n                              if(i == 0):\n                                  if(j%2 == 0):\n
if(j == 0):\n                          rgb_img[i,j,2] = bayer_image[i+1,j+1]\n
else:\n                          rgb_img[i,j,2] = (bayer_image[i+1,j+1] +
bayer_image[i+1,j-1])/2\n                          else:\n                              rgb_img[i,j,2] =

```

```

bayer_image[i+1,j]\n                else:\n                if(j%2 == 0):\n
if(j == 0):\n                rgb_img[i,j,2] = (bayer_image[i-1,j+1] +
bayer_image[i+1,j+1])/2\n                else:\n                rgb_img[i,j,2] = (
bayer_image[i-1,j-1]+bayer_image[i-1,j+1]+bayer_image[i+1,j-
1]+bayer_image[i+1,j+1])/4\n                else:\n                rgb_img[i,j,2] =
(bayer_image[i-1,j] + bayer_image[i+1,j])/2\n                else:\n                if(j%2 ==
0):\n                if(j == 0):\n                rgb_img[i,j,2] =
bayer_image[i,j+1]\n                else:\n                rgb_img[i,j,2] =
(bayer_image[i,j-1] + bayer_image[i,j+1])/2\n                else:\n
rgb_img[i,j,2] = bayer_image[i,j]\n\n    return rgb_img\n'

```

```

[40]: '''
def student_demosaicking(bayer_img_input):
    """Converts Bayer data into a full RGB image.

    Input data should be ndarray of shape [height, width] with 2x2 mosaic
    ↪ pattern:

        -----
        |red  |green|
        -----
        |green|blue |
        -----

    Args:
        bayer_img: [H, W] numpy array. Contains values in the bayer pattern

    Returns:
        rgb_img: [H,W,3] numpy array.

    Potential Implementation:

    [Lecture 2] A potential implementation is bilinear interpolation
    where each pixel value is averaged from its four neighbors. Where those
    ↪ neighbors
    are located will vary based on the color you are trying to interpolate. Our
    ↪ code will
    sanity check bilinear interpolation.
    """
    bayer_image = np.pad(bayer_img_input, 1, mode='wrap')
    H_pad,W_pad = bayer_image.shape[0],bayer_image.shape[1]
    rgb_img = np.zeros((H_pad, W_pad, 3))
    for i in range(1,H_pad-1):
        for j in range(1,W_pad-1):
            #RED
            if(i % 2 == 1):
                if(j % 2 == 1):

```

```

        rgb_img[i,j,0] = bayer_image[i,j]
    else:
        rgb_img[i,j,0] = (bayer_image[i,j-1] + bayer_image[i,j+1])/ 2
    else:
        if(j%2 == 1):
            rgb_img[i,j,0] = (bayer_image[i-1,j] + bayer_image[i+1,j])/2
        else:
            rgb_img[i,j,0] = (bayer_image[i-1,j-1] +bayer_image[i-1,j+1]+
↪bayer_image[i+1,j-1] + bayer_image[i+1,j+1])/4

    #GREEN
    if(i%2 == 1):
        if(j%2 == 1):
            rgb_img[i,j,1] = (bayer_image[i-1,j] + bayer_image[i+1,j] +
↪bayer_image[i,j+1]+ bayer_image[i,j-1])/4
        else:
            rgb_img[i,j,1] = bayer_image[i,j]
    else:
        if(j%2 == 1):
            rgb_img[i,j,1] = bayer_image[i,j]
        else:
            rgb_img[i,j,1] = (bayer_image[i-1,j] + bayer_image[i+1,j] +
↪bayer_image[i,j+1]+ bayer_image[i,j-1])/4

    #BLUE
    if(i%2 == 1):
        if(j%2 == 1):
            rgb_img[i,j,2] =
↪(bayer_image[i-1,j-1]+bayer_image[i-1,j+1]+bayer_image[i+1,j-1]+bayer_image[i+1,j+1])/
↪4
        else:
            rgb_img[i,j,2] = (bayer_image[i-1,j] + bayer_image[i+1,j])/2
    else:
        if(j%2 == 1):
            rgb_img[i,j,2] = (bayer_image[i,j-1] + bayer_image[i,j+1])/2
        else:
            rgb_img[i,j,2] = bayer_image[i,j]
    org_size_img = rgb_img[1:H_pad-1,1:W_pad-1,:]
    return org_size_img
'''

```

[40]: 'ndef student_demosaicking(bayer_img_input):\n """Converts Bayer data into a full RGB image.\n\n Input data should be ndarray of shape [height, width] with 2x2 mosaic pattern:\n -----\n |red |green|\n -----\n |green|blue |\n -----\n\n Args:\n bayer_img: [H, W] numpy array. Contains values in the bayer pattern\n Returns:\n rgb_img: [H,W,3] numpy array.\n\n Potential


```

Implementation:\n\n    [Lecture 2] A potential implementation is bilinear
interpolation\n    where each pixel value is averaged from its four neighbors.
Where those neighbors\n    are located will vary based on the color you are
trying to interpolate. Our code will\n    sanity check bilinear interpolation.\n
"""\n    bayer_image = np.pad(bayer_img_input, 1, mode='wrap')\n
H_pad,W_pad = bayer_image.shape[0],bayer_image.shape[1]\n    rgb_img =
np.zeros((H_pad, W_pad, 3))\n    for i in range(1,H_pad-1):\n        for j in
range(1,W_pad-1):\n            #RED\n                if(i % 2 == 1):\n                    if(j % 2 ==
1):\n                        rgb_img[i,j,0] = bayer_image[i,j]\n                    else:\n
rgb_img[i,j,0] = (bayer_image[i,j-1] + bayer_image[i,j+1])/ 2\n                else:\n
if(j%2 == 1):\n                    rgb_img[i,j,0] = (bayer_image[i-1,j] +
bayer_image[i+1,j])/2\n                else:\n                    rgb_img[i,j,0] =
(bayer_image[i-1,j-1] +bayer_image[i-1,j+1]+ bayer_image[i+1,j-1] +
bayer_image[i+1,j+1])/4\n\n                #GREEN\n                    if(i%2 == 1):\n
if(j%2 == 1):\n                        rgb_img[i,j,1] = (bayer_image[i-1,j] +
bayer_image[i+1,j] + bayer_image[i,j+1]+ bayer_image[i,j-1])/4\n                    else:\n
rgb_img[i,j,1] = bayer_image[i,j]\n                else:\n
if(j%2 == 1):\n                    rgb_img[i,j,1] = bayer_image[i,j]\n                else:\n
rgb_img[i,j,1] = (bayer_image[i-1,j] + bayer_image[i+1,j] + bayer_image[i,j+1]+
bayer_image[i,j-1])/4\n\n                #BLUE\n                    if(i%2 == 1):\n
if(j%2 == 1):\n                        rgb_img[i,j,2] = (bayer_image[i-1,j-1]+bayer_image[i-
1,j+1]+bayer_image[i+1,j-1]+bayer_image[i+1,j+1])/4\n                    else:\n
rgb_img[i,j,2] = (bayer_image[i-1,j] + bayer_image[i+1,j])/2\n                else:\n
if(j%2 == 1):\n                    rgb_img[i,j,2] = (bayer_image[i,j-1] +
bayer_image[i,j+1])/2\n                else:\n                    rgb_img[i,j,2] =
bayer_image[i,j]\n    org_size_img = rgb_img[1:H_pad-1,1:W_pad-1,:]\n    return
org_size_img\n'

```

```

[41]: '''
def student_white_balancing(demosaicked_image):
    """White balances an image.

    Args:
        demoisaicked_image: [H,W,3] numpy array containing RGB values

    Returns:

        white_balanced_img: [H,W,3] numpy array

    Potential Implementation:

    [Lecture 2] Two common implementations are the gray-world assumption or the
    white-world assumption. Both can be implemented using a matrix_
    ↪multiplication.

    Our code will sanity check the gray-world assumption.
    """
    R_avg = np.mean(demosaicked_image[:, :, 0])

```

```

G_avg = np.mean(demosaicked_image[:, :, 1])
B_avg = np.mean(demosaicked_image[:, :, 2])
matrix = np.array([[G_avg/R_avg, 0, 0],
                   [0, 1, 0],
                   [0, 0, G_avg/B_avg]])
H, W = demosaicked_image.shape[0], demosaicked_image.shape[1]
white_balanced_img = np.zeros((H, W, 3))
for i in range(H):
    for j in range(W):
        rgb = np.
↪array([demosaicked_image[i, j, 0], demosaicked_image[i, j, 1], demosaicked_image[i, j, 2]]).
↪reshape(-1, 1)
        rgb_white_balanced = np.matmul(matrix, rgb)
        white_balanced_img[i, j, 0] = rgb_white_balanced[0]
        white_balanced_img[i, j, 1] = rgb_white_balanced[1]
        white_balanced_img[i, j, 2] = rgb_white_balanced[2]

    return white_balanced_img
'''

```

```

[41]: '\ndef student_white_balancing(demosaicked_image):\n    """White balances an
image.\n\n    Args:\n        demoisaicked_image: [H,W,3] numpy array containing
RGB values\n\n    Returns:\n\n        white_balanced_img: [H,W,3] numpy
array\n\n    Potential Implementation:\n\n        [Lecture 2] Two common
implementations are the gray-world assumption or the\n        white-world
assumption. Both can be implemented using a matrix multiplication.\n        Our code
will sanity check the gray-world assumption.\n        """\n        R_avg =
np.mean(demosaicked_image[:, :, 0])\n        G_avg =
np.mean(demosaicked_image[:, :, 1])\n        B_avg =
np.mean(demosaicked_image[:, :, 2])\n        matrix = np.array([[G_avg/R_avg, 0, 0],\n
[0, 1, 0],\n                                [0, 0, G_avg/B_avg]])\n        H, W =
demosaicked_image.shape[0], demosaicked_image.shape[1]\n        white_balanced_img =
np.zeros((H, W, 3))\n        for i in range(H):\n            for j in range(W):\n
rgb = np.array([demosaicked_image[i, j, 0], demosaicked_image[i, j, 1], demosaicked_im
age[i, j, 2]]).reshape(-1, 1)\n            rgb_white_balanced = np.matmul(matrix, rgb)\n
white_balanced_img[i, j, 0] = rgb_white_balanced[0]\n
white_balanced_img[i, j, 1] = rgb_white_balanced[1]\n
white_balanced_img[i, j, 2] = rgb_white_balanced[2]\n\n        return
white_balanced_img\n'

```

```

[42]: '''
def student_color_transform(white_balanced_image):
    """Color transform from camera space to rgb

    Args:
        white_balanced_image: [H,W,3] numpy array in camera color space

```

Returns:

rgb_image: [H,W,3] numpy array in RGB color space

Potential Implementation:

How would you combine the provided matrices to get the image into RGB space?
"""

```
matrix = np.matmul(xyz2cam, rgb2xyz)
inv_matrix = np.linalg.inv(matrix)

H,W = white_balanced_image.shape[0],white_balanced_image.shape[1]
rgb_image = np.zeros((H, W, 3))
for i in range(H):
    for j in range(W):
        cam = np.
↪array([white_balanced_image[i,j,0],white_balanced_image[i,j,1],white_balanced_image[i,j,2]]
↪reshape(-1,1)
        rgb = np.matmul(inv_matrix,cam)
        rgb_image[i,j,0] = rgb[0]
        rgb_image[i,j,1] = rgb[1]
        rgb_image[i,j,2] = rgb[2]
    return rgb_image
'''
```

```
[42]: '\ndef student_color_transform(white_balanced_image):\n    """Color transform\nfrom camera space to rgb\n\n    Args:\n        white_balanced_image: [H,W,3]\n        numpy array in camera color space\n\n    Returns:\n\n        rgb_image: [H,W,3]\n        numpy array in RGB color space\n\n    Potential Implementation:\n\n        How would\nyou combine the provided matrices to get the image into RGB space?\n    """\n\n    matrix = np.matmul(xyz2cam,rgb2xyz)\n    inv_matrix = np.linalg.inv(matrix)\n\n    H,W = white_balanced_image.shape[0],white_balanced_image.shape[1]\n    rgb_image\n= np.zeros((H, W, 3))\n    for i in range(H):\n        for j in range(W):\n            cam = np.array([white_balanced_image[i,j,0],white_balanced_image[i,j,1],white_ba\nlanced_image[i,j,2]]).reshape(-1,1)\n            rgb = np.matmul(inv_matrix,cam)\n            rgb_image[i,j,0] = rgb[0]\n            rgb_image[i,j,1] = rgb[1]\n            rgb_image[i,j,2] = rgb[2]\n        return rgb_image\n'
```

```
[43]: '''
def student_hdr_reconstruct(imgs):
    """
    Recovers a HDR image from multiple LDR images.

    Args:
        imgs: a list of tuples containing: LDR image ([H,W,3]), 1/shutter_
↪speed, f-stop, gain
'''
```

```

Returns:
    hdr_img: a [H,W,3] HDR image
"""
n_images = len(imgs)
inv_shutter_speed_list = []
for i in range(n_images):
    inv_shutter_speed_list.append(imgs[i][1])
H,W = imgs[0][0].shape[0],imgs[0][0].shape[1]
hdr_img = np.zeros((H,W,3))

n_valid_pixel = np.zeros((H,W))

for i in range(H):
    for j in range(W):
        pixel_sum = np.zeros((1,3))
        weight_sum = np.zeros((1,3))
        for k in range(n_images):
            pixel_RGB = imgs[k][0][i,j,:] / 255
            if(np.all(pixel_RGB > 0.05) and np.all(pixel_RGB < 0.95)):
                weight_new = pixel_RGB / (np.abs(np.
↪log2(inv_shutter_speed_list[k])) + 1)
                pixel_sum += pixel_RGB * (weight_new)
                weight_sum += weight_new

        pixel_hdr = pixel_sum / weight_sum
        hdr_img[i,j,:] = pixel_hdr

    return hdr_img
'''

```

```

[43]: '\ndef student_hdr_reconstruct(imgs):\n    """\n    Recovers a HDR image from\n    multiple LDR images.\n\n    Args:\n        imgs: a list of tuples containing:\n        LDR image ([H,W,3]), 1/shutter speed, f-stop, gain\n\n    Returns:\n        hdr_img: a [H,W,3] HDR image\n    """\n    n_images = len(imgs)\n    inv_shutter_speed_list = []\n    for i in range(n_images):\n        inv_shutter_speed_list.append(imgs[i][1])\n    H,W =\n    imgs[0][0].shape[0],imgs[0][0].shape[1]\n    hdr_img = np.zeros((H,W,3))\n\n    n_valid_pixel = np.zeros((H,W))\n\n    for i in range(H):\n        for j in\n        range(W):\n            pixel_sum = np.zeros((1,3))\n            weight_sum =\n            np.zeros((1,3))\n            for k in range(n_images):\n                pixel_RGB =\n                imgs[k][0][i,j,:] / 255\n                if(np.all(pixel_RGB > 0.05) and\n                np.all(pixel_RGB < 0.95)):\n                    weight_new = pixel_RGB /\n                    (np.abs(np.log2(inv_shutter_speed_list[k])) + 1)\n                    pixel_sum +=\n                    pixel_RGB * (weight_new)\n                    weight_sum += weight_new\n\n            pixel_hdr = pixel_sum / weight_sum\n            hdr_img[i,j,:] = pixel_hdr\n\n    return hdr_img\n'

```

```

[28]: '''
#n_add^2 = g^2 * sigma_read^2 + sigma_adc^2
def student_estimate_read_adc(size, N_levels=10, N=10):
    """
    Estimates n_read and n_adc.

    Potential Implementation based on Lecture 5:
    1. Compute mean and variance for various gray levels (with dark current_
    ↪ correction)
    2. Fit a line to the data and estimate parameters

    Returns:
        n_read: estimated n_read
        n_adc: estimated n_adc
    """
    set_vals(D_val=0)

    max_flux = 1
    t = 1e10

    n_g_level = 10
    gain_levels = np.linspace(0.1, 1.1, n_g_level)
    gray_levels = np.linspace(0.01, max_flux, N_levels)

    #print(gain_levels)
    g_est_list = []
    n_add_est_list = []
    for k in range(len(gain_levels)):
        E_list = [] # 5x256x256
        var_list = [] # 5x256x256
        set_vals(g_val=gain_levels[k])

        for i in range(len(gray_levels)):
            I_samples = []
            I_sum = np.zeros((size))
            for j in range(N):
                I = student_get_I(t, gray_level_flux(size, gray_levels[i]))
                I_samples.append(I)
                I_sum += I
            E_I_est = I_sum / (N)

            var_sum = np.zeros((size))
            for j in range(N):
                var_sum += (I_samples[j] - E_I_est) ** 2
            var_I_est = var_sum / (N-1)
            E_list.append(E_I_est)
            var_list.append(var_I_est)

```

```

E_array = np.array(E_list)
var_array = np.array(var_list)
g_slope_array = np.zeros(size)
var_add_constant_array = np.zeros(size)

#print(E_array)
#print(var_array)

for i in range(size[0]):
    for j in range(size[1]):
        x = np.array(E_array[:,i,j])
        y = np.array(var_array[:,i,j])
        fit_1 = np.polyfit(x,y,1)
        g_slope_array[i,j] = fit_1[0]
        var_add_constant_array[i,j] = fit_1[1]
    g_est_list.append(np.mean(g_slope_array))
    n_add_est_list.append(np.mean(var_add_constant_array))
print(g_est_list)
print("ESTIMATED sigma_add")
print(np.sqrt(n_add_est_list))
print("TRUE N_ADD")
print(np.sqrt((sigma_read**2) * (np.array(gain_levels)**2) +
↳ (sigma_adc**2)))
x = (np.array(g_est_list)**2)
y = (np.array(n_add_est_list))
fit_2 = np.polyfit(x,y,1)
var_read_m, var_adc_c = fit_2[0],fit_2[1]
sigma_read_est = np.sqrt(var_read_m)
sigma_adc_est = np.sqrt(var_adc_c)
print(sigma_read_est)
print(sigma_adc_est)
return sigma_read_est, sigma_adc_est
'''

```

```

[28]: '\n#n_add^2 = g^2 * sigma_read^2 + sigma_adc^2\ndef
student_estimate_read_adc(size, N_levels=10, N=10):\n    """\n    Estimates
n_read and n_adc.\n\n    Potential Implementation based on Lecture 5:\n    1.
Compute mean and variance for various gray levels (with dark current
correction)\n    2. Fit a line to the data and estimate parameters\n\n
Returns:\n        n_read: estimated n_read\n        n_adc: estimated n_adc\n
"""\n    set_vals(D_val=0)\n\n    max_flux = 1\n    t = 1e10\n\n    n_g_level =
10\n    gain_levels = np.linspace(0.1,1.1,n_g_level)\n    gray_levels =
np.linspace(0.01,max_flux,N_levels)\n\n    #print(gain_levels)\n    g_est_list =
[]\n    n_add_est_list = []\n    for k in range(len(gain_levels)):\n        E_list
= [] # 5x256x256\n        var_list = [] # 5x256x256\n
set_vals(g_val=gain_levels[k])\n\n        for i in range(len(gray_levels)):\n

```

```

I_samples = []\n          I_sum = np.zeros((size))\n          for j in range(N):\n
I = student_get_I(t,gray_level_flux(size, gray_levels[i]))\n
I_samples.append(I)\n          I_sum += I\n          E_I_est = I_sum / (N)\n
var_sum = np.zeros((size))\n          for j in range(N):\n          var_sum +=\n
(I_samples[j] - E_I_est) ** 2\n          var_I_est = var_sum / (N-1)\n
E_list.append(E_I_est)\n          var_list.append(var_I_est)\n          E_array =\n
np.array(E_list)\n          var_array = np.array(var_list)\n          g_slope_array =\n
np.zeros(size)\n          var_add_constant_array = np.zeros(size)\n
#print(E_array)\n          #print(var_array)\n          for i in range(size[0]):\n
for j in range(size[1]):\n          x = np.array(E_array[:,i,j])\n          y =\n
np.array(var_array[:,i,j])\n          fit_1 = np.polyfit(x,y,1)\n
g_slope_array[i,j] = fit_1[0]\n          var_add_constant_array[i,j] =\n
fit_1[1]\n          g_est_list.append(np.mean(g_slope_array))\n
n_add_est_list.append(np.mean(var_add_constant_array))\n          print(g_est_list)\n
print("ESTIMATED sigma_add")\n          print(np.sqrt(n_add_est_list))\n
print("TRUE N_ADD")\n          print(np.sqrt((sigma_read**2) *\n
(np.array(gain_levels)**2) + (sigma_adc**2)))\n          x =\n
(np.array(g_est_list)**2)\n          y = (np.array(n_add_est_list))\n          fit_2 =\n
np.polyfit(x,y,1)\n          var_read_m, var_adc_c = fit_2[0],fit_2[1]\n
sigma_read_est = np.sqrt(var_read_m)\n          sigma_adc_est = np.sqrt(var_adc_c)\n
print(sigma_read_est)\n          print(sigma_adc_est)\n          return sigma_read_est,\n
sigma_adc_est\n'

```

```

[29]: '''
#n_add^2 = g^2 * sigma_read^2 + sigma_adc^2
def student_estimate_read_adc(size, N_levels=5, N=1000):
    """
    Estimates n_read and n_adc.

    Potential Implementation based on Lecture 5:
    1. Compute mean and variance for various gray levels (with dark current_
    ↪ correction)
    2. Fit a line to the data and estimate parameters

    Returns:
        n_read: estimated n_read
        n_adc: estimated n_adc
    """
    set_vals(D_val=0)

    max_flux = 1
    t = 10

    n_g_level = 10
    gain_levels = np.linspace(1,10,n_g_level)
    gray_levels = np.linspace(0.01,max_flux,N_levels)

```

```

g_est_list = []
n_add_est_list = []
for i in range(len(gain_levels)):
    E_list = [] # N_levelx256x256
    var_list = [] # N_levelx256x256

    set_vals(g_val=gain_levels[i])

    for j in range(len(gray_levels)):

        I_values = np.array([student_get_I(t,
        ↪gray_level_flux(size,gray_levels[j])) for _ in range(N)])
        I_sum = np.sum(I_values, axis=0)
        E_I_est = I_sum / N

        E_I_est_repeated = np.repeat(E_I_est[np.newaxis,...],N,axis = 0)
        var_sum = np.zeros((size))
        var_I_est = np.sum((I_values - E_I_est)**2,axis = 0)/(N-1)

        E_list.append(np.mean(E_I_est))
        var_list.append(np.mean(var_I_est))
        #print("E_I")
        #print(np.mean(E_I_est))
        #print("var_I")
        #print(np.mean(var_I_est))

E_array = np.array(E_list)
var_array = np.array(var_list)
#print(E_array)
#print(var_array)
#g_slope_array = np.zeros(size)
#var_add_constant_array = np.zeros(size)
fit_1 = np.polyfit(E_array,var_array,1)
print(fit_1)
print(g)
print("EST VALUE",np.mean(var_array) - np.mean(E_array) * g)
print("TRUE VALUE",g**2 * sigma_read**2 + sigma_adc **2 )
#print(E_array)
#print(var_array)

for i in range(size[0]):
    for j in range(size[1]):
        x = np.array(E_array[:,i,j])
        y = np.array(var_array[:,i,j])
        fit_1 = np.polyfit(x,y,1)
        g_slope_array[i,j] = fit_1[0]
        var_add_constant_array[i,j] = fit_1[1]

```



```

        g_est_list.append(np.mean(g_slope_array))
        n_add_est_list.append(np.mean(var_add_constant_array))
    print(g_est_list)
    print("ESTIMATED sigma_add")
    print(np.sqrt(n_add_est_list))
    print("TRUE N_ADD")
    print(np.sqrt((sigma_read**2) * (np.array(gain_levels)**2) +
    ↪ (sigma_adc**2)))
    x = (np.array(g_est_list)**2)
    y = (np.array(n_add_est_list))
    fit_2 = np.polyfit(x,y,1)
    var_read_m, var_adc_c = fit_2[0],fit_2[1]
    sigma_read_est = np.sqrt(var_read_m)
    sigma_adc_est = np.sqrt(var_adc_c)
    print(sigma_read_est)
    print(sigma_adc_est)
    return sigma_read_est, sigma_adc_est
'''

```

```

[29]: '\n#n_add^2 = g^2 * sigma_read^2 + sigma_adc^2\ndef
student_estimate_read_adc(size, N_levels=5, N=1000):\n    """\n    Estimates
n_read and n_adc.\n\n    Potential Implementation based on Lecture 5:\n    1.
Compute mean and variance for various gray levels (with dark current
correction)\n    2. Fit a line to the data and estimate parameters\n\n
Returns:\n        n_read: estimated n_read\n        n_adc: estimated n_adc\n
"""\n    set_vals(D_val=0)\n\n    max_flux = 1\n    t = 10\n\n    n_g_level =
10\n    gain_levels = np.linspace(1,10,n_g_level)\n    gray_levels =
np.linspace(0.01,max_flux,N_levels)\n\n    g_est_list = []\n    n_add_est_list =
[]\n    for i in range(len(gain_levels)):\n        E_list = [] # N_levelx256x256\n
var_list = [] # N_levelx256x256\n\n    set_vals(g_val=gain_levels[i])\n\n
for j in range(len(gray_levels)):\n\n        I_values =
np.array([student_get_I(t, gray_level_flux(size,gray_levels[j])) for _ in
range(N)])\n        I_sum = np.sum(I_values, axis=0)\n        E_I_est = I_sum /
N\n\n        E_I_est_repeated = np.repeat(E_I_est[np.newaxis,...],N,axis = 0)\n
var_sum = np.zeros((size))\n        var_I_est = np.sum((I_values -
E_I_est)**2,axis = 0)/(N-1)\n\n        E_list.append(np.mean(E_I_est))\n
var_list.append(np.mean(var_I_est))\n        #print("E_I")\n
#print(np.mean(E_I_est))\n        #print("var_I")\n
#print(np.mean(var_I_est))\n\n        E_array = np.array(E_list)\n        var_array
= np.array(var_list)\n        #print(E_array)\n        #print(var_array)\n
#g_slope_array = np.zeros(size)\n        #var_add_constant_array =
np.zeros(size)\n        fit_1 = np.polyfit(E_array,var_array,1)\n
print(fit_1)\n        print(g)\n        print("EST VALUE",np.mean(var_array) -
np.mean(E_array) * g)\n        print("TRUE VALUE",g**2 * sigma_read**2 + sigma_adc
**2 )\n        #print(E_array)\n        #print(var_array)\n        \n        for i in
range(size[0]):\n            for j in range(size[1]):\n                x =
np.array(E_array[:,i,j])\n                y = np.array(var_array[:,i,j])\n

```

```

fit_1 = np.polyfit(x,y,1)\n          g_slope_array[i,j] = fit_1[0]\n
var_add_constant_array[i,j] = fit_1[1]\n
g_est_list.append(np.mean(g_slope_array))\n
n_add_est_list.append(np.mean(var_add_constant_array))\n    print(g_est_list)\n
print("ESTIMATED sigma_add")\n    print(np.sqrt(n_add_est_list))\n
print("TRUE N_ADD")\n    print(np.sqrt((sigma_read**2) *\n
(np.array(gain_levels)**2) + (sigma_adc**2)))\n    x =\n
(np.array(g_est_list)**2)\n    y = (np.array(n_add_est_list))\n    fit_2 =\n
np.polyfit(x,y,1)\n    var_read_m, var_adc_c = fit_2[0],fit_2[1]\n
sigma_read_est = np.sqrt(var_read_m)\n    sigma_adc_est = np.sqrt(var_adc_c)\n
print(sigma_read_est)\n    print(sigma_adc_est)\n    return sigma_read_est,\n
sigma_adc_est\n    '

```