CS445: Computational Photography

Programming Project 4: Image-Based Lighting

Recovering HDR Radiance Maps

Load libraries and data

In [1]:
```
# jupyter extension that allows reloading functions from imports without cl
%load_ext autoreload
%autoreload 2
```

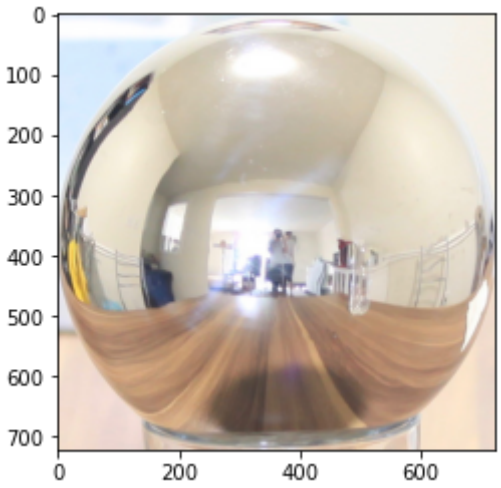
In [2]:
```
# from google.colab import drive
# drive.mount('/content/drive')
```

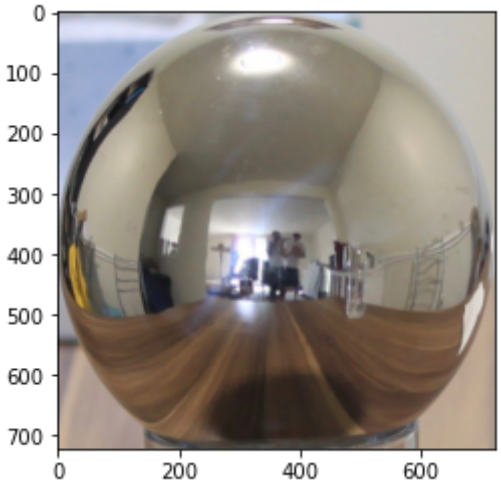
In [206]:
```
# System imports
from os import path
import math
import copy
# Third-Party Imports
import cv2
import matplotlib.pyplot as plt
import numpy as np
from scipy.interpolate import griddata

# # modify to where you store your project data including utils
# datadir = "/content/drive/My Drive/cs445_projects/proj4/"

# utilfn = datadir + "utils"
# !cp -r "$utilfn" .
# samplesfn = datadir + "samples"
# !cp -r "$samplesfn" .

# # can change this to your output directory of choice
# !mkdir "images"
# !mkdir "images/outputs"

# import starter code
import utils
from utils.io import read_image, write_image, read_hdr_image, write_hdr_ima
from utils.display import display_images_linear_rescale, rescale_images_lin
from utils.hdr_helpers import gsolve
from utils.hdr_helpers import get_equirectangular_image
from utils.bilateral_filter import bilateral_filter
```

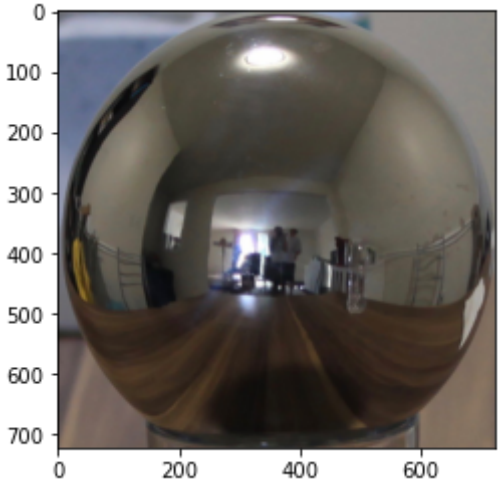
Reading LDR images

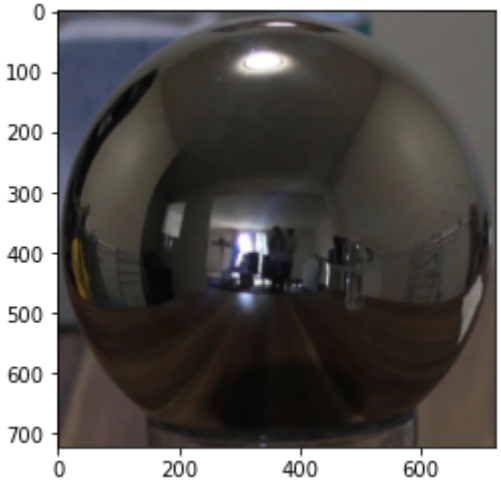
You can use the provided samples or your own images. You get more points for using your own images, but it might help to get things working first with the provided samples.

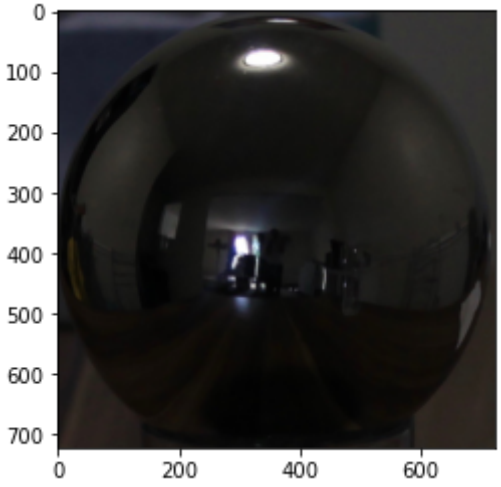
In [207]:
```
# TODO: Replace this with your path and files

# imdir = 'samples'
imdir = 'mysample'
imfns = ['0024.jpg', '0060.jpg', '0120.jpg', '0205.jpg', '0553.jpg']
exposure_times = [1/24.0, 1/60.0, 1/120.0, 1/205.0, 1/553.0]
# imfns = ['0024.jpg', '0060.jpg', '0120.jpg']
# exposure_times = [1/24.0, 1/60.0, 1/120.0]
ldr_images = []
for f in np.arange(len(imfns)):
    im = read_image(imdir + '/' + imfns[f])
    if f==0:
        imsize = int((im.shape[0] + im.shape[1])/2) # set width/height of b
        ldr_images = np.zeros((len(imfns), imsize, imsize, 3))

    ldr_images[f] = cv2.resize(im, (imsize, imsize))
    plt.imshow(ldr_images[f])
    plt.show()

background_image_file = imdir + '/' + 'empty.jpg'
background_image = read_image(background_image_file)

plt.imshow(background_image)
plt.show()
```

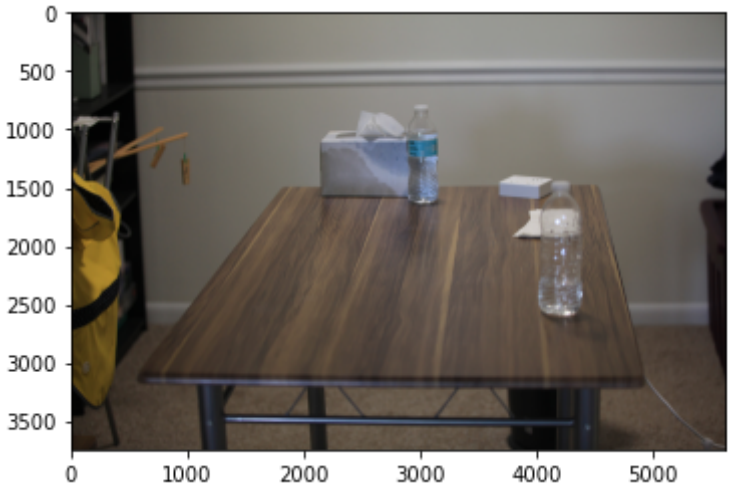





0
100
200
300
400
500
600
700
0
200
400
600


0
100
200
300
400
500
600
700
0
200
400
600


0
100
200
300
400
500
600
700
0
200
400
600



Naive LDR merging

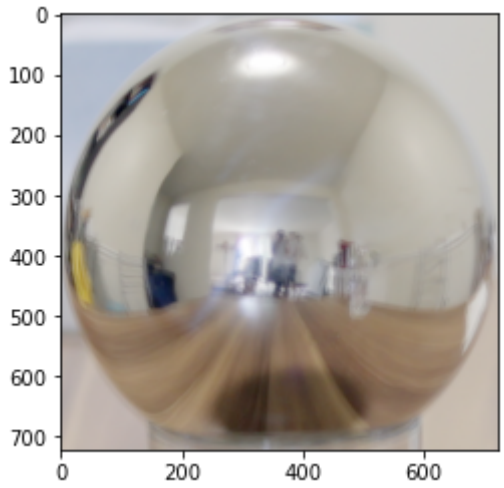
Compute the HDR image as average of irradiance estimates from LDR images

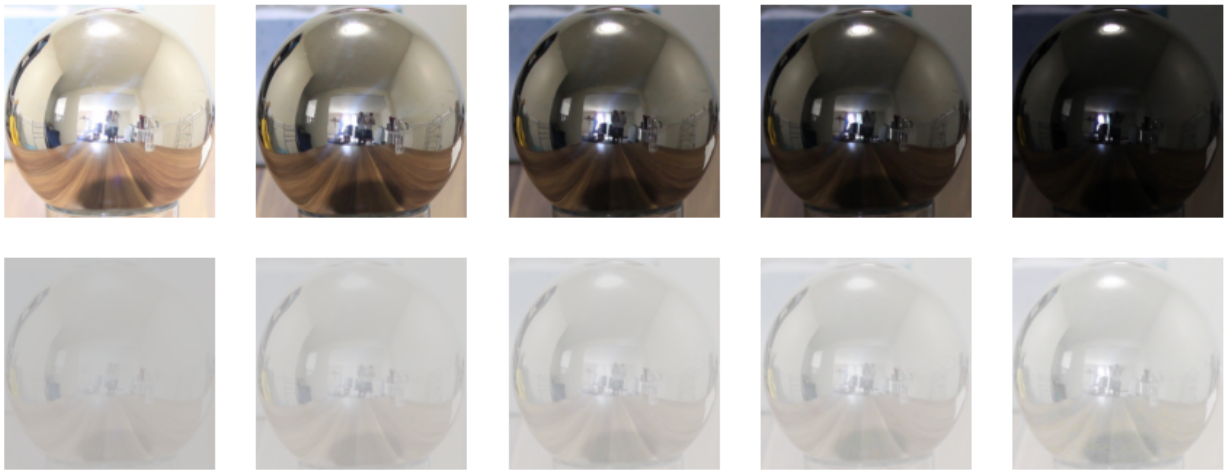
In [5]:
```
def display_hdr_image(im_hdr):
    '''
    Maps the HDR intensities into a 0 to 1 range and then displays.
    Three suggestions to try:
      (1) Take log and then linearly map to 0 to 1 range (see display.py fo
      (2) img_out = im_hdr / (1 + im_hdr)
      (3) HDR display code in a python package
    '''

    img_out_log = np.zeros(im_hdr.shape)
    new_im_hdr = im_hdr
    im_out_log = np.log(new_im_hdr)
    log_min = im_out_log[im_out_log != -float('inf')].min()
    log_max =im_out_log[im_out_log != float('inf')].max()
#     print("log_min", log_min)
#     print("log_max", log_max)
    im_out_log[im_out_log == float('inf')] = log_max
    im_out_log[im_out_log == -float('inf')] = log_min
    im_out_log = (im_out_log - log_min) / (log_max - log_min)
    plt.imshow(im_out_log)
    plt.show()


    return
```

In [343]:
```
def make_hdr_naive(ldr_images: np.ndarray, exposure_times: list) -> (np.nda
    N, H, W, C = ldr_images.shape
    # sanity check
    assert N == len(exposure_times)

    hdr_image = np.zeros(ldr_images[0,:,:,:].shape)
#     print("ldr_images.shape",ldr_images.shape)
#     print("ldr_images[0,:,:,:].shape", ldr_images[0,:,:,:].shape)
    log_irradiances = np.zeros(ldr_images.shape)

    for i in range(N):
#         exposure_times = [1/24.0, 1/60.0, 1/120.0, 1/205.0, 1/553.0]
        log_irradiances[i,:,:,:] = np.log((ldr_images[i,:,:,:] + 0.00001)/(
        hdr_image += ldr_images[i,:,:,:]
    hdr_image /= 5



    return hdr_image, log_irradiances
```

In [344]:
```
# for i in range(5):
#     plt.imshow(ldr_images[i])
#     plt.show()
# get HDR image, log irradiance
naive_hdr_image, naive_log_irradiances = make_hdr_naive(ldr_images, exposur

# write HDR image to directory
write_hdr_image(naive_hdr_image, 'images/outputs/naive_hdr_Divide.hdr')

# display HDR image
print('HDR Image')
display_hdr_image(naive_hdr_image)

# display original images (code provided in utils.display)
display_images_linear_rescale(ldr_images)

# display log irradiance image (code provided in utils.display)
display_images_linear_rescale(naive_log_irradiances)
```

```
HDR Image
```



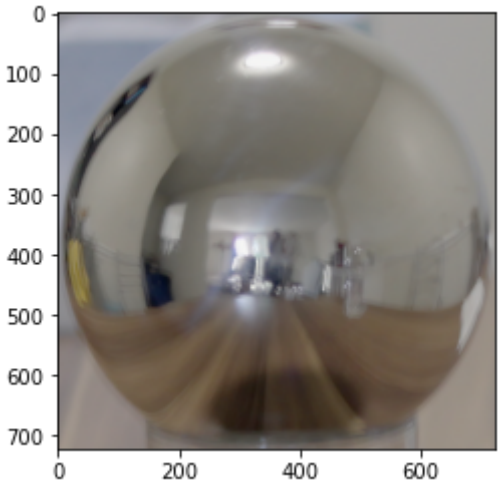


Weighted LDR merging

Compute HDR image as a weighted average of irradiance estimates from LDR images, where weight is based on pixel intensity so that very low/high intensities get less weight

In [351]:
```
def make_hdr_weighted(ldr_images: np.ndarray, exposure_times: list) -> (np.
    '''
    Makes HDR image using multiple LDR images, and its corresponding exposu

    The steps to implement:
    1) compute weights for images with based on intensities for each exposu
        - This can be a binary mask to exclude low / high intensity values

    2) Divide each images by its exposure time.
        - This will rescale images as if it has been exposed for 1 second.

    3) Return weighted average of above images


    Args:
        ldr_images(np.ndarray): N x H x W x 3 shaped numpy array representi
            N ldr images with width W, height H, and channel size of 3 (RGB
        exposure_times(list): list of length N, representing exposures of e
            Each exposure should correspond to LDR images' exposure value.
    Return:
        (np.ndarray): H x W x 3 shaped numpy array representing HDR image m
            under - over exposed regions

    '''
    N, H, W, C = ldr_images.shape
    # sanity check
    assert N == len(exposure_times)
    hdr_image = np.zeros(ldr_images[0,:,:,:].shape)
    local_images = copy.deepcopy(ldr_images)
    m = np.zeros((N,H,W,C))
#     print(np.amax(local_images))
#     print(np.amin(local_images))
    for i in range(N):
        hdr_img_loop = (local_images[i,:,:,:]+0.00001)/(exposure_times[i]+0
        filt = (128-abs(local_images[i,:,:,:]-128))
#         print("np.amax(filt)", np.amax(filt))
#         print("np.amin(filt)",np.amin(filt))

#         plt.imshow(filt)
#         plt.show()

        m[i,:,:,:] = filt

        hdr_image += hdr_img_loop * filt
    hdr_image = hdr_image / np.sum(m, axis=0)
    hdr_image /= N

    return hdr_image
```

In [352]:
```
# for i in range(5):
#     plt.imshow(ldr_images[i])
#     plt.show()
# # get HDR image, log irradiance
weighted_hdr_image = make_hdr_weighted(ldr_images, exposure_times)


# # # # write HDR image to directory
# write_hdr_image(weighted_hdr_image, 'images/outputs/weighted_hdr_nov9.hdr

# # display HDR image
display_hdr_image(weighted_hdr_image)
```



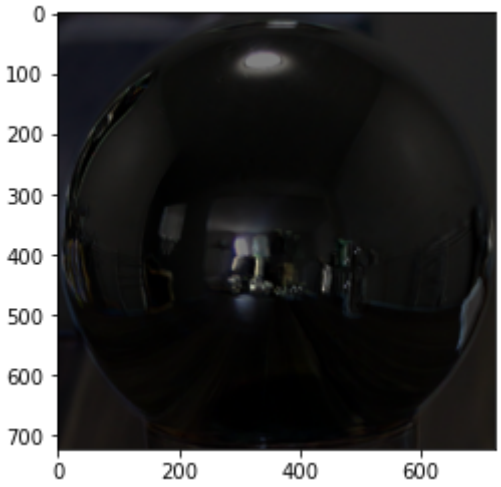
Display of difference between naive and weighted for your own inspection

Where does the weighting make a big difference increasing or decreasing the irradiance estimate? Think about why.

In [353]:
```
# display difference between naive and weighted
print(np.amax(naive_hdr_image))
print(np.amax(weighted_hdr_image))
log_diff_im = np.log(weighted_hdr_image)-np.log(naive_hdr_image)
print('Min ratio = ', np.exp(log_diff_im).min(), '  Max ratio = ', np.exp(l
plt.figure()
plt.imshow(rescale_images_linear(log_diff_im))
```

```
1.0
42.889143298562296
Min ratio =  13.542111978566258   Max ratio =  100.95115007448342
```

Out[353]:
```
<matplotlib.image.AxesImage at 0xc347e8748>
```



LDR merging with camera response function estimation

Compute HDR after calibrating the photometric reponses to obtain more accurate irradiance estimates from each image

Some suggestions on using `gsolve`:

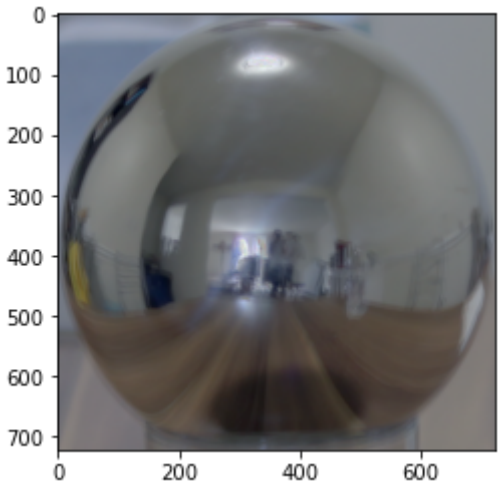
- When providing input to gsolve, don't use all available pixels, otherwise you will likely run out of memory / have very slow run times. To overcome, just randomly sample a set of pixels (1000 or so can suffice), but make sure all pixel locations are the same for each exposure.
- The weighting function w should be implemented using Eq. 4 from the paper (this is the same function that can be used for the previous LDR merging method).
- Try different lambda values for recovering *g*. Try lambda=1 initially, then solve for *g* and plot it. It should be smooth and continuously increasing. If lambda is too small, g will be bumpy.
- Refer to Eq. 6 in the paper for using g and combining all of your exposures into a final image. Note that this produces log irradiance values, so make sure to exponentiate the result and save irradiance in linear scale.

In [355]:

```
import random
def new_make_hdr_estimation(ldr_images: np.ndarray, exposure_times: list, l
    #init variables
    local_ldr_images = copy.deepcopy(ldr_images)
    local_ldr_images = (local_ldr_images * 255).astype(int)
#     for i in range(5):
#         plt.imshow(local_ldr_images[i])
#         plt.show()
    N, H, W, C = local_ldr_images.shape
    hdr_image = np.zeros(local_ldr_images[0,:,:,:].shape)
    log_irradiances = np.zeros(local_ldr_images.shape)
    random_total = 5000
#     create a circle mask
    circle_mask = np.ones((H, W))
    for i in range(H):
        for j in range(W):
            if (H/2 - i)**2 + (W/2 - j)**2 > (H/2)**2:
                circle_mask[i, j] = 0
#     plt.imshow(circle_mask)
#     plt.show()
#pick random pixels from the circle, N pictures
    circle_h, circle_w = np.where(circle_mask == 1)
    random_h = []
    random_w = []
    for rand in range(random_total):
        local_rand = random.randint(0, len(circle_w))
        random_h.append(circle_h[local_rand])
        random_w.append(circle_w[local_rand])

#     Z = np.zeros((N,total_random))
#     B = np.log(exposure_times)
#     l = lm
#     w = lambda z: float(128-abs(z-128))
#     g_values = np.zeros((C,256))
    B = np.log(exposure_times)
    l = lm
    w = lambda z: (128-abs(z-128))
    g_val = []

    ##use gsolve
    for c in range(C):
        Z = np.zeros((N, random_total), dtype=int)
        for img_num in range(N):
            loop_ldr = copy.deepcopy(local_ldr_images[img_num])
            Z[img_num] = loop_ldr[random_h, random_w, c]
        g, le = gsolve(Z, B, l, w)
        g_val.append(g)

        hdr_weights = []
        for img_num,(loop_ldr,log_expo) in enumerate(zip(local_ldr_images,B
            cur_ldr = loop_ldr[:,:,c]
#             hdr_image[:,:,c]+=w(cur_ldr).astype(float)*(g[cur_ldr]-log_ex
            hdr_image[:,:,c]+=w(cur_ldr).astype(float)*(g[cur_ldr]-log_expo
            hdr_weights.append(w(cur_ldr).astype(float))
            log_irradiances[img_num,:,:,c]=(g[cur_ldr]-log_expo)
        hdr_image[:,:,c]/=np.sum(hdr_weights,axis=0).astype(float)
```

```
    hdr_image = np.exp(hdr_image)
    return hdr_image, log_irradiances, np.asarray(g_val)
```

In [356]:
```
lm = 3000
# get HDR image, log irradiance
# calib_hdr_image, calib_log_irradiances, g = make_hdr_estimation_2(ldr_ima
calib_hdr_image, calib_log_irradiances, g = new_make_hdr_estimation(ldr_ima



# # write HDR image to directory
# write_hdr_image(calib_hdr_image, 'images/outputs/calib_hdrHi.hdr')

# display HDR image
display_hdr_image(calib_hdr_image)
```

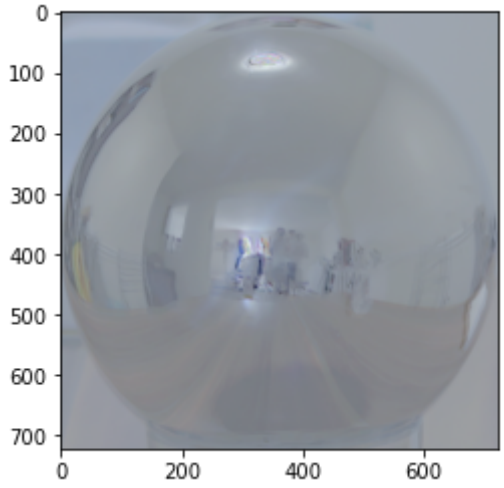


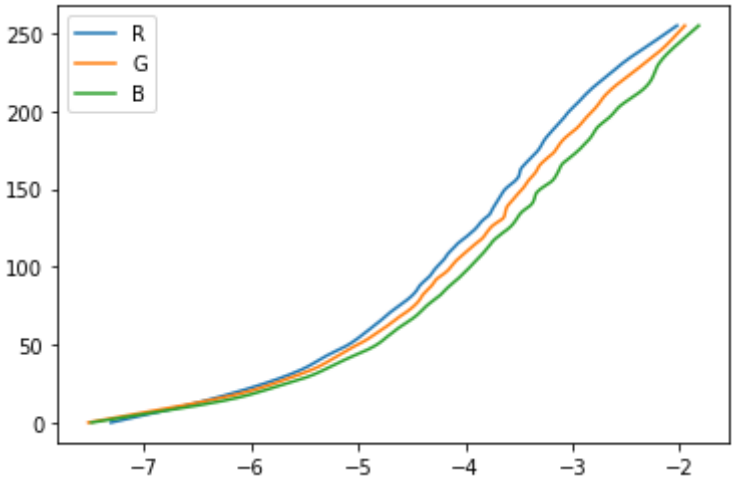
The following code displays your results. You can copy the resulting images and plots directly into your report where appropriate.

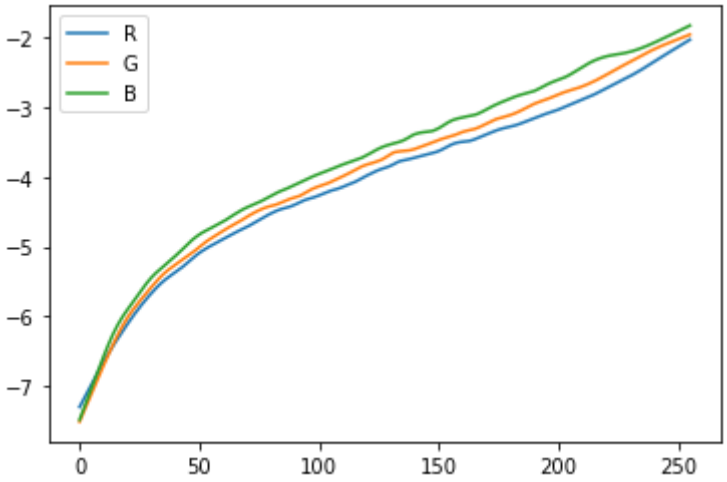
In [357]:
```
# display difference between calibrated and weighted
log_diff_im = np.log(calib_hdr_image/calib_hdr_image.mean())-np.log(weighte
print('Min ratio = ', np.exp(log_diff_im).min(), '  Max ratio = ', np.exp(l
plt.figure()
plt.imshow(rescale_images_linear(log_diff_im))

# display original images (code provided in utils.display)
display_images_linear_rescale(ldr_images)

# display log irradiance image (code provided in utils.display)
display_images_linear_rescale(calib_log_irradiances)

# plot g vs intensity, and then plot intensity vs g
N, NG = g.shape
labels = ['R', 'G', 'B']
plt.figure()
for n in range(N):
    plt.plot(g[n], range(NG), label=labels[n])
plt.gca().legend(('R', 'G', 'B'))

plt.figure()
for n in range(N):
    plt.plot(range(NG), g[n], label=labels[n])
plt.gca().legend(('R', 'G', 'B'))
```

```
Min ratio =  0.0814276951988353   Max ratio =  4.865780006263132
```

Out[357]:
```
<matplotlib.legend.Legend at 0xc287df438>
```




R
G
B
250
200
150
100
50
0
−7
−6
−5
−4
−3
−2


R
G
B
−2
−3
−4
−5
−6
−7
0
50
100
150
200
250

In [358]:
```
def weighted_log_error(ldr_images, hdr_image, log_irradiances):
  # computes weighted RMS error of log irradiances for each image compared
    N, H, W, C = ldr_images.shape
    w = 1-abs(ldr_images - 0.5)*2
    err = 0
    for n in np.arange(N):
        err += np.sqrt(np.multiply(w[n], (log_irradiances[n]-np.log(hdr_ima
    return err


# compare solutions
err = weighted_log_error(ldr_images, naive_hdr_image, naive_log_irradiances
print('naive:  \tlog range = ', round(np.log(naive_hdr_image).max() - np.lo
err = weighted_log_error(ldr_images, weighted_hdr_image, naive_log_irradian
print('weighted:\tlog range = ', round(np.log(weighted_hdr_image).max() - n
err = weighted_log_error(ldr_images, calib_hdr_image, calib_log_irradiances
print('calibrated:\tlog range = ', round(np.log(calib_hdr_image).max() - np

# display log hdr images (code provided in utils.display)
display_images_linear_rescale(np.log(np.stack((naive_hdr_image/naive_hdr_im
```

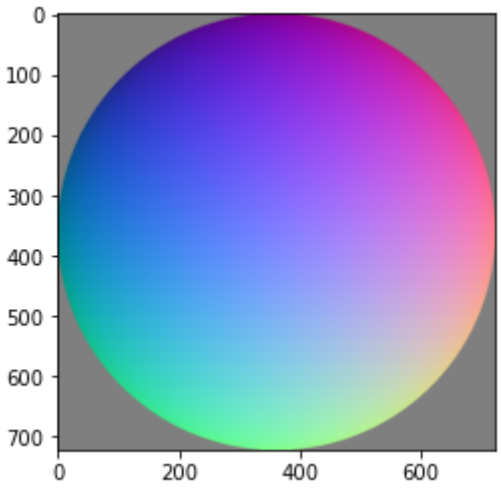
```
naive:          log range =  2.755      avg RMS error =  4.574
weighted:       log range =  3.878      avg RMS error =  1.814
calibrated:     log range =  5.828      avg RMS error =  0.188
```

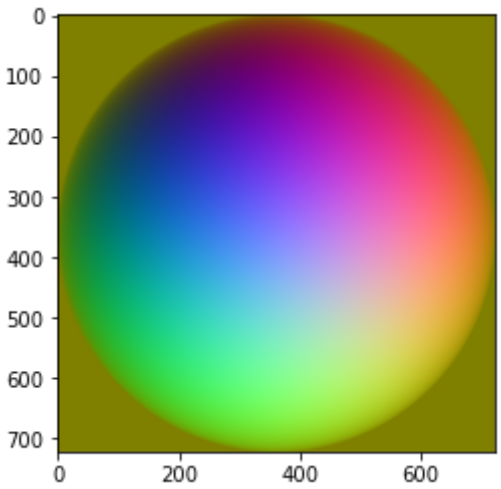
Panoramic transformations

Compute the equirectangular image from the mirrorball image

In [192]:
```
def panoramic_transform(hdr_image):
    '''
    Given HDR mirror ball image,

    Expects mirror ball image to have center of the ball at center of the i
    width and height of the image to be equal.

    Steps to implement:
    1) Compute N image of normal vectors of mirror ball
    2) Compute R image of reflection vectors of mirror ball
    3) Map reflection vectors into spherical coordinates
    4) Interpolate spherical coordinate values into equirectangular grid.

    Steps 3 and 4 are implemented for you with get_equirectangular_image

    '''
    H, W, C = hdr_image.shape
    h_h, h_w = H/2, W/2 #half of the origin
    assert H == W
    assert C == 3

    N = np.zeros((H,W,C))

    for i in range(H):
        for j in range(W):
            if((i-h_h)**2 + (j-h_w)**2 > h_h**2):
                N[j][i] = (0,0,0)
                continue
            Nx = (j - h_w)/ h_w
            Ny = (i - h_h)/ h_h
            Nz = np.sqrt(1 -  Ny**2 - Nx**2 )
            if(Nz == float("NaN")):
                Nz = 0
            N[i][j] = (Nx, Ny, Nz)
    # R = V - 2 * dot(V,N) * N
#     V = [0,0,1]
    V= np.array([0,0,-1])
    R = np.zeros((H,W,C))
    for i in range(H):
        for j in range(W):
            # R = V - 2 * dot(V,N) * N
            R[j][i] = V - 2 * np.dot(V,N[j][i]) * N[j][i]
    plt.imshow((N+1)/2)
    plt.show()
    plt.imshow((R+1)/2)
    plt.show()
    equirectangular_image = get_equirectangular_image(R, hdr_image)
    return equirectangular_image
```

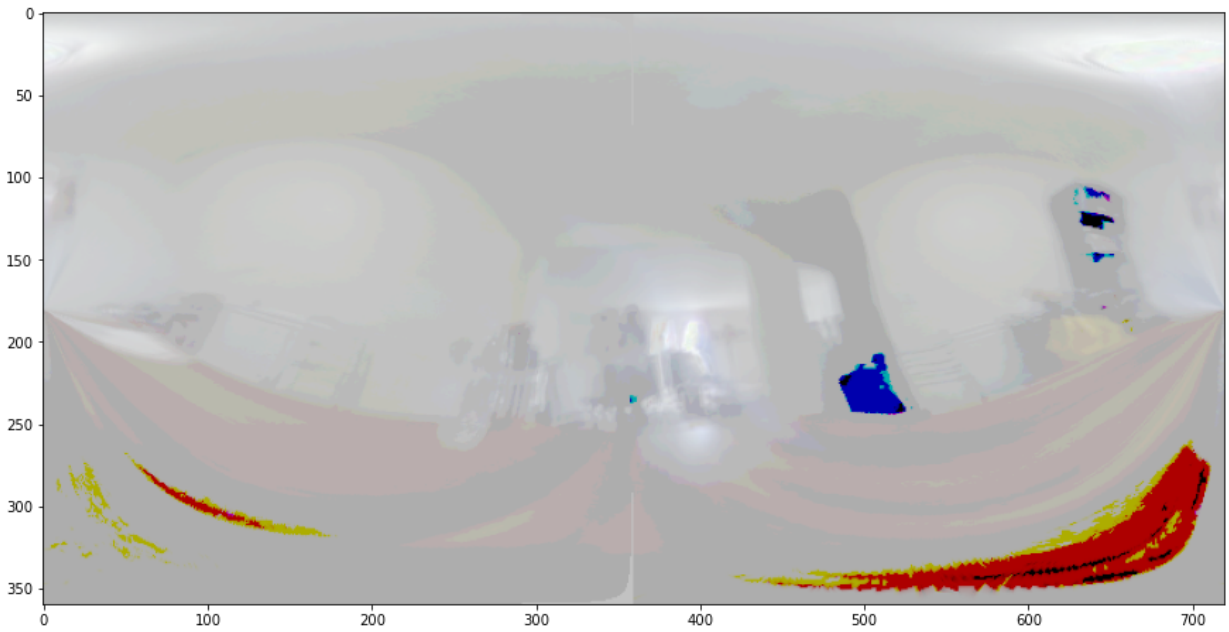
In [194]:
```
# hdr_mirrorball_image = read_hdr_image('images/outputs/calib_hdr.hdr')
hdr_mirrorball_image = read_hdr_image('images/outputs/calib_hdrHi.hdr')
eq_image = panoramic_transform(hdr_mirrorball_image)

write_hdr_image(eq_image, 'images/outputs/equirectangular2.hdr')

plt.figure(figsize=(15,15))
display_hdr_image(eq_image)
```






```
/Users/MedicalDoctor/opt/anaconda3/envs/py36/lib/python3.6/site-package
s/ipykernel_launcher.py:12: RuntimeWarning: divide by zero encountered
```

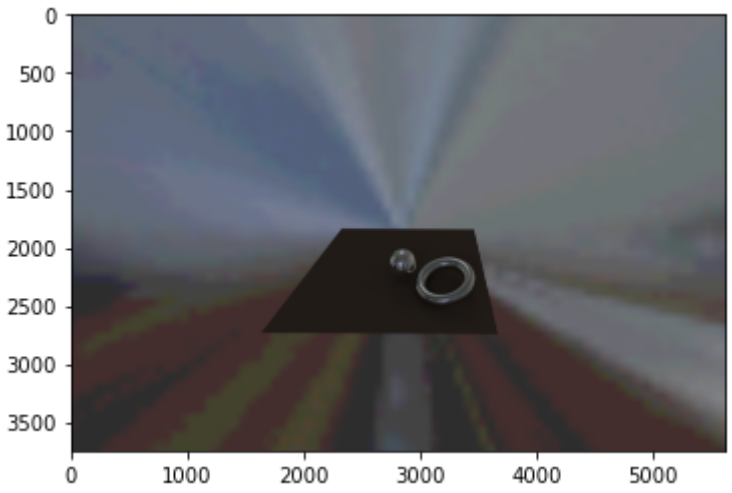
```
in log
  if sys.path[0] == '':
```

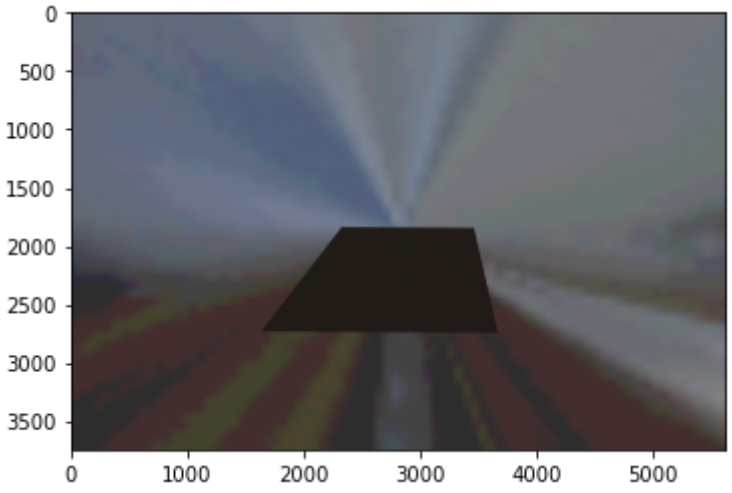


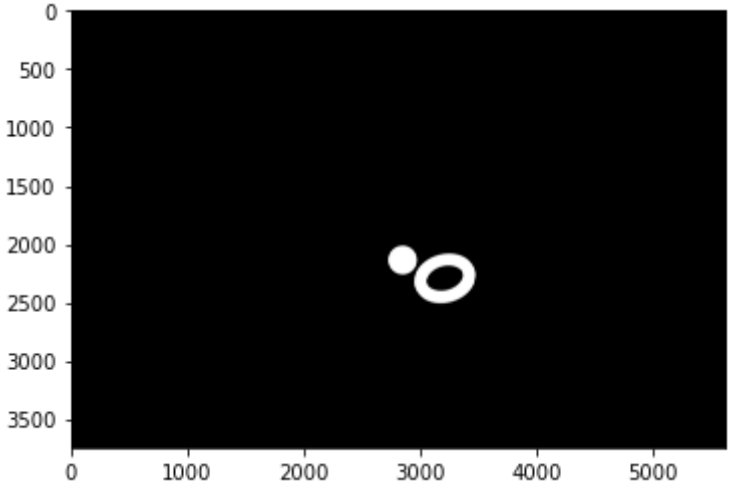
Rendering synthetic objects into photographs

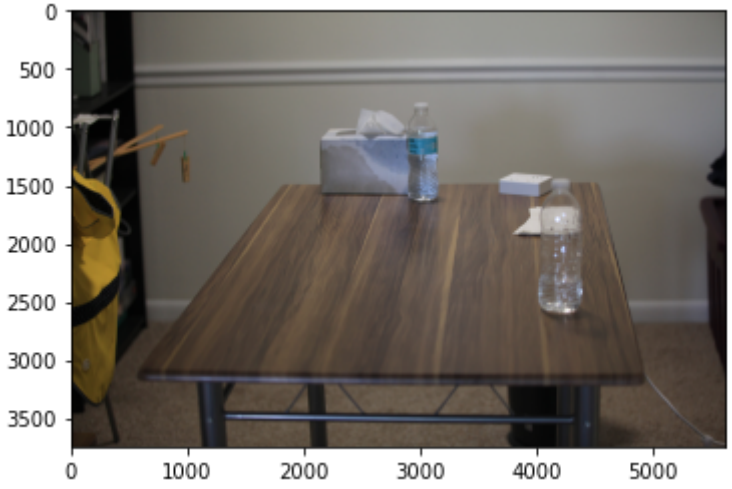
Use Blender to render the scene with and with objects and obtain the mask image. The code below should then load the images and create the final composite.

In [200]:
```
# Read the images that you produced using Blender.  Modify names as needed.
O = read_image('images/proj4_objects02.png')
E = read_image('images/proj4_empty02.png')
M = read_image('images/proj4_mask02.png')
M = M > 0.5
I = background_image
I = cv2.resize(I, (M.shape[1], M.shape[0]))
plt.imshow(O)
plt.show()
plt.imshow(E)
plt.show()
plt.imshow(M.astype('double'))
plt.show()
plt.imshow(I)
plt.show()
```






0
500
1000
1500
2000
2500
3000
3500
0
1000
2000
3000
4000
5000


0
500
1000
1500
2000
2500
3000
3500
0
1000
2000
3000
4000
5000

In [205]:
```
# TO DO: compute final composite
# composite = M*R + (1-M)*I + (1-M)*(R-E)*c
result = []
c=4
result = M*O + (1-M)*I + (1-M)*(O-E)*c

plt.figure(figsize=(20,20))
plt.imshow(result)
plt.show()

write_image(result, 'images/outputs/final_compositelargeC.png')
```

```
Clipping input data to the valid range for imshow with RGB data ([0..1] f
or floats or [0..255] for integers).
```

Bells & Whistles (Extra Points)

Additional Image-Based Lighting Result

Other panoramic transformations

Photographer/tripod removal

Local tonemapping operator

In [ ]: