Credits

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Contents

Step 1 - Initialization

```
clear
cie = loadCIEdata;
```

Step 2 - Setup ref2XYZ

This function takes Surface reflectance, Color Matching Function, Illumination and converts it to XYZ tristimulus values. refs = Surface reflectance nx1 vector

```
cmfs = Color matching functions nx3 vector
       in [x,y,z] order

illum = SPD of light source nx1 vector

%                      R(λ)  x,y,z  S(λ)
function XYZ = ref2XYZ(refs, cmfs,  illum)
k = 100 / sum(cmfs(:, 2).*illum);
X = k * sum(cmfs(:, 1).*illum.*refs);
Y = k * sum(cmfs(:, 2).*illum.*refs);
Z = k * sum(cmfs(:, 3).*illum.*refs);
XYZ = [X;Y;Z];
end
```

Step 3 - Test ref2XYZ

```
spectra.CC = load('ColorChecker_380-780-5nm.txt');
CC_Light.XYZs.D65 = ref2XYZ(spectra.CC(:,2:25),cie.cmf2deg,cie.illD65);

CC_Light.XYZs.D65
```

```
ans =

  Columns 1 through 7

   11.5145   39.1346   18.3488   11.1492   25.8437   31.7110   37.1457
   10.3819   36.5981   19.6332   13.8551   24.3868   43.8600   29.5592
    7.1502   27.0564   35.6470    7.4267   45.6142   44.8778    6.5006

  Columns 8 through 14

   13.8627   29.1328    8.5889   33.9174   46.1864    8.9183   15.0353
   12.3179   19.8475    6.4569   44.1533   42.4957    6.4177   24.1079
   39.3093   14.9941   15.4745   11.4297    8.6771   32.2736    9.6379

  Columns 15 through 21

   19.3447   55.8457   29.6768   14.4138   87.8402   57.9621   35.2286
   11.3576   58.9726   19.3515   19.9750   92.3781   61.0426   37.0414
    5.5526    9.6411   32.2626   39.0008   95.6125   65.4909   40.2256

  Columns 22 through 24

   19.3492    8.7646    3.2111
   20.4708    9.2915    3.3763
   22.1545   10.3188    3.9312
```

Step 4 - Setup XYZ2Lab

This function takes XYZ tristimulus values and XYZn tristimulus values (of reference illuminant) and converts it to L*a*b*

```
XYZ  = Tristimulus values 3xn vector
       3xn vector, [X;Y;Z]

XYZn = Tristimulus values (of ref. illuminant)
       3x1 vector [X;Y;Z]

function Lab = XYZ2Lab(XYZ, XYZn)
% Calculate Ratios, the 'x' to be compared in the Piecewise function
Ratios = XYZ ./ XYZn;

% Define anonymous functions, the parts of the Piecewise function
Cond1 = @(x) x.^(1/3)        ; %x > 0.008856
Cond2 = @(x) 7.787*x + 16/116; %x ≤ 0.008856

% Apply operations of Piecewise
cond1Index = Ratios > 0.008856            ;
Ratios(cond1Index)  = Cond1(Ratios(cond1Index)) ;
Ratios(~cond1Index) = Cond2(Ratios(~cond1Index));

% Calculate L*a*b*
L = 116*Ratios(2,:)-16            ;
a = 500*(Ratios(1,:) - Ratios(2,:));
b = 200*(Ratios(2,:) - Ratios(3,:));

Lab = [L;a;b];
end
```

Step 5 - Test XYZ2Lab

Calculate XYZn values

```
CC_Light.XYZn.D65 = ref2XYZ(cie.PRD,cie.cmf2deg,cie.illD65);

% Calculate Lab values
CC_Light.Lab.D65 = XYZ2Lab(CC_Light.XYZs.D65, CC_Light.XYZn.D65);

% The name of each patch in the Macbeth Color Checker
names = textread('ColorChecker_names.txt','%s','delimiter','|'); %#ok<DTXTRD>


% TABLE - Header
fprintf('%s', 'ColorChecker XYZ and Lab values (D65 illuminant and 2 deg. observer)', newline, newline)
fprintf('%s %4s %8s %8s %8s %8s %8s %8s %14s\n', 'Patch #', 'X', 'Y', 'Z', 'L*', 'a*', 'b*', 'Patch Name')

% TABLE - Body
fspec = '%5.0f %8.3f %8.3f %8.3f %8.3f %8.3f %8.3f %s %2s\n';
for patchnum = 1:size(CC_Light.Lab.D65,2)
%          format     1       X,Y,Z       L,a,b      Patch name
    fprintf(fspec, patchnum, CC_Light.XYZs.D65(1, patchnum), CC_Light.XYZs.D65(2,patchnum), CC_Light.XYZs.D65(3,patchnum), CC_Light.Lab.D65(1,patchnum), CC_Light.La
end
```

```
ColorChecker XYZ and Lab values (D65 illuminant and 2 deg. observer)

Patch #    X        Y        Z       L*       a*       b*     Patch Name
    1   11.515   10.382    7.150   38.519   12.410   13.309   Dark Skin
    2   39.135   36.598   27.056   66.974   14.329   17.320   Light Skin
    3   18.349   19.633   35.647   51.420   -1.624  -21.603   Blue Sky
    4   11.149   13.855    7.427   44.024  -13.963   21.774   Foliage
    5   25.844   24.387   45.614   56.473   11.544  -24.698   Blue Flower
    6   31.711   43.860   44.878   72.135  -33.101    3.115   Bluish Green
    7   37.146   29.559    6.501   61.272   32.497   55.059   Orange
    8   13.863   12.318   39.309   41.717   14.416  -42.900   Purplish Blue
    9   29.133   19.847   14.994   51.664   45.468   13.382   Moderate Red
   10    8.589    6.457   15.474   30.537   23.785  -24.136   Purple
   11   33.917   44.153   11.430   72.331  -26.083   57.948   Yellow Green
   12   46.186   42.496    8.677   71.211   17.187   64.297   Orange Yellow
   13    8.918    6.418   32.274   30.443   27.024  -53.277   Blue
   14   15.035   24.108    9.638   56.196  -40.771   35.342   Green
   15   19.345   11.358    5.553   40.176   51.976   22.689   Red
   16   55.846   58.973    9.641   81.277   -0.508   78.575   Yellow
   17   29.677   19.352   32.263   51.096   50.004  -17.653   Magenta
   18   14.414   19.975   39.001   51.809  -25.642  -25.126   Cyan
   19   87.840   92.378   95.613   96.975    0.076    3.262   White
   20   57.962   61.043   65.491   82.402   -0.133    0.831   Neutral 8
   21   35.229   37.041   40.226   67.308    0.079    0.125   Neutral  6.5
   22   19.349   20.471   22.154   52.365   -0.541    0.237   Neutral 5
   23    8.765    9.291   10.319   36.540   -0.568   -0.600   Neutral 3.5
   24    3.211    3.376    3.931   21.492    0.035   -1.462   Black
```

Step 6 - Darker CC Spectra

Darker CC Spectra

```
CC_Dark.XYZs.D65 = CC_Light.XYZs.D65*0.02;

% Dark L*a*b* values
CC_Dark.Lab.D65 = XYZ2Lab(CC_Dark.XYZs.D65, CC_Light.XYZn.D65);


fprintf('%s', 'ColorChecker (Dark) XYZ and Lab values (D65 illuminant and 2 deg. observer)', newline, newline);
fprintf('%s %4s %8s %8s %8s %8s %8s %14s\n', 'Patch #', 'X', 'Y', 'Z', 'L*', 'a*', 'b*', 'Patch Name')

% TABLE - Body
fspec = '%5.0f %8.3f %8.3f %8.3f %8.3f %8.3f %8.3f %s %2s\n';
for patchnum = 1:size(CC_Light.Lab.D65,2)
%          format     1       X,Y,Z       L,a,b      Patch name
    fprintf(fspec, patchnum, CC_Dark.XYZs.D65(1, patchnum), CC_Dark.XYZs.D65(2,patchnum), CC_Dark.XYZs.D65(3,patchnum), CC_Dark.Lab.D65(1,patchnum), CC_Dark.Lab.D65
end
```

```
ColorChecker (Dark) XYZ and Lab values (D65 illuminant and 2 deg. observer)

Patch #    X        Y        Z       L*       a*       b*     Patch Name
    1    0.230    0.208    0.143    1.876    1.350    1.188   Dark Skin
    2    0.783    0.732    0.541    6.612    3.565    3.659   Light Skin
    3    0.367    0.393    0.713    3.547   -0.255   -4.082   Blue Sky
    4    0.223    0.277    0.149    2.503   -1.654    2.191   Foliage
    5    0.517    0.488    0.912    4.406    2.184   -5.453   Blue Flower
    6    0.634    0.877    0.898    7.924   -8.173    0.823   Bluish Green
    7    0.743    0.591    0.130    5.340    7.416    7.347   Orange
    8    0.277    0.246    0.786    2.225    1.766   -7.409   Purplish Blue
    9    0.583    0.397    0.300    3.586    8.414    1.893   Moderate Red
   10    0.172    0.129    0.309    1.166    2.009   -2.416   Purple
   11    0.678    0.883    0.229    7.977   -6.593   10.483   Yellow Green
   12    0.924    0.850    0.174    7.677    4.646   10.754   Orange Yellow
   13    0.178    0.128    0.645    1.159    2.309   -7.234   Blue
   14    0.301    0.482    0.193    4.355   -6.454    4.752   Green
   15    0.387    0.227    0.111    2.052    7.005    1.949   Red
   16    1.117    1.179    0.193   10.405   -0.138   15.181   Yellow
   17    0.594    0.387    0.645    3.496    9.246   -3.202   Magenta
   18    0.288    0.399    0.780    3.609   -3.745   -4.935   Cyan
   19    1.757    1.848    1.912   14.666    0.021    0.885   White
   20    1.159    1.221    1.310   10.710   -0.036    0.226   Neutral 8
   21    0.705    0.741    0.805    6.692    0.019    0.030   Neutral  6.5
   22    0.387    0.409    0.443    3.698   -0.088    0.038   Neutral 5
   23    0.175    0.186    0.206    1.679   -0.054   -0.058   Neutral 3.5
   24    0.064    0.068    0.079    0.610    0.002   -0.073   Black
```

Step 7 - Setup deltaEab

Takes 2 sets of Lab and converts them to Delta Eab values

```
Lab is a 3xn matrix

DEab is a 1xn matrix

function DEab = deltaEab(Lab1, Lab2)
%                    L1* - L2*                   a1* - a2*                   b1* - b2*
DEab = sqrt(  (Lab1(1, :)-Lab2(1,:)).^2  +  (Lab1(2,:)-Lab2(2,:)).^2  +  (Lab1(3,:)-Lab2(3,:)).^2  );
end
```

Step 8 - Test deltaEab

```
spectra.MC = load('MetaChecker_380-780-5nm.txt');
% Use 'spectra.' struct for spectra data

% Calculate XYZ for MC, both under illA and illD65
MC_Light.XYZs.D65 = ref2XYZ(spectra.MC(:,2:25),cie.cmf2deg,cie.illD65);
MC_Light.XYZs.A   = ref2XYZ(spectra.MC(:,2:25),cie.cmf2deg,cie.illA);

% Calculate XYZn for MC, both under illA and illD65
MC_Light.XYZn.D65 = ref2XYZ(cie.PRD,cie.cmf2deg,cie.illD65);
MC_Light.XYZn.A   = ref2XYZ(cie.PRD,cie.cmf2deg,cie.illA);

% Calculate LAB for MC, both under illA and illD65
MC_Light.Lab.D65 = XYZ2Lab(MC_Light.XYZs.D65, MC_Light.XYZn.D65);
MC_Light.Lab.A   = XYZ2Lab(MC_Light.XYZs.A  , MC_Light.XYZn.A)  ;


% Calculate XYZs for CC, both under illA and illD65
CC_Light.XYZs.D65; %Already made
CC_Light.XYZs.A = ref2XYZ(spectra.CC(:,2:25),cie.cmf2deg,cie.illA);
```

```
% Calculate XYZn for CC, both under illA and illD65
CC_Light.XYZn.D65; %Already made
CC_Light.XYZn.A = ref2XYZ(cie.PRD,cie.cmf2deg,cie.illA);

% Calculate LAB for CC, under illA and illD65
CC_Light.Lab.D65; %Already made
CC_Light.Lab.A = XYZ2Lab(CC_Light.XYZs.A,CC_Light.XYZn.A);

% Calculate DEab(65) and DEab(A)
DEab.D65 = deltaEab(MC_Light.Lab.D65, CC_Light.Lab.D65); %DEab - D65
DEab.A   = deltaEab(MC_Light.Lab.A,   CC_Light.Lab.A)  ; %DEab - A

% TABLE - Header
fprintf('%s', "ColorChecker and Metachecker color differences", newline, newline);
fprintf('%s %10s %11s\n', "Patch #", "DEab(D65)", "DEab(illA)");

% TABLE - Body
fspec = '%7.0f %10.3s %7.3f\n';

for patchnum = 1:size(DEab.A, 2)
    fprintf(fspec, patchnum, DEab.D65(1, patchnum), DEab.A(1, patchnum));
end
```

```
ColorChecker and Metachecker color differences

Patch #  DEab(D65)  DEab(illA)
      1  2.597e-07  22.636
      2  1.136e-07  22.178
      3  1.056e-07  32.275
      4  1.905e-07  28.232
      5  3.980e-07  25.937
      6  1.326e-07  29.487
      7  8.581e-08  17.309
      8  1.454e-07  27.241
      9  1.665e-07  12.210
     10  2.907e-07  19.509
     11  1.561e-07  22.623
     12  1.305e-07  16.970
     13  1.083e-07  20.083
     14  1.193e-07  26.099
     15  6.708e-08   7.053
     16  1.330e-07  11.532
     17  6.468e-09  10.690
     18  8.581e-08  31.619
     19  2.661e-07   2.545
     20  6.948e-08  15.940
     21  1.846e-07  28.926
     22  8.337e-08  26.751
     23  3.668e-07  20.574
     24  1.022e-07  18.567
```

Step 9 - Calculated, LAB, DeltaE

```
% ~Code imported from Proj3~
CalcPatchData;

% Calculate XYZn for D50
CC_Light.XYZn.D50 = ref2XYZ(cie.PRD,cie.cmf2deg,cie.illD50);

% Calculated values for LAB Patch 1
patch1.CalcrealLab = XYZ2Lab(patch1.CalcrealXYZ, CC_Light.XYZn.D50);
patch1.CalcimagedLab = XYZ2Lab(patch1.CalcimagedXYZ, CC_Light.XYZn.D50);
patch1.CalcmatchingLab = XYZ2Lab(patch1.CalcmatchingXYZ, CC_Light.XYZn.D50);

% Calculated values for LAB Patch 2
patch2.CalcrealLab = XYZ2Lab(patch2.CalcrealXYZ, CC_Light.XYZn.D50);
patch2.CalcimagedLab = XYZ2Lab(patch2.CalcimagedXYZ, CC_Light.XYZn.D50);
patch2.CalcmatchingLab = XYZ2Lab(patch2.CalcmatchingXYZ, CC_Light.XYZn.D50);

% Patch1 DEab
%                                  Patch 1 real        Patch 1 imaged
patch1.DEab.real_imaged   = deltaEab(patch1.CalcrealLab, patch1.CalcimagedLab)  ;
%                                  Patch 1 real        Patch 1 matching
patch1.DEab.real_matching = deltaEab(patch1.CalcrealLab, patch1.CalcmatchingLab);

% Patch2 DEab
%                                  Patch 2 real        Patch 2 imaged
patch2.DEab.real_imaged   = deltaEab(patch2.CalcrealLab, patch2.CalcimagedLab)  ;
%                                  Patch 2 real        Patch 2 matching
patch2.DEab.real_matching = deltaEab(patch2.CalcrealLab, patch2.CalcmatchingLab);

% TABLE 5.1 - Header
fprintf('%s\n\n','Calculated XYZ, Lab, and deltaE values (w.r.t. real patches)');
```

```
fprintf('%48s\n', "patch 5.1");
fprintf('%13s %9s %9s %10s %9s %9s %9s\n', "X", "Y", "Z", "L", "a", "b", "dEab");

% TABLE 5.1 - Body
fprintf('%8s %2.4f   %2.4f   %2.4f %s', 'real',patch1.CalcrealXYZ, '   ');
fprintf('%2.4f   %2.4f   %2.4f\n', patch1.CalcrealLab);
fprintf('%8s %2.4f   %2.4f   %2.4f %s', 'imaged', patch1.CalcimagedXYZ, '   ');
fprintf('%2.4f   %2.4f   %2.4f %s %2.4f\n', patch1.CalcimagedLab, ' ', patch1.DEab.real_imaged);
fprintf('%8s %2.4f   %2.4f   %2.4f %s', 'matching', patch1.CalcmatchingXYZ,'   ');
fprintf('%2.4f   %2.4f   %2.4f %s %2.4f\n\n\n', patch1.CalcmatchingLab, ' ', patch1.DEab.real_matching);


% TABLE 5.2 - Header
fprintf('%48s\n', "patch 5.2");
fprintf('%13s %9s %9s %10s %9s %8s %9s\n', "X", "Y", "Z", "L", "a", "b", "dEab");

% TABLE 5.2 - Body
fprintf('%8s %2.4f   %2.4f   %2.4f %s', 'real',patch2.CalcrealXYZ, '   ');
fprintf('%2.4f   %2.4f   %2.4f\n', patch2.CalcrealLab);
fprintf('%8s %2.4f   %2.4f   %2.4f %s', 'imaged', patch2.CalcimagedXYZ, '   ');
fprintf('%2.4f   %2.4f   %2.4f %s %2.4f\n', patch2.CalcimagedLab, ' ', patch2.DEab.real_imaged);
fprintf('%8s %2.4f   %2.4f   %2.4f %s', 'matching', patch2.CalcmatchingXYZ,'   ');
fprintf('%2.4f %8.4f   %2.4f %s %2.4f\n\n\n', patch2.CalcmatchingLab, ' ', patch2.DEab.real_matching);
```

```
Calculated XYZ, Lab, and deltaE values (w.r.t. real patches)

                                  patch 5.1
           X         Y         Z          L         a         b      dEab
    real 59.5211   48.4238   21.6636    75.0914   33.0997   28.9963
  imaged 58.5066   48.1247   21.1848    74.9035   31.4772   29.6227   1.7493
matching 57.4105   44.1494   20.6318    72.3282   39.9174   26.2984   7.8356


                                  patch 5.2
           X         Y         Z          L         a         b      dEab
    real 72.7950   73.7131   39.5527    88.7867   3.6180   24.1522
  imaged 68.9412   68.9101   35.5713    86.4595   5.4686   25.5782   3.2976
matching 75.1286   76.4988   43.0917    90.0904   2.8126   21.8646   2.7534
```

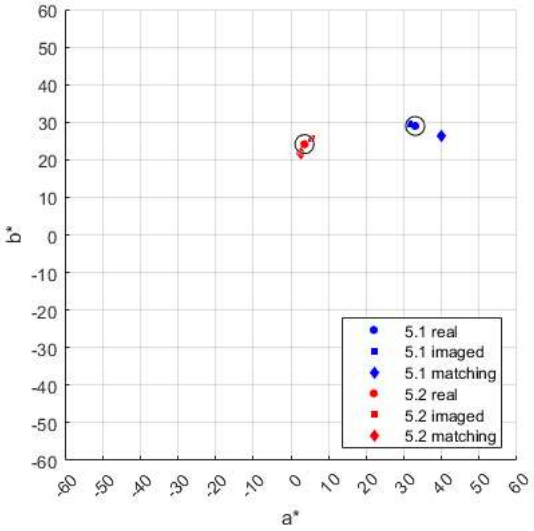
Step 10 - Visualize Color Differences

```
figure(1)
hold on
% Plot Patch 1
plot(patch1.CalcrealLab(2,1),patch1.CalcrealLab(3,1)        ,'o'      ,'MarkerFaceColor', 'b', 'MarkerEdgeColor', 'b', 'MarkerSize', 4, 'DisplayName', '5.1 real');
plot(patch1.CalcimagedLab(2,1),patch1.CalcimagedLab(3,1)    ,'square' ,'MarkerFaceColor', 'b', 'MarkerEdgeColor', 'b', 'MarkerSize', 4, 'DisplayName', '5.1 imaged')
plot(patch1.CalcmatchingLab(2,1),patch1.CalcmatchingLab(3,1),'diamond','MarkerFaceColor', 'b', 'MarkerEdgeColor', 'b', 'MarkerSize', 4, 'DisplayName', '5.1 matching

% Plot Patch 2
plot(patch2.CalcrealLab(2,1),patch2.CalcrealLab(3,1)        ,'o'      ,'MarkerFaceColor', 'r', 'MarkerEdgeColor', 'r', 'MarkerSize', 4, 'DisplayName', '5.2 real');
plot(patch2.CalcimagedLab(2,1),patch2.CalcimagedLab(3,1)    ,'square' ,'MarkerFaceColor', 'r', 'MarkerEdgeColor', 'r', 'MarkerSize', 4, 'DisplayName', '5.2 imaged')
plot(patch2.CalcmatchingLab(2,1),patch2.CalcmatchingLab(3,1),'diamond','MarkerFaceColor', 'r', 'MarkerEdgeColor', 'r', 'MarkerSize', 4, 'DisplayName', '5.2 matching

% Draw viscircles
% Requires the "Image Processing Toolbox" Add-on to be installed
% [x1 , Y1]
% [x2 , y2]
% radius 2.5, as that's the average of 2-3 DEab JND's
viscircles([patch1.CalcrealLab(2,1), patch1.CalcrealLab(3,1) ; ...
            patch2.CalcrealLab(2,1), patch2.CalcrealLab(3,1)], ...
            2.5, 'Color', 'k', LineWidth=.7);

% Format plot
axis square %So the circles look like circles
grid on     %Add gridlines
xlabel('a*')
ylabel('b*')
xticks(-60:10:60)
yticks(-60:10:60)
xlim([-60 60]);
ylim([-60 60]);
legend({'5.1 real', '5.1 imaged', '5.1 matching', ...
        '5.2 real', '5.2 imaged', '5.2 matching'}, ...
        'Location', 'southeast', 'FontSize',9)
```



Feedback

i) Gian-Mateo wrote the functions. Cooper and Gian-Mateo coded the lab.

ii) The largest 'setbacks' were optimizing the XYZ2Lab function without for-loops. Also, having to reinstall MATLAB for the "Image Processing Toolbox" - which wouldn't otherwise install.

iii) Focusing on how to fully utilize MATLAB, i.e. without for loops, focusing on matrix operations. Also, embedding structs within structs.

iv) Reintroducing, or delaying, the introduction of Matrix operations (such as calling items at an array indexes + how MATLAB interprets 1 as "True" when knowing where to call an index) closer to Projects 3 and 4

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