Lab 2
Energy Efficient Displays

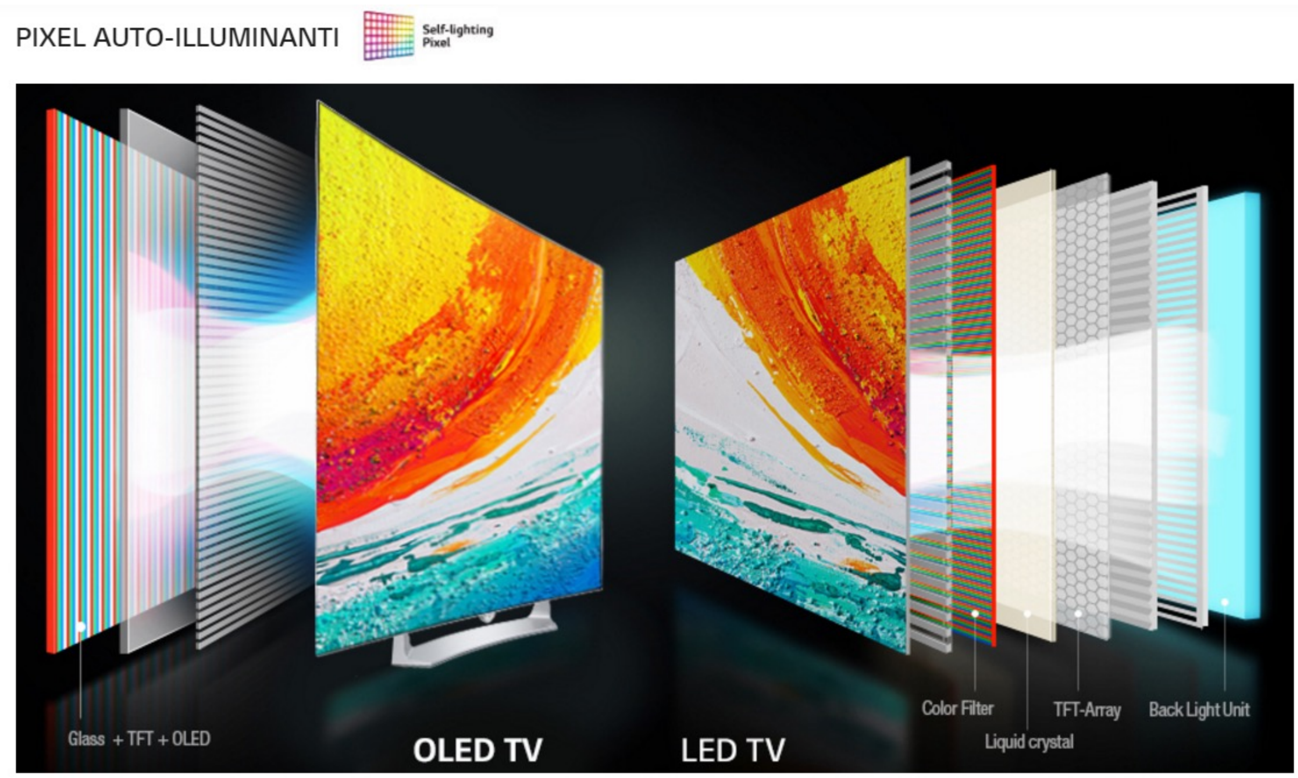
Objective and organization

- Demonstrates how manipulation of an image can be used to tradeoff image quality and power saving in emissive displays
  - 1 report – 2 days
  - Matlab

- Organize all implemented methods in functions and scripts to **automatically** test and evaluate all images and all techniques

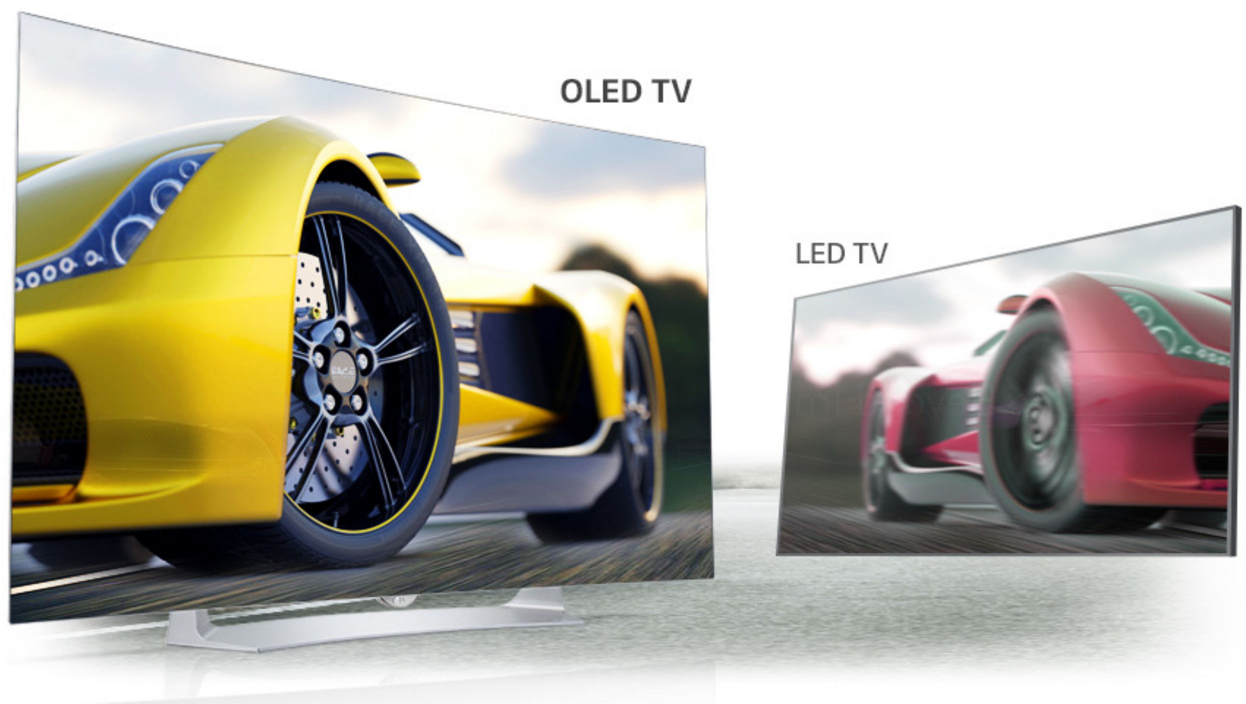
OLED vs LED

- OLED TVs
  - Do not require external lighting
    - Better black levels



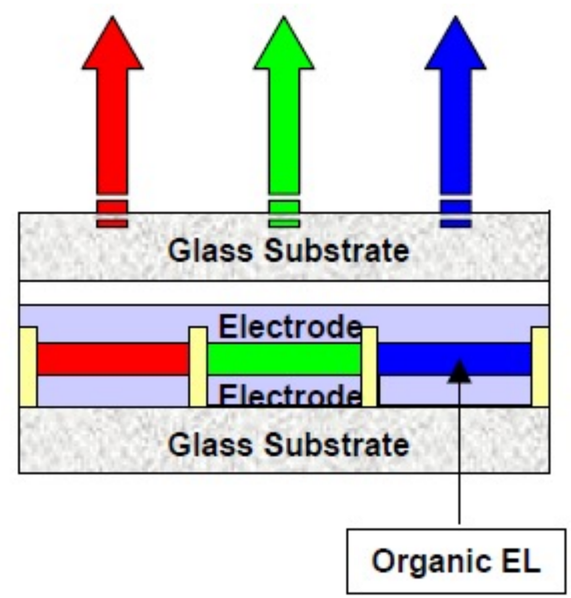
OLED vs LED

- OLED TVs
  - Pixels are independent from each other
    - More sense of depth
    - Higher contrast makes images more realistic



OLED

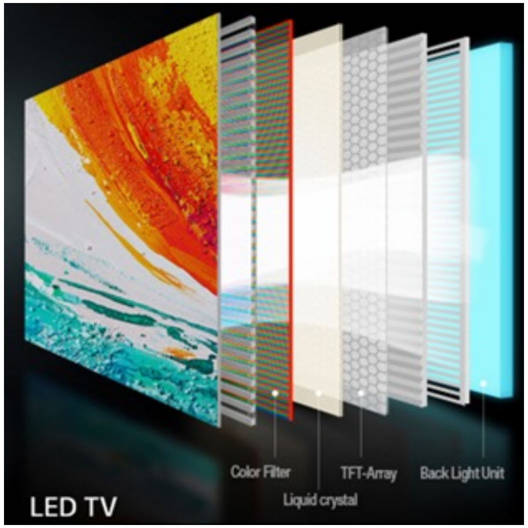
- Interesting case study from our perspective…
- Organic light-emitting diode (OLED)
  - Do not require external lighting
  - Pixels are emissive
    - Emissive layer is a film of organic compound which *emits light in response to an electric current*
  - Each pixel is made of three devices corresponding to red, green and blue components



OLED

- In LCDs, backlight dominates power consumption and color has only negligible power impact

- With OLED displays, the color of a pixel impacts on power consumption
  - E.g., hungry blue
  - Different luminance efficacies
  - Different images imply different power consumption

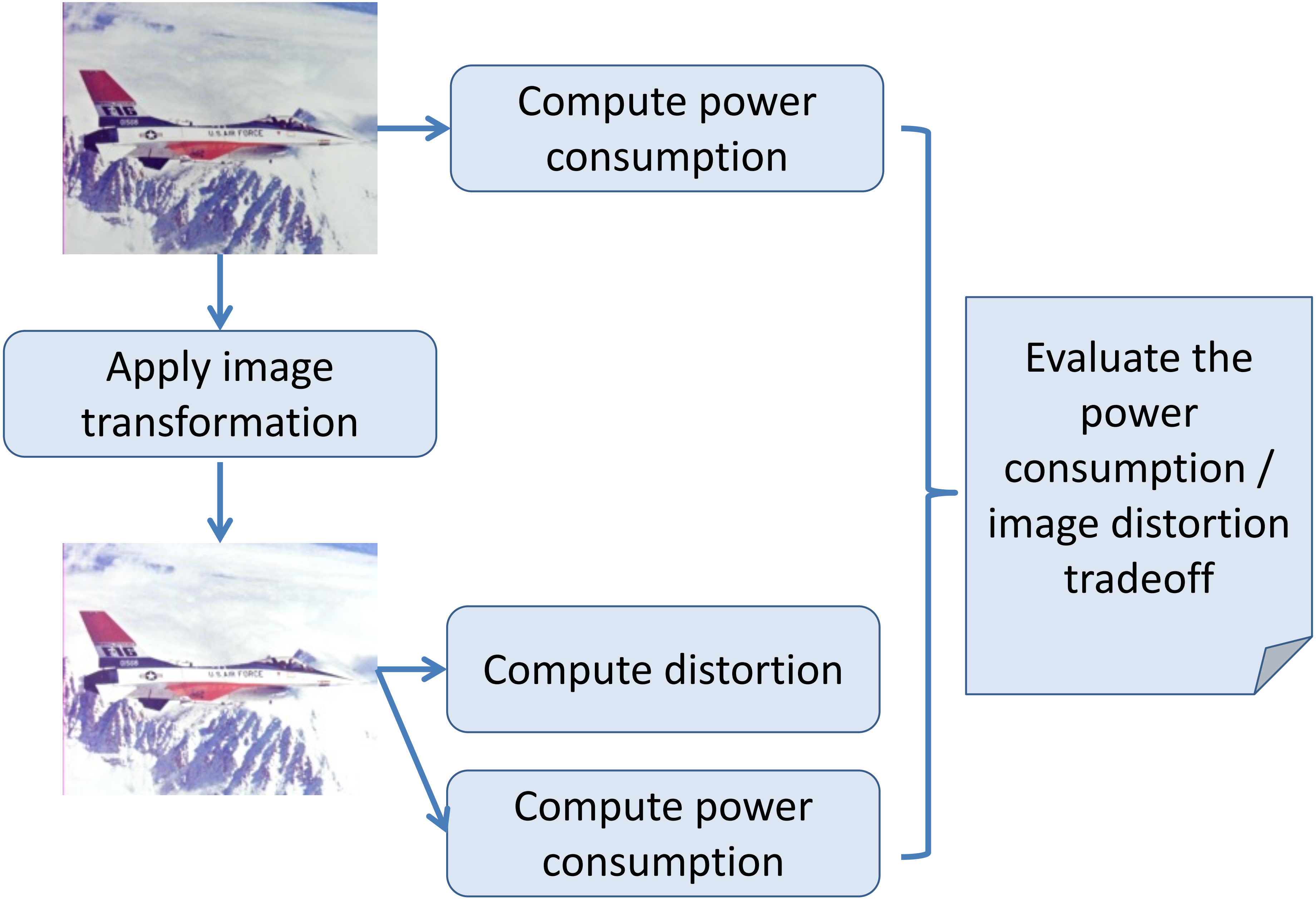


Day 1
Energy efficient image processing

OLED

- Power consumption depends on color components of a pixel…
  - So we can save power by changing the spectrum of the image!
  - First class of power saving methods:
    - Change pixel color
    - Given a certain tolerance level on color distorsion

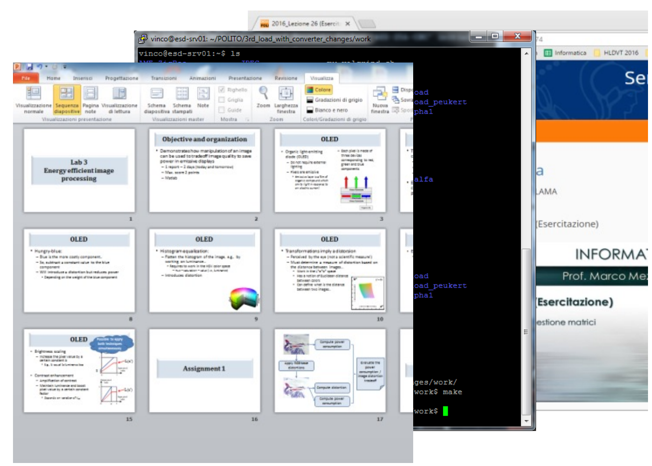
Assignment 2 – Part 1



Compute power consumption
Apply image transformation
Compute distortion
Compute power consumption
Evaluate the power consumption / image distortion tradeoff

1. Identification of images

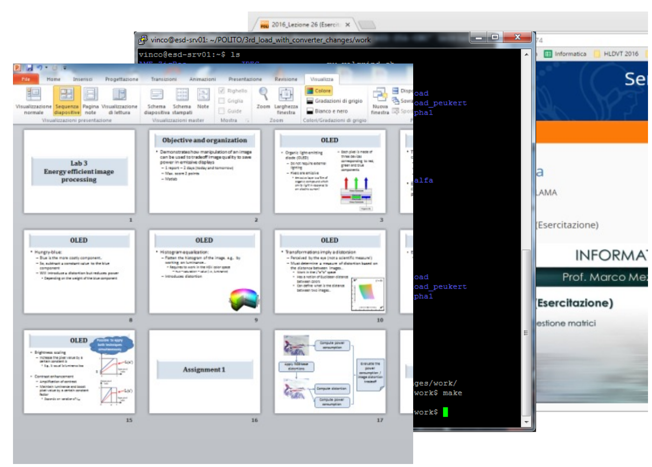
- Test images will be:
  - The images from the USC SIPI database
    - http://sipi.usc.edu/database/database.php?volume=misc
  - The images from the BSDS500 training set
    - https://www2.eecs.berkeley.edu/Research/Projects/CS/vision/grouping/BSR/BSR_bsds500.tgz
  - 5 images representing screenshots of your computer
- Different colors and characteristics…



1. Identification of images

- Test images will be:
  - The images from the USC SIPI database
    - http://sipi.usc.edu/database/database.php?volume=misc
  - The images from the BSD 00 training set
    - n/grouping
  - 5 r
- Diffe

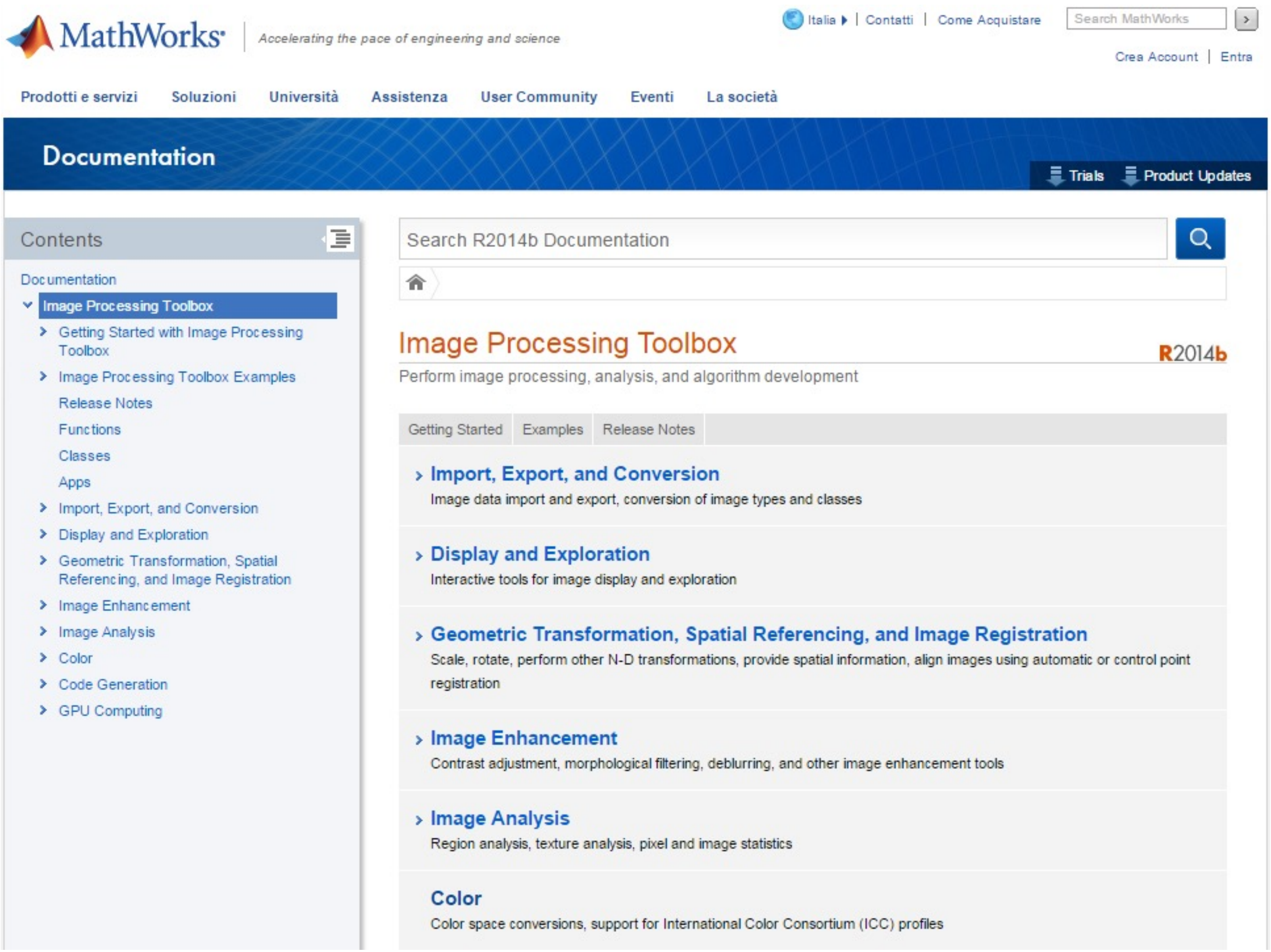
Some grayscale images are present, you can skip them!!



2. Manipulation of images

- Experiments require to adopt different color spaces…
- **TASK:** Learn how to:
  - Import the image
    - imread() function
  - Extract the R, G, B channels
  - Convert between different color spaces

- Refer to:
  - http://it.mathworks.com/help/images/index.html



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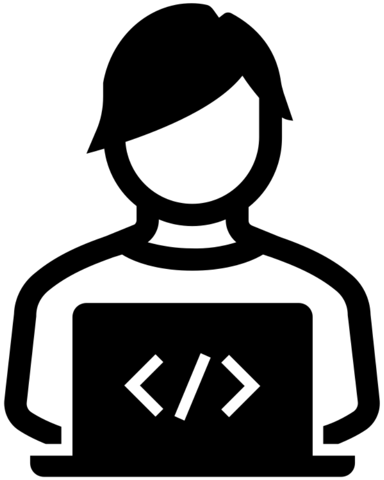
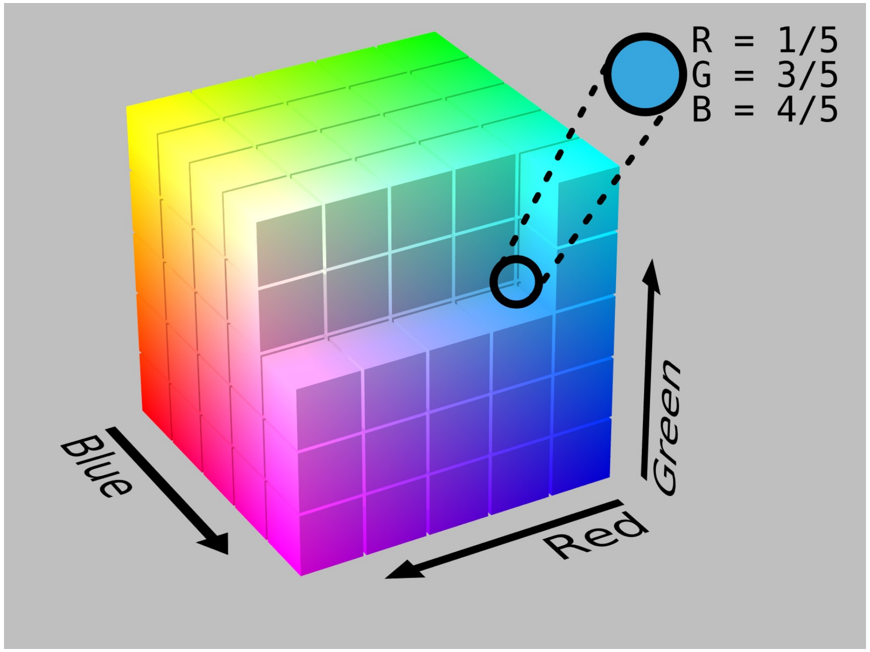
Geometric Transformation, Spatial Referencing, and Image Registration
Scale, rotate, perform other N-D transformations, provide spatial information, align images using automatic or control point registration
Image Enhancement
Contrast adjustment, morphological filtering, deblurring, and other image enhancement tools
Image Analysis
Region analysis, texture analysis, pixel and image statistics
Color
Color space conversions, support for International Color Consortium (ICC) profiles



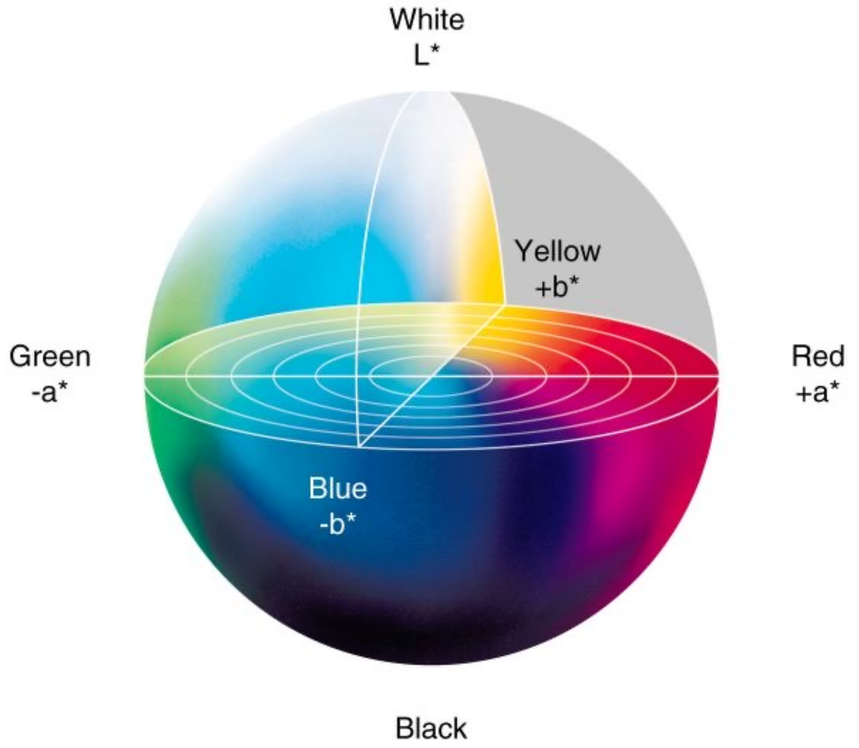
2. Manipulation of images

- RGB
  - Additive color space
    - All possible colors that can be made from three colorants for red, green and blue
  - Stores individual values for red, green and blue
  - Convenient color model for computer graphics as it is similar to the human visual system
    - Used in LCDs



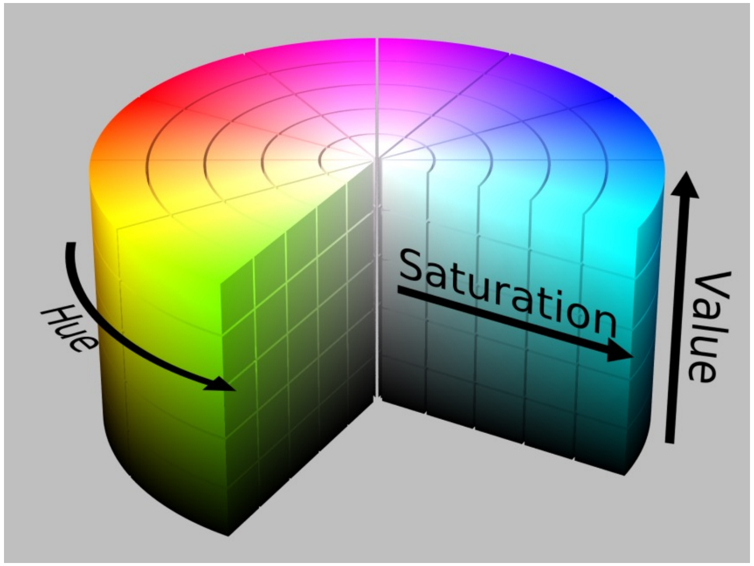
2. Manipulation of images

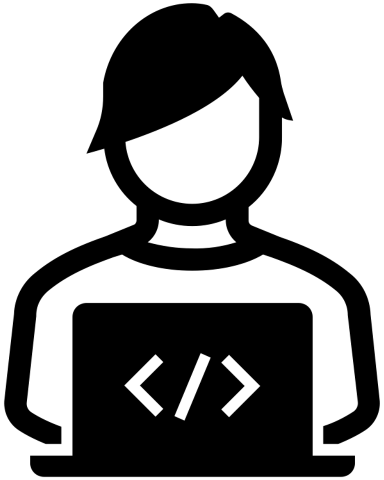
- Lab
  - One channel for luminance (L) and two color channels (a and b)
  - Includes all perceivable colors
    - Super-set of RGB
  - The space is a three-dimensional Real number space
    - Allows the definition of Euclidean distance

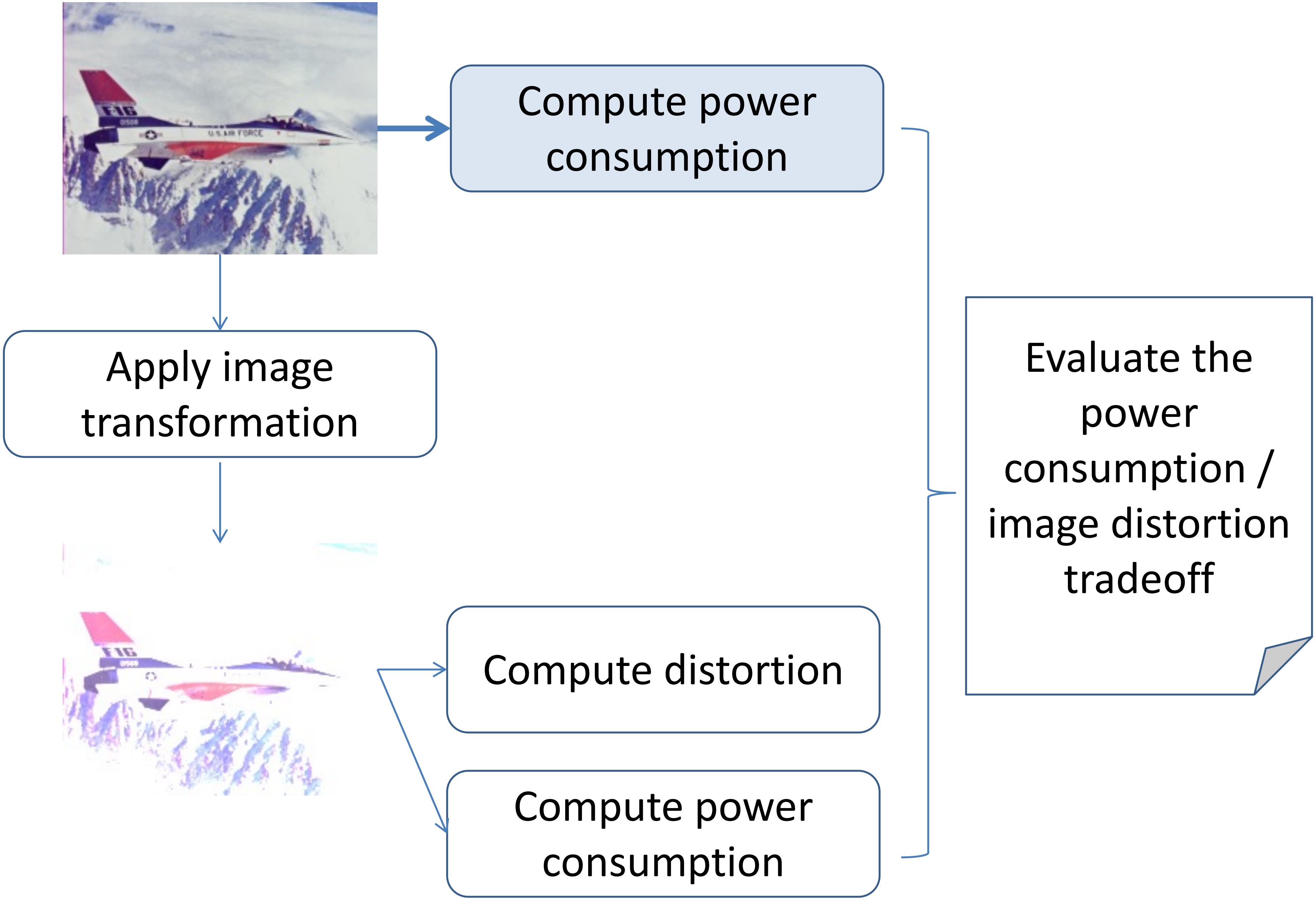


2. Manipulation of images

- HSV
  - Hue
    - Perceived color
  - Saturation
    - Colorfulness, amount of white component
  - Value
    - Brightness
  - Cylindrical-coordinate representations of points in an RGB color model
  - Widely used in computer graphics





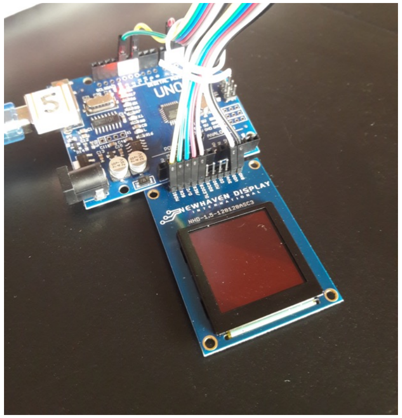

Compute power consumption
Apply image transformation
Compute distortion
Compute power consumption
Evaluate the power consumption / image distortion tradeoff

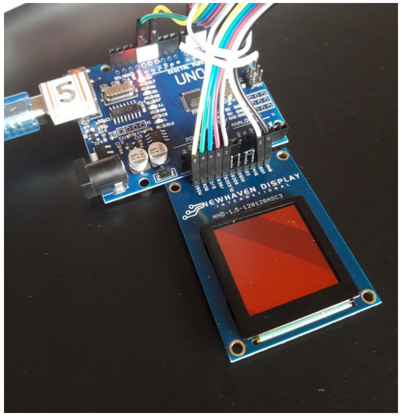
3. Evaluation of power consumption

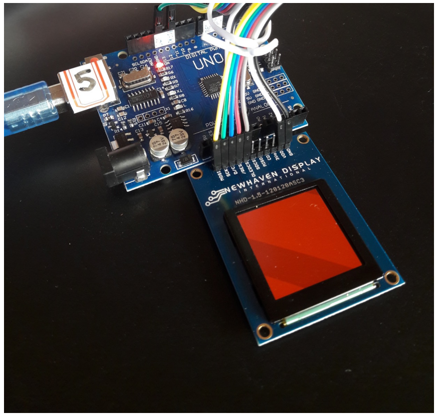
- Power model
  - $P_{pixel} = f(R) + h(G) + k(B)$
    - Depends on pixel color in terms of RGB components
    - f, h and k determined experimentally by:
      - Setting black screen to estimate C
      - For f, set G and B components to 0 and vary R component
      - Similar for h and k
  - $P_{image} = C + \sum_{i=1}^{n} \{f(R_i) + h(G_i) + k(B_i)\}$
    - Sums up power contributions of single pixels
    - C static power independent of pixel values

1. Evaluation of power consumption

- Experimental Setup:
  - Show monochromatic images with different RGB values on the OLED, e.g.:



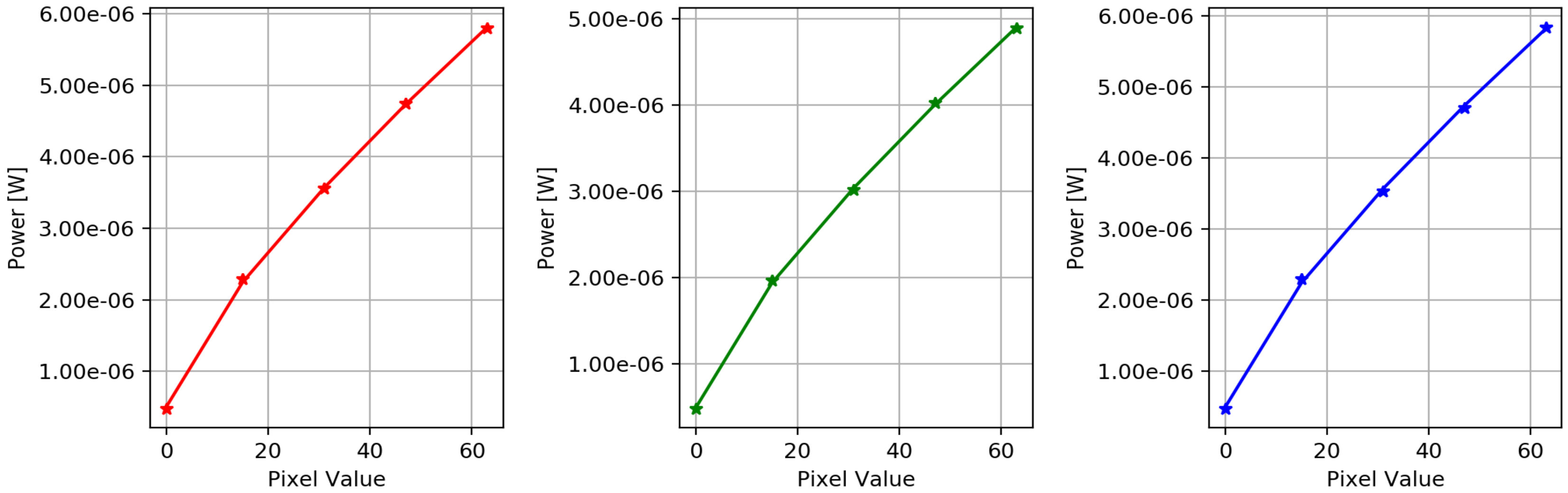




  - Measure power supply current (and convert to power)

1. Power model for the provided OLED (cont'd)

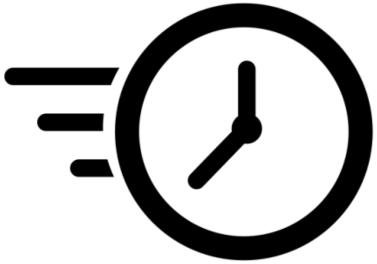
- Interpolation:
  - Find regression model type that fits best the data and determine the corresponding parameters



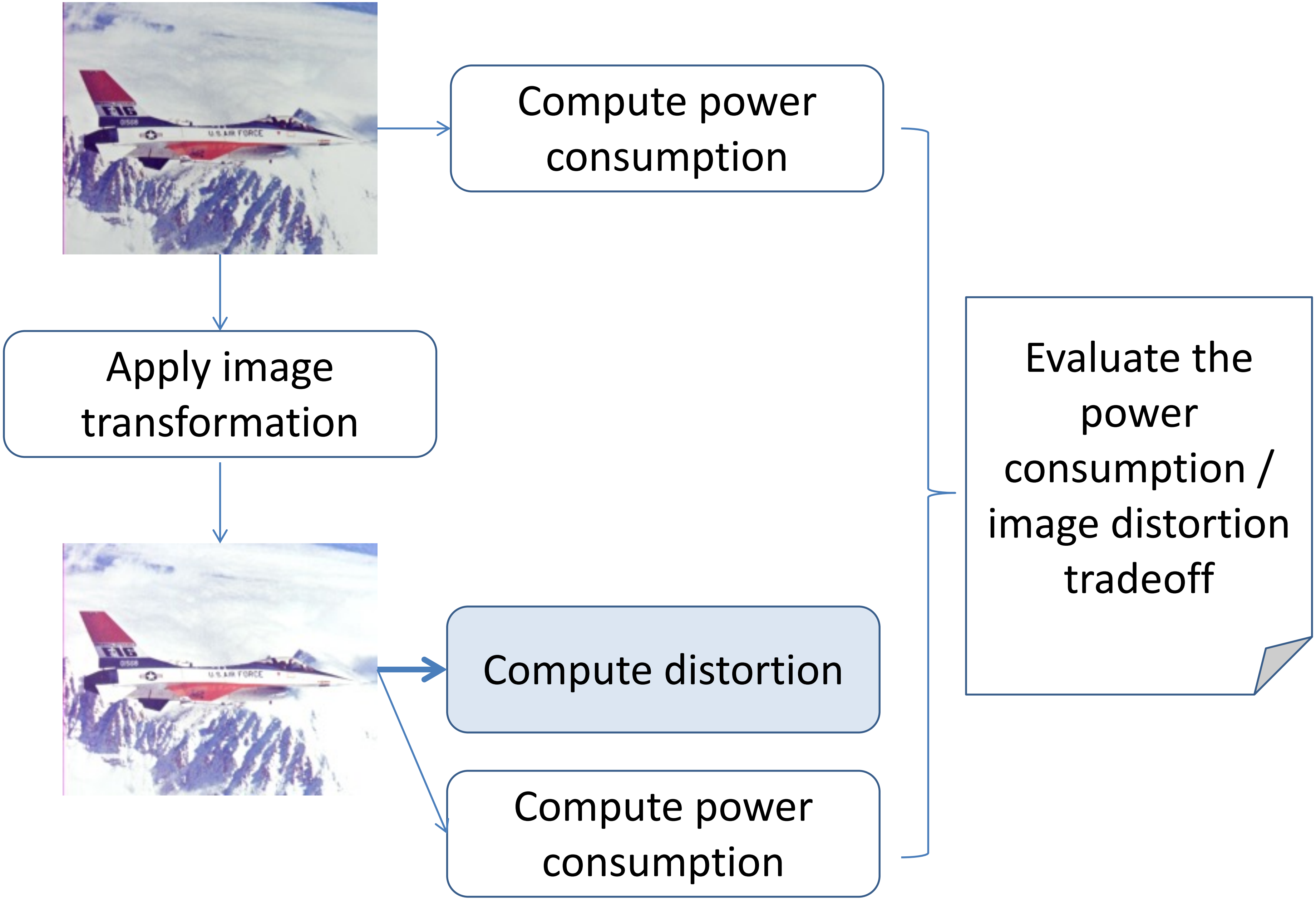
  - For this Lab, we used a model format from literature (see next slide)

Assignment 2 – Part 1

- **TASK:** Define a MATLAB function that estimates power consumed to display an image
  - $P_{pixel} = w_R * R^{\gamma} + w_G * G^{\gamma} + w_B * B^{\gamma}$
  - $P_{image} = w_0 + \sum_{i=1}^{n}\{P_i(R, G, B)\}$
  - R, G, B are pixel values between 0 and 255

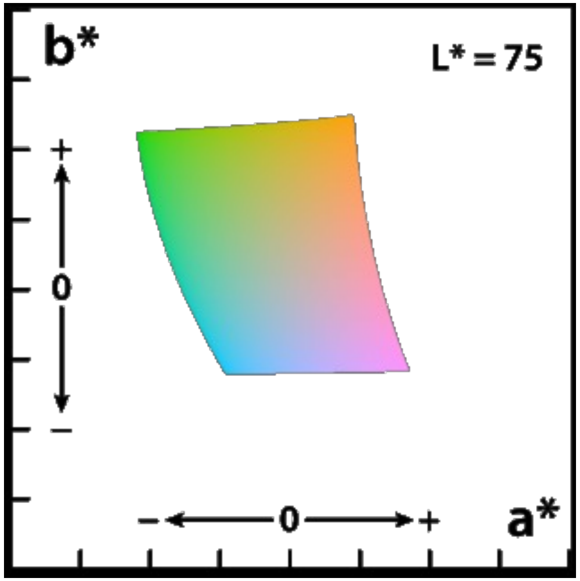


γ	W_0	W_R	W_G	W_B
0.7755	**$1.48169521*10^{-6}$**	**$2.13636845*10^{-7}$**	**$1.77746705*10^{-7}$**	**$2.14348309*10^{-7}$**


Compute power consumption
Apply image transformation
Compute distortion
Compute power consumption
Evaluate the power consumption / image distortion tradeoff

4. Evaluation of image distortion

- Transformations imply a distorsion
  - Must determine a measure of distortion based on the *distance* between images…
    - We will work in the L*a*b* space
    - Has a notion of Euclidean distance between colors that well matches the perceived distortion
    - Can define what is the distance between two images..
  - Importantly, distortion is different from perceived **visual quality**, which is subjective, not a scientific measure!



4. Evaluation of image distortion

- Evaluation of image distortion
  - Difference between two images
    - $\varepsilon\left(image_i, image_j\right) =$
      $$\sum_{k=1}^{N}\left(\sqrt{(L_{i,k}-L_{j,k})^2 + (a_{i,k} - a_{j,k})^2 + (b_{i,k} - b_{j,k})^2}\right)$$
    - N = number of pixels
    - k = k^{th} pixel
    - Pixel per pixel, compute the difference of L, a and b components between the two images

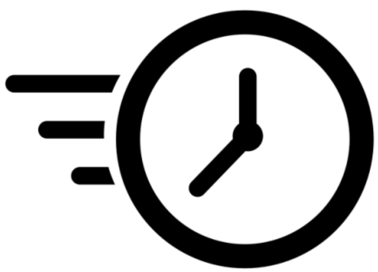
Assignment 2 – Part 1

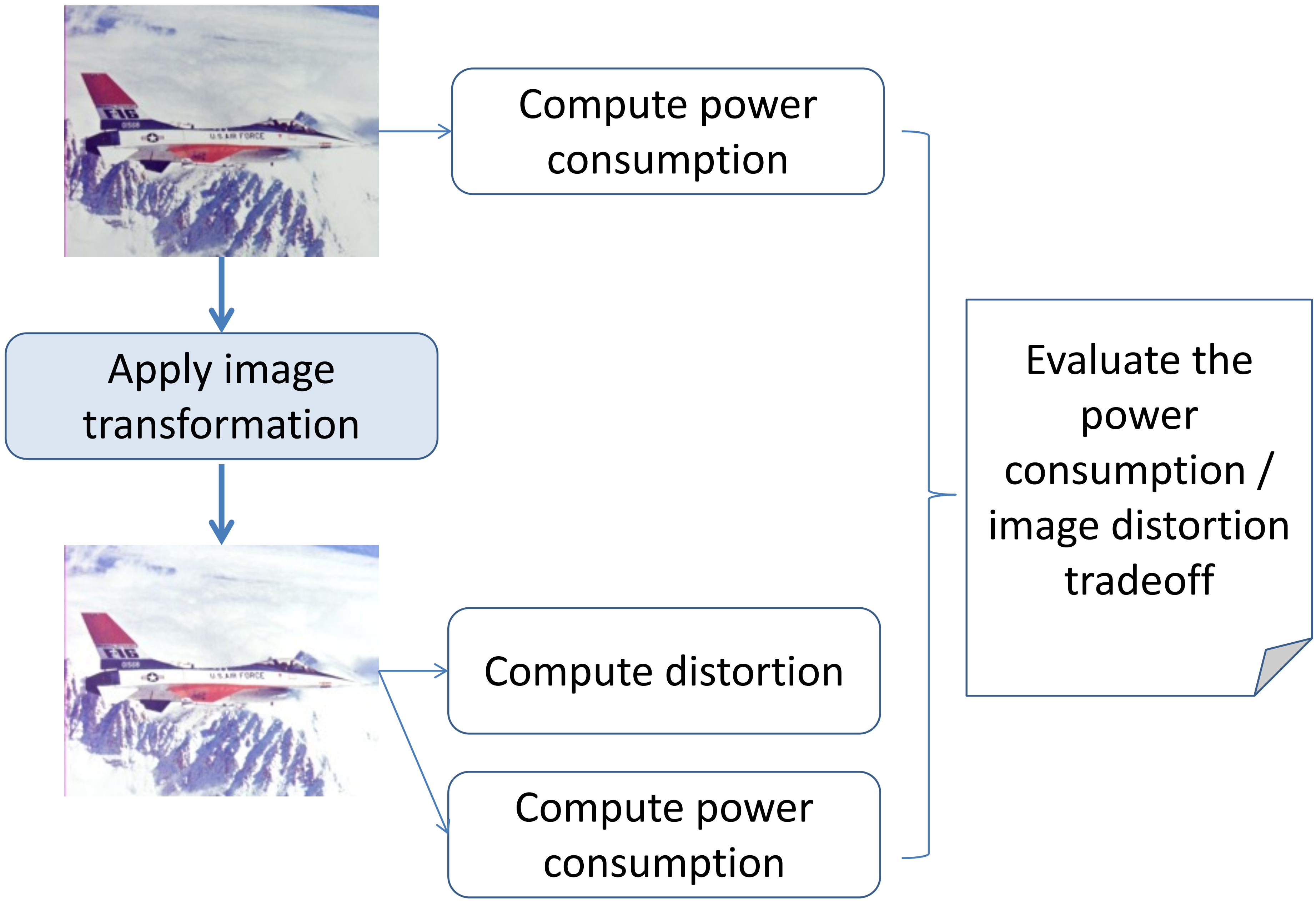
- **TASK:** Define a MATLAB function that estimated the distortion w.r.t. the original image
  - $\varepsilon\left(image_i, image_j\right) = \sum_{k=1}^{N}\left(\sqrt{(L_{i,k}-L_{j,k})^2 + (a_{i,k} - a_{j,k})^2 + (b_{i,k} - b_{j,k})^2}\right)$
  - Work in the L*a*b* space and compute the Euclidian distance pixel per pixel
  - Convert by using MATLAB's r*gb2lab()* and *lab2rgb()* functions

Assignment 2 – Part 1

- Easier to reason in terms of **percentage** distortion
  - E.g., distortion of new image w.r.t. maximum possible distance between 2 images in Lab space.
  - $dist = \frac{\varepsilon(image_{new}, image_{orig})}{W * H * \sqrt{(100^2 + 255^2 + 255^2)}} \cdot 100 \qquad (\%)$

NOTE: This will be quite small for most transformations!
So, use a small constraint (1%, 2%, 3%)




Compute power consumption
Apply image transformation
Compute distortion
Compute power consumption
Evaluate the power consumption / image distortion tradeoff

Assignment 2 – Part 1

- **TASK:** Experiment with various **image manipulation strategies** to reduce power consumption:
  - Pixel-wise transformations
    - Work on colors
  - Histogram equalization
    - Work on luminance (requires HVS color space)
  - Other types of brightness/contrast modifications

Assignment 2 – Part 1

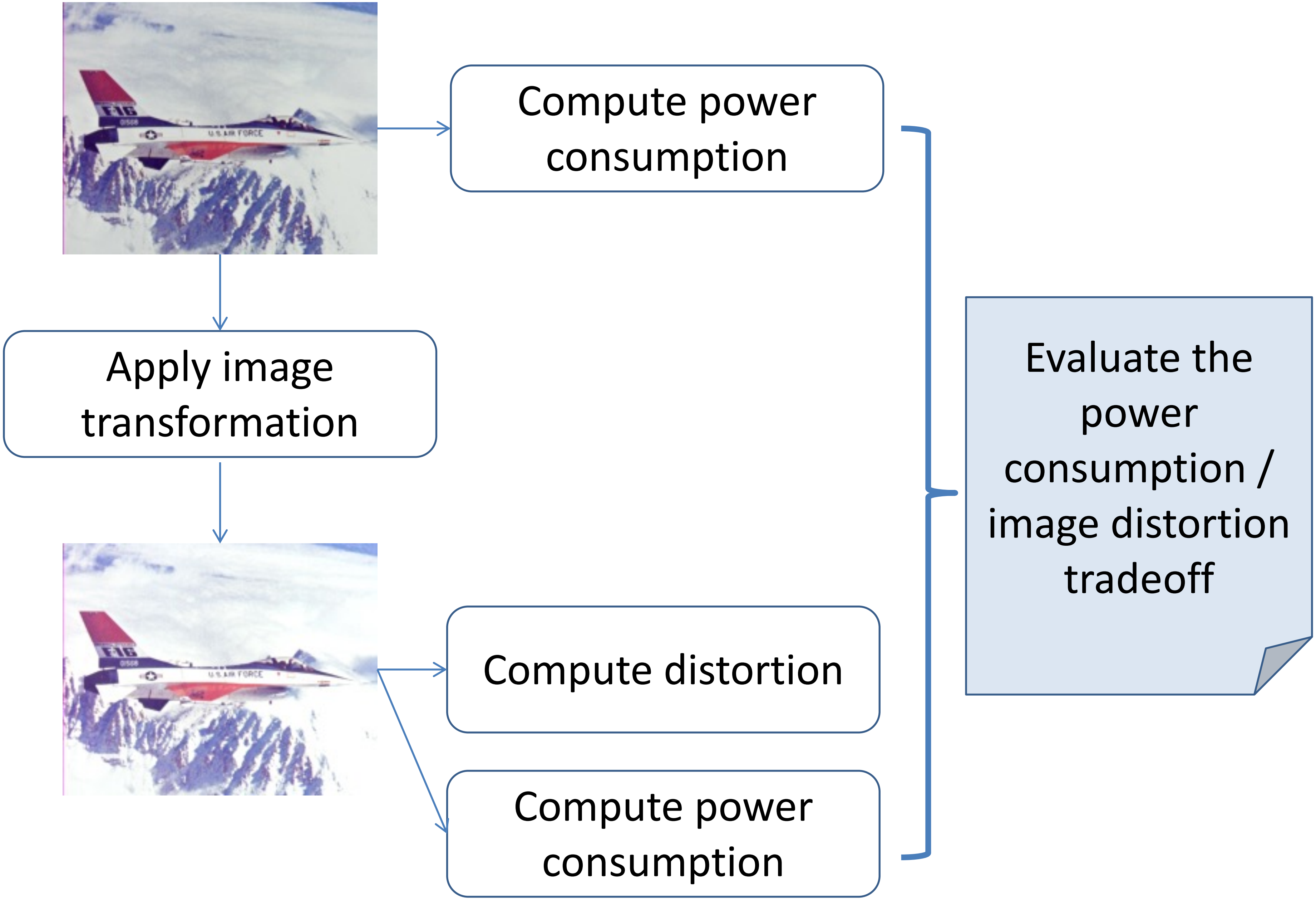
- Apply each transformation **to all images!**
  - In your report, show (and comment) summary tables. For example:
    - Average, min, max power saving
    - Average, min, max distortion
  - Moreover, show (and comment) **some representative examples** of transformations outputs
    - E.g., the images for which you get most/least saving/distortion.
    - Do **not** include 50 pictures for each transformation in the report!!

Image Transformations

- **Hungry-blue:**
  - Blue is the more costly component..
  - So, subtract a constant value to the blue component
  - Will introduce a distortion but reduces power
    - Depending on the weight of the blue component

- **Histogram equalization:**
  - Flatten the histogram of the image, e.g., by working on luminance…
  - Requires to work in the HSV color space
    - Hue – saturation – value (i.e., luminance)
  - Introduces distortion. What about power?

- **Other types of brightness/contrast transformations:**
  - E.g. Convert to HSV and scale the value component ($V \rightarrow k*V$ with $k < 1$) or do some more complex transformation
  - **Use your creativity!!!**


Compute power consumption
Apply image transformation
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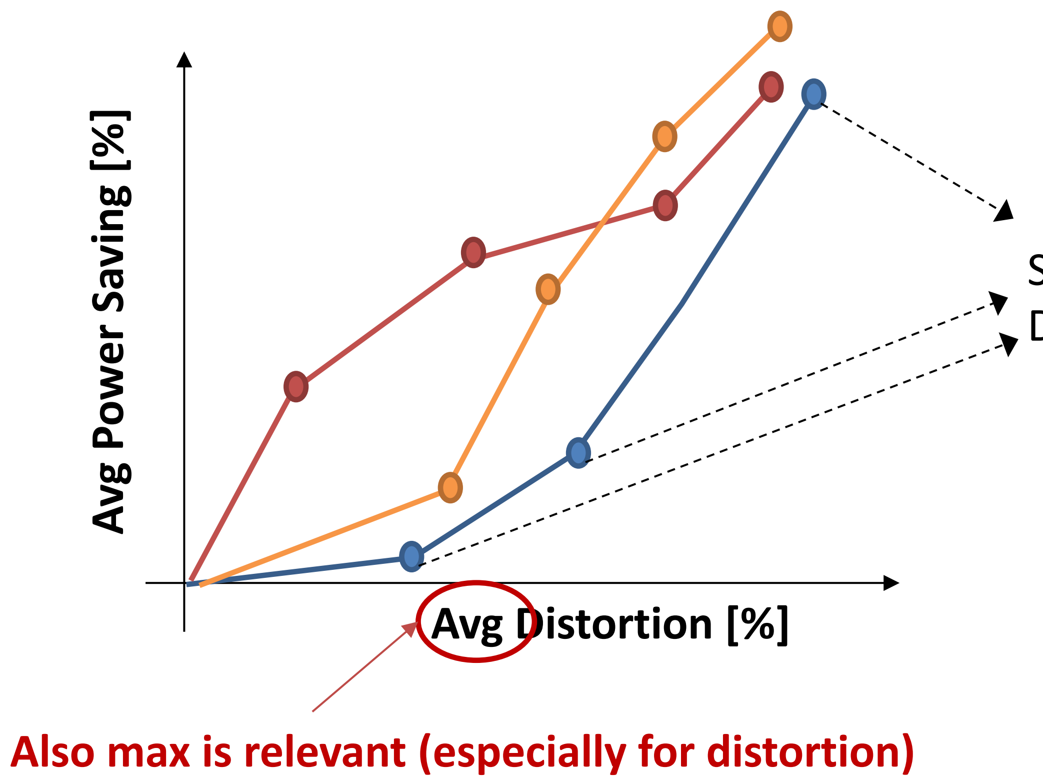
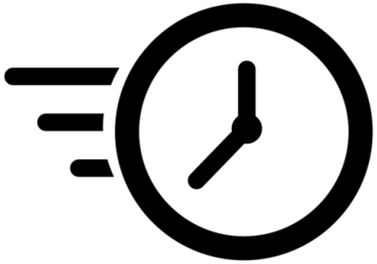
Assignment 2 – Part 1

- Analyse power/distortion tradeoff
  - Do different images behave differently?
  - What changes in terms of power consumption with different manipulation strategies?
  - How can I save more power with lower distorsions?
  - Etc.

Assignment 2 – Part 1

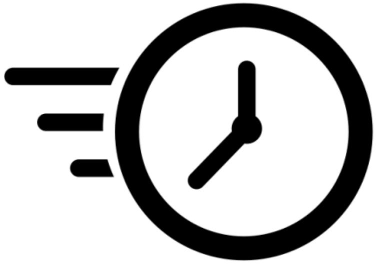
- Example: Pareto curve





Assignment 2 – Part 1

- Compare the transformations you applied and find the solution that:
  - **Minimizes the average power consumption** (i.e., maximizes avg power saving)
  - Under an **average distortion** constraint (e.g., avg distortion smaller than 0.5%, 1%, 2%, 3%)



Assignment 2 – Part 1

- Example:
  - Blue reduction
    - Power saving 29.11%
    - Distortion 3.99%
  - Histogram equalization
    - Power saving 11.99%
    - Distortion 2.46%

Original image

After blue reduction

After histogram equalization

Day 2
Dynamic Voltage Scaling

Dynamic Voltage Scaling of OLEDs

- Power consumption of OLEDs depends only on pixels…
  - No back light
  - Pixels are emissive, i.e., emits light in response to an electric current

- … and pixels power consumption depends on:
  - Displayed colors
    - Hungry blue / low power green
  - **Input current**

DVS for OLEDs

- Supply voltage is set to maximum to support full luminance of pixel
  - But maximum luminance may not be necessary

- Dynamic Voltage Scaling
  - Scale the supply voltage
    - Reduces maximum current that can flow
    - Saves power
  - Note that reducing current implies changing the RGB color of some pixels!
    - Sacrifice image quality for power saving

DVS for OLEDs

- Effects of DVS
  - Reducing current implies changing the RGB color of pixels!
    - Emitted color strictly depends on input current
    - Reduced voltage → reduced current through some pixels

ORIGINAL IMAGE

SIMULATED VOLTAGE SCALING

DVS for OLEDs

- Effects of DVS
  - Sacrifice image quality for power saving
    - Reduced color luminance
    - Color distortion in displayed images
  - Saved power

ORIGINAL IMAGE

SIMULATED VOLTAGE SCALING APPROX. 20% POWER SAVING

DVS for OLEDs

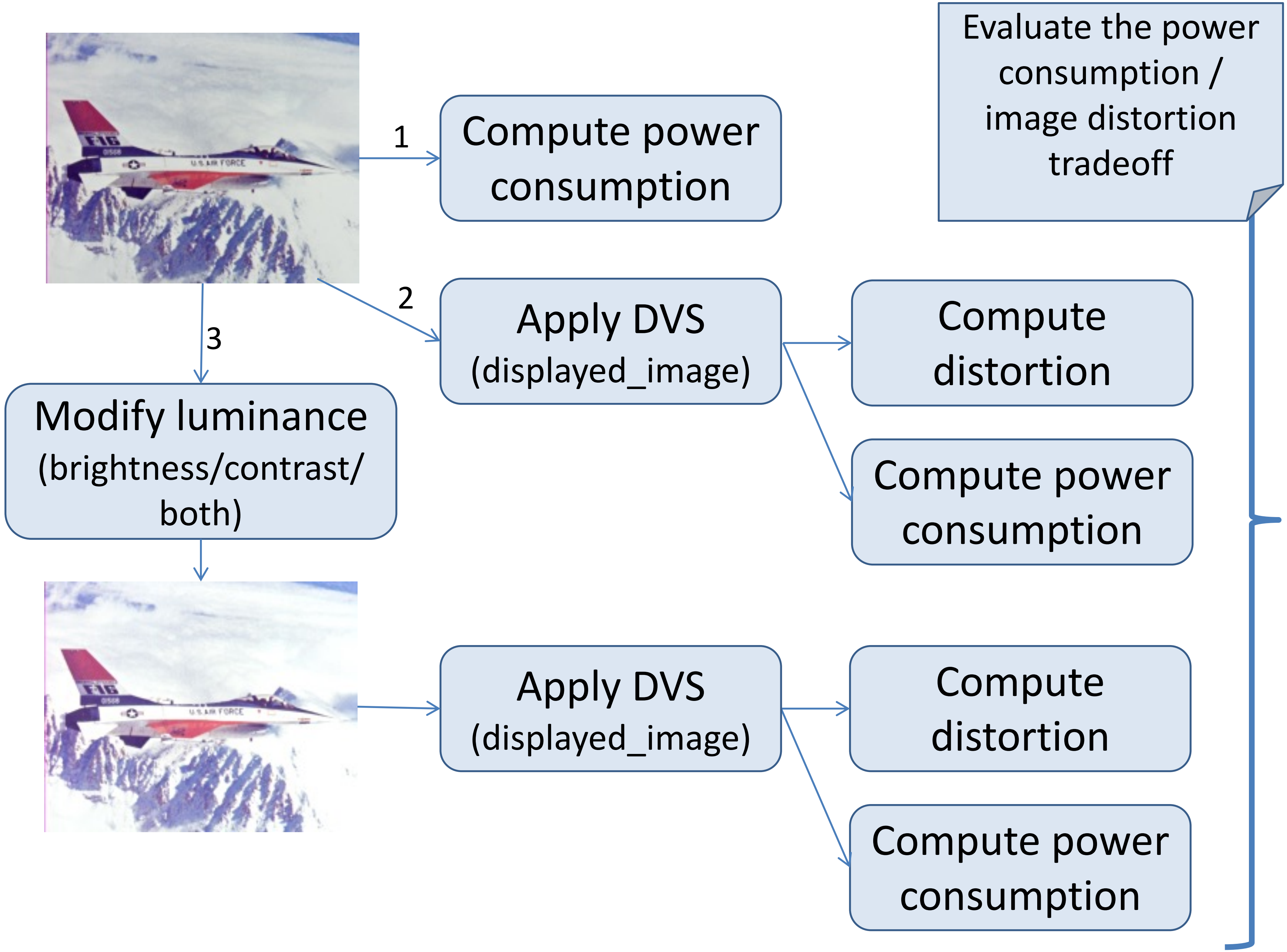
- Can compensate the image distortion by applying an image compensation
  - E.g., working on image luminance

Original image

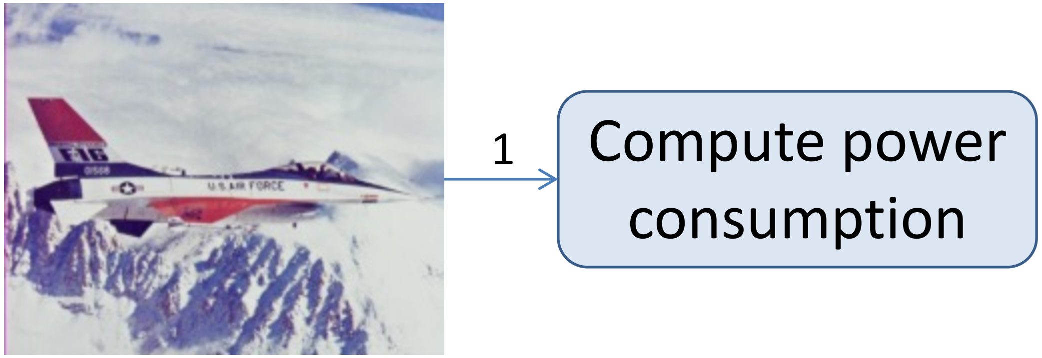
Effect of voltage scaling

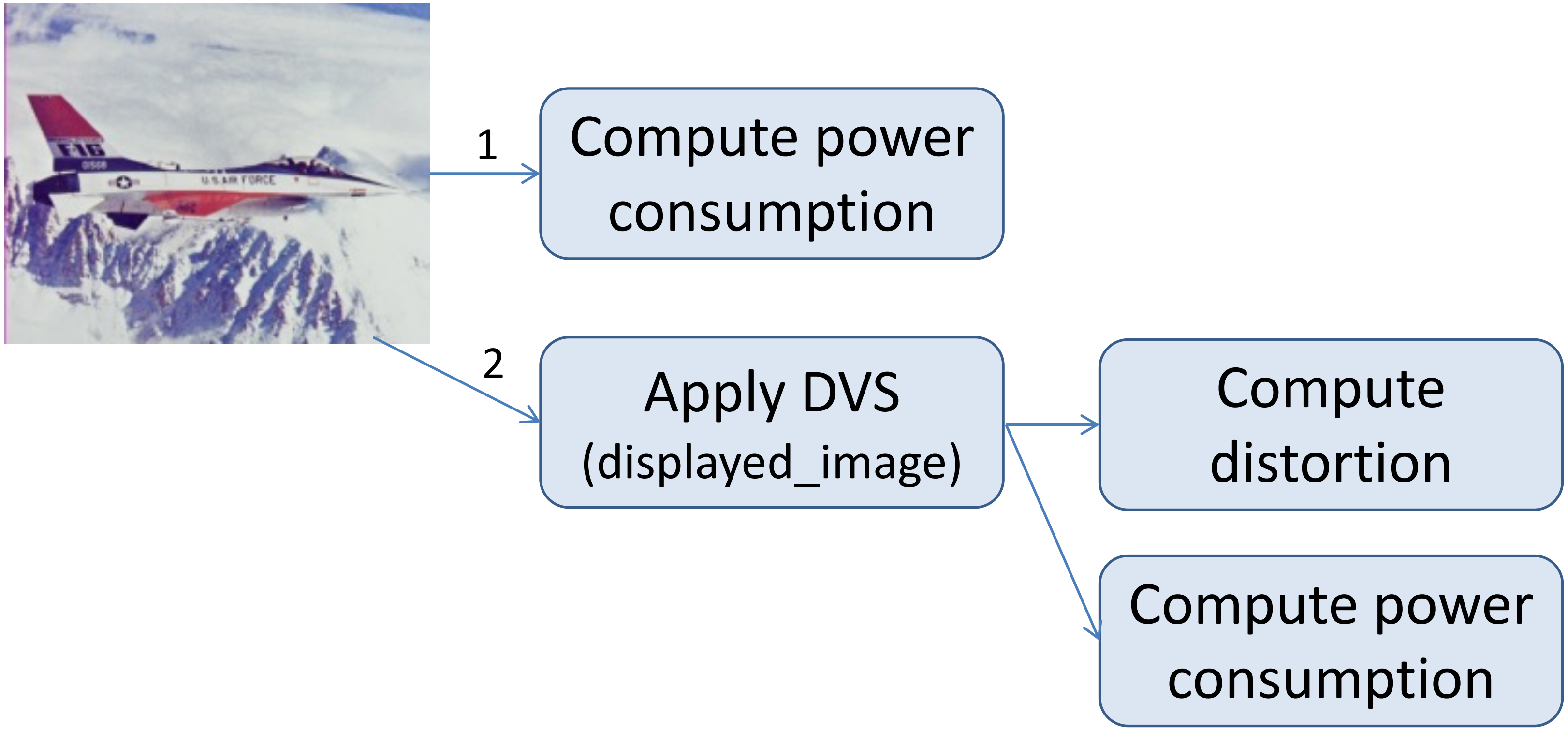
Effect of image compensation + voltage scaling

Assignment 2 – Part 2



Evaluate the power consumption / image distortion tradeoff
1
Compute power consumption
2
Apply DVS (displayed_image)
Compute distortion
Compute power consumption
3
Modify luminance (brightness/contrast/ both)
Apply DVS (displayed_image)
Compute distortion
Compute power consumption


F16
U.S. AIR FORCE
1
Compute power consumption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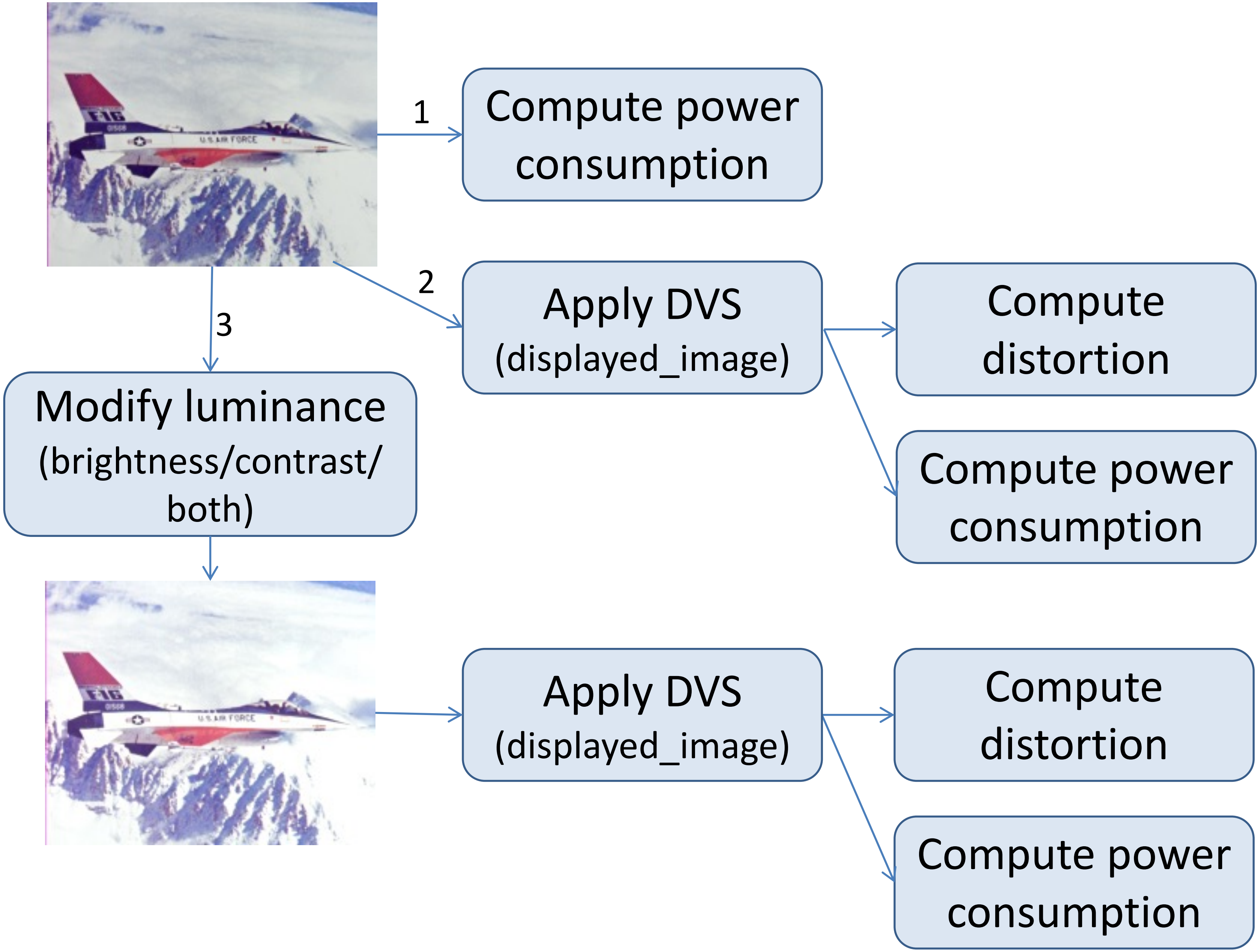
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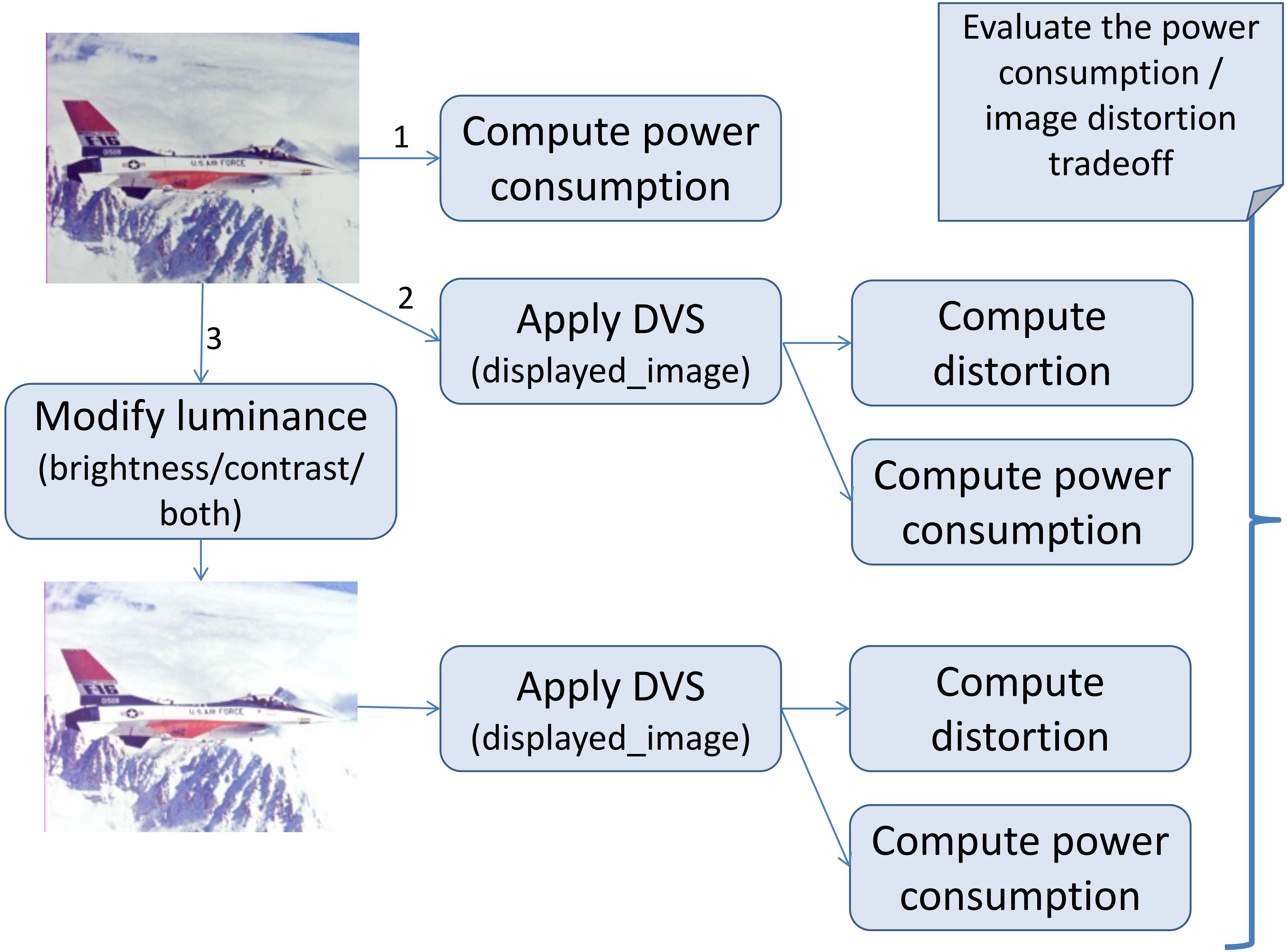
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Compute power consumption
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Apply DVS (displayed_image)
Compute distortion
Compute power consumption
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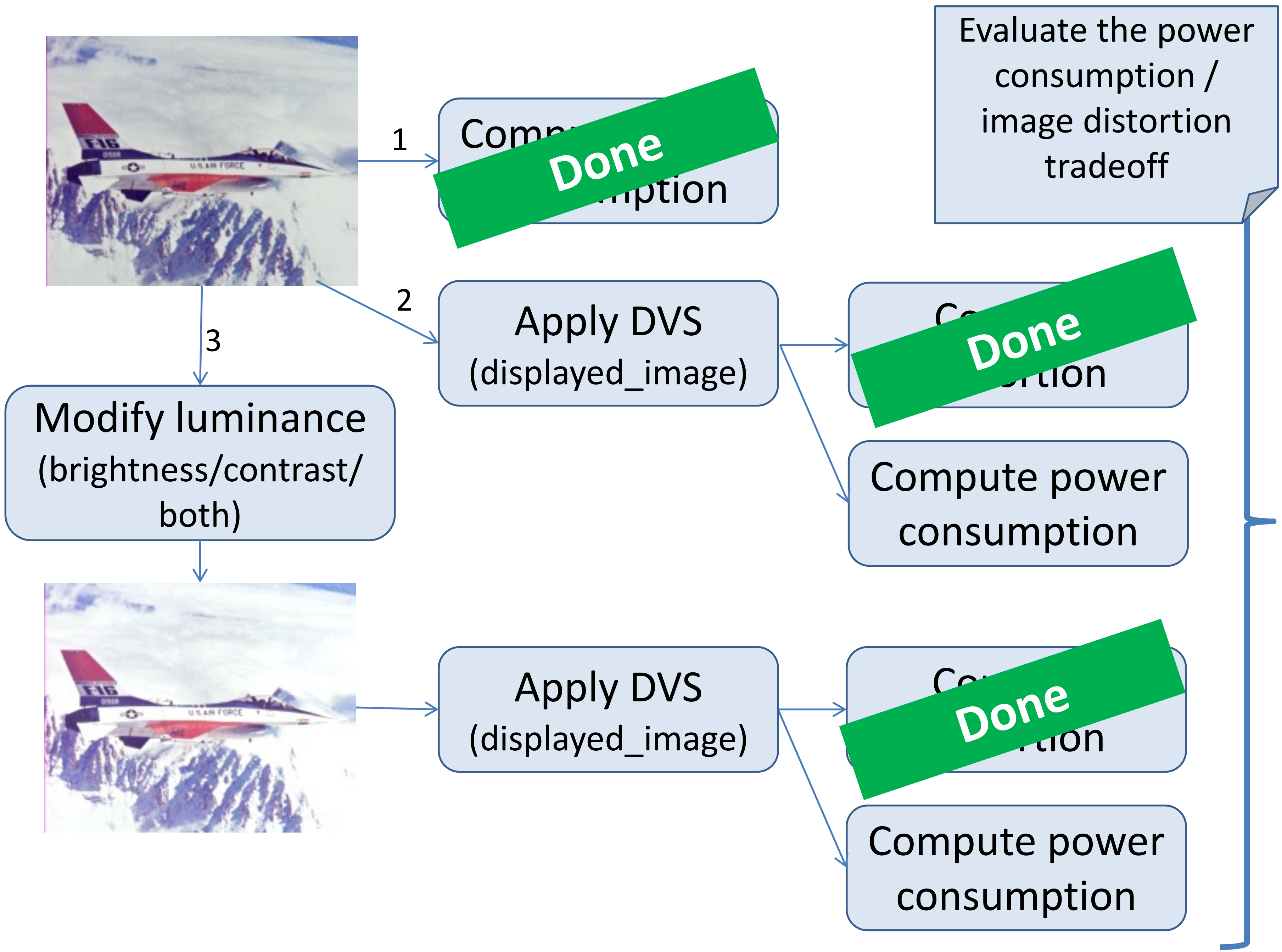
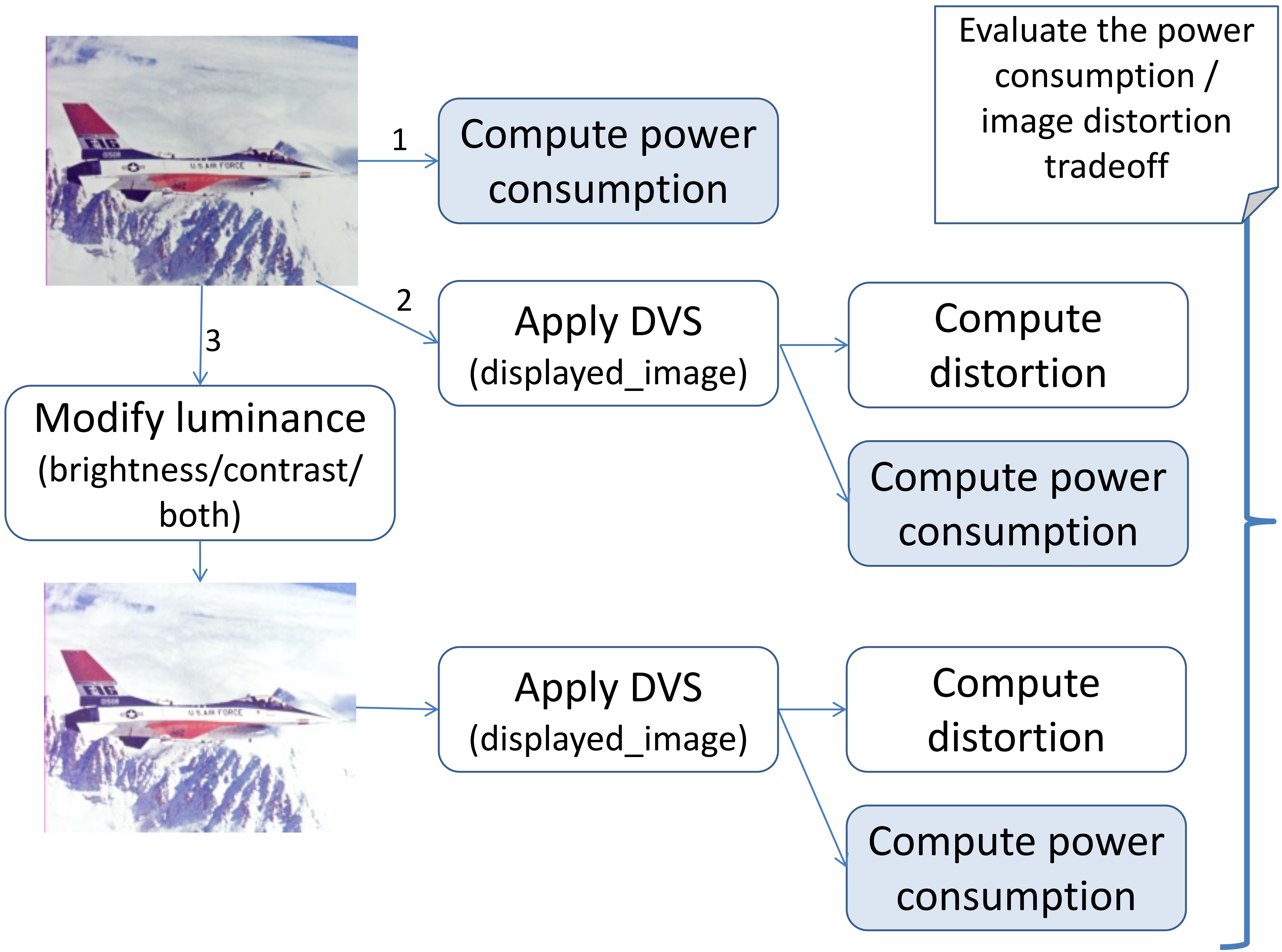
Modify luminance (brightness/contrast/ both)
Apply DVS (displayed_image)
Compute distortion
Compute power consumption


Evaluate the power consumption / image distortion tradeoff
1
Done
2
Apply DVS (displayed_image)
Done
3
Modify luminance (brightness/contrast/ both)
Compute power consumption
Apply DVS (displayed_image)
Done
Compute power consumption

Assignment 2 - Part 2: How To



Evaluate the power consumption / image distortion tradeoff
1
Compute power consumption
2
Apply DVS (displayed_image)
Compute distortion
Compute power consumption
3
Modify luminance (brightness/contrast/ both)
Apply DVS (displayed_image)
Compute distortion
Compute power consumption

1. Cell current calculation and evaluation of power consumption

- Given the RGB color of each pixel, determine current flowing through the cell

$$I_{cell} = \frac{p_1 V_{dd} D_{RGB}}{255} + \frac{p_2 D_{RGB}}{255} + p_3 \qquad [mA]$$

D_{RGB} is the RGB color value of current pixel

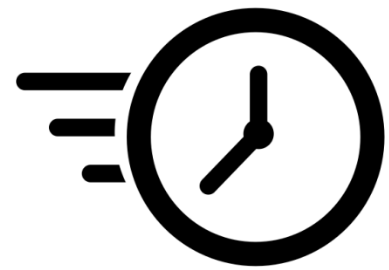
- Determine power consumption
  - **Different (less accurate) model w.r.t. the one used in Part 1**, but expressing dependency from DVS
  - $P_{panel} = V_{dd} \sum_{i=1}^{W} \sum_{j=1}^{H} \sum_{\{R,G,B\}} I_{cell(i,j)} \qquad [mW]$

Assignment 2 – Part 2

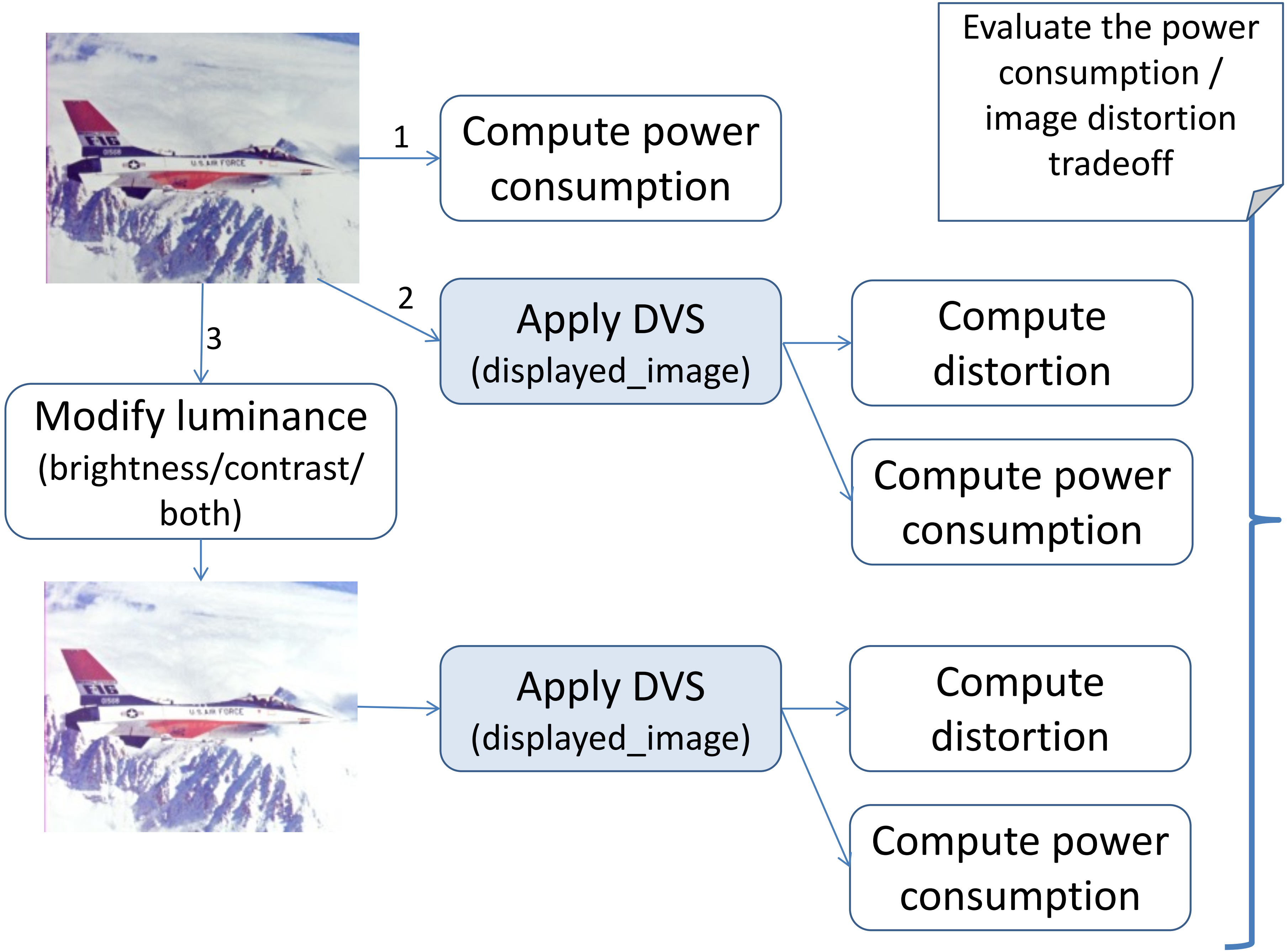
- **TASK:** Implement the new current and power models

  - $I_{cell} = \left(\frac{p_1 V_{dd} D_{RGB}}{255}\right) + \left(\frac{p_2 D_{RGB}}{255}\right) + p_3 \qquad [mA]$
    - p_1 = +4.251e-05
    - p_2 = -3.029e-4
    - p_3 = +3.024e-5
    - Default V_{dd} = 15V

Better to have two separate functions (see later)



  - $P_{panel} = V_{dd} \sum_{i=1}^{W} \sum_{j=1}^{H} \sum_{\{R,G,B\}} I_{cell(i,j)} \qquad [mW]$



Evaluate the power consumption / image distortion tradeoff
1
Compute power consumption
2
Apply DVS (displayed_image)
Compute distortion
Compute power consumption
3
Modify luminance (brightness/contrast/ both)
Apply DVS (displayed_image)
Compute distortion
Compute power consumption

2. Application of voltage scaling

- Voltage supply determines the maximum current that can flow in the OLED
  - Current value → pixel color

- Effect simulated by the function

  displayed_image(I_{cell}, V_{dd}, *mode*)

  - Given an image as the matrix of currents corresponding to pixels
  - Applies voltage scaling with the specified V_{dd}
  - **This function is provided. You don't have to implement it.**
    - **Try example.m in the test code**

2. Application of voltage scaling

- Effect simulated by the *displayed_image()* function
  - Computes the maximum current that can flow with the new V_{dd}
  - Determines the corresponding maximum RGB value RGB_{max}
  - Any RGB value higher than RGB_{max} is saturated to RGB_{max}

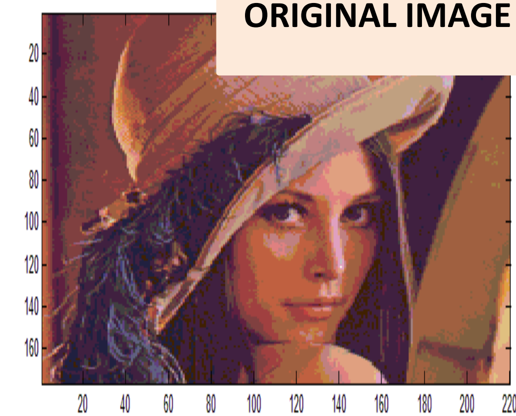
2. Application of voltage scaling

- Given
  - $I_{cell} = \left(\frac{p_1\, V_{dd}\, D_{RGB}}{255}\right) + \left(\frac{p_2\, D_{RGB}}{255}\right) + p_3$
- The maximum current given V_{dd} is:
  - $I_{max} = \left(\frac{p_1\, V_{dd}\, [255\ 255\ 255]}{255}\right) + \left(\frac{p_2 [255\ 255\ 255]}{255}\right) + p_3$
- …and the maximum RGB that can be displayed without distortion is:
  - $RGB_{max} = \frac{(I_{max} - p_3)\, 255}{p_1 V_{dd} + p_2}$
    - Whenever I_{cell} > I_{max} the pixel is assigned RGB value RGB_{max}
    - Saturate to the maximum RGB value that can be generated given V_{dd}

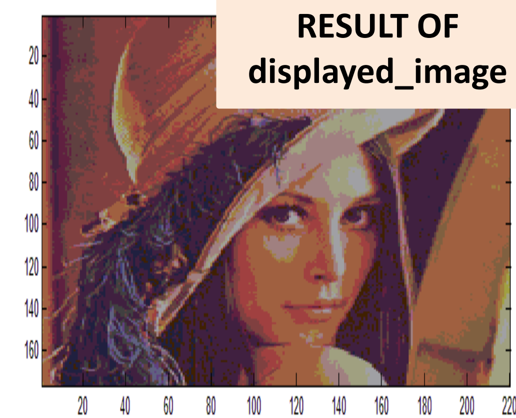
2. Application of voltage scaling

- Note: the image RGB values do not actually change!
  - What changes is the *effect* on the display
  - *displayed_image()* function simulates this effect

ORIGINAL IMAGE



RESULT OF displayed_image



2. Image after voltage scaling

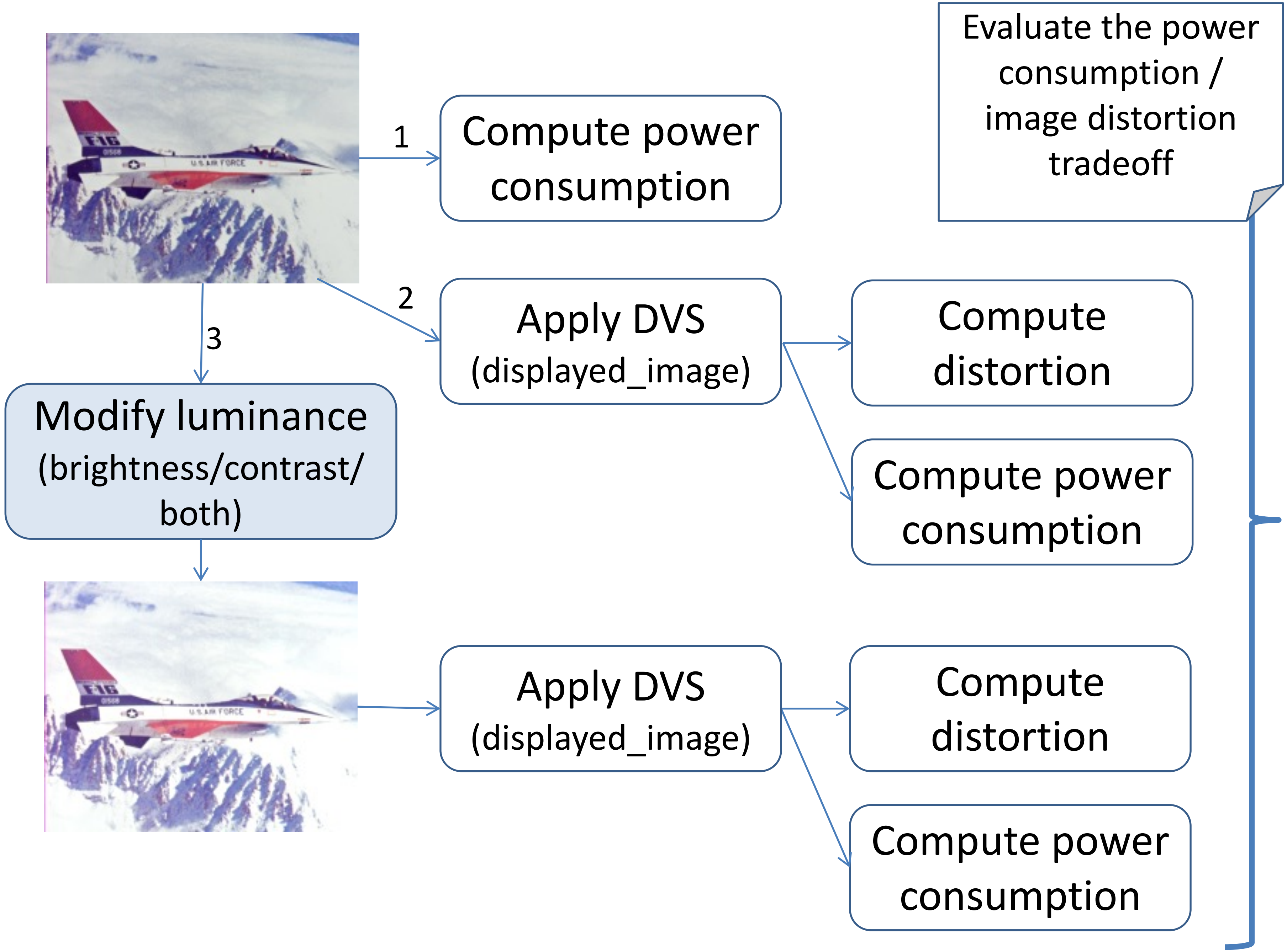
```
function out = displayed_image(I_cell, Vdd, mode)

SATURATED = 1;
DISTORTED = 2;

p1 =   4.251e-05;
p2 =  -3.029e-04;
p3 =   3.024e-05;
Vdd_org = 15;

I_cell_max = (p1 * Vdd * 1) + (p2 * 1) + p3;
image_RGB_max = (I_cell_max - p3)/(p1*Vdd_org+p2) * 255;
out = round((I_cell - p3)/(p1*Vdd_org+p2) * 255);

if (mode == SATURATED)
   out(find(I_cell > I_cell_max)) = image_RGB_max;

else if (mode == DISTORTED)
      out(find(I_cell > I_cell_max)) = round(255 - out(find(I_cell > I_cell_max)));
   end
end
end
```

Maximum current that can flow with reduced voltage

Maximum RGB value that can be represented (lower than 255)

Matrix of RGB values of the original image (given the currents)

Saturates to max RGB value (Focus on this mode!)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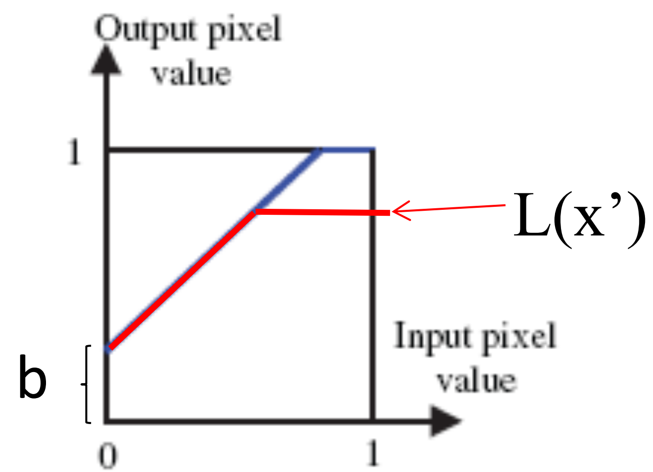
3. Apply image compensation

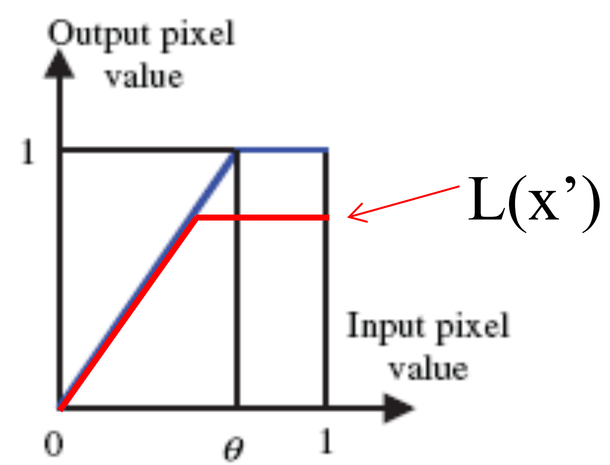
- Want to improve quality of resulting image
  - Apply some techniques **before** DVS!
  - Enhance brightness/contrast of image

- The goal is to increase the perceived image quality!

3. Apply image compensation

- Brightness scaling
  - Increase the pixel values by a certain constant b
    - E.g., b equal to luminance loss
    - V' = v + b
- Contrast enhancement
  - Amplification of contrast
    - V' = V * b
  - Multiply pixel values by a certain constant factor
    - Depends on variation of V_{dd}

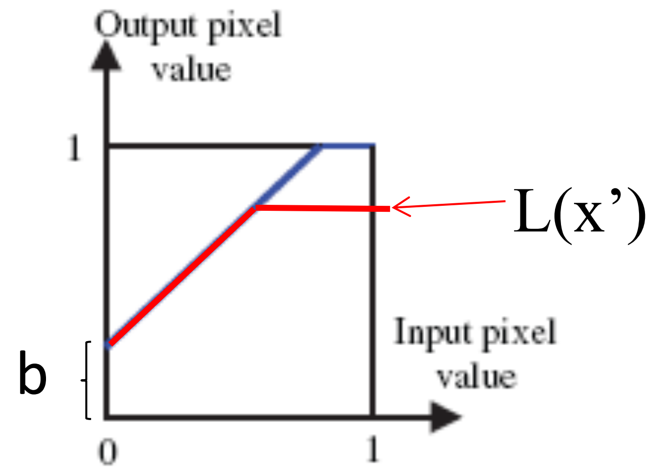


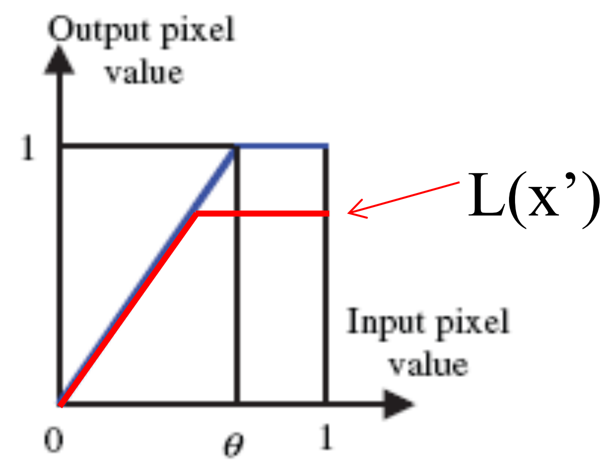


3. Apply image compensation

- **Implemented in the HSV space**

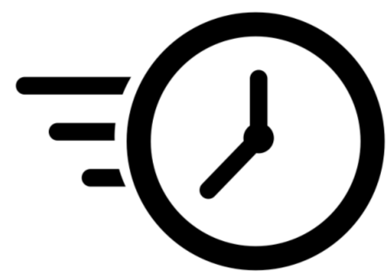
- You can determine the factor b as dependent from the original V_{dd} and new (scaled) V_{dd}
  - Brightness compensation
    - V’ = V + b
    - b($V_{dd}\ original, V_{dd}\ new$)
  - Contrast enhancement
    - V’ = V * b
    - b($V_{dd}\ original, V_{dd}\ new$)
  - **Application of both**

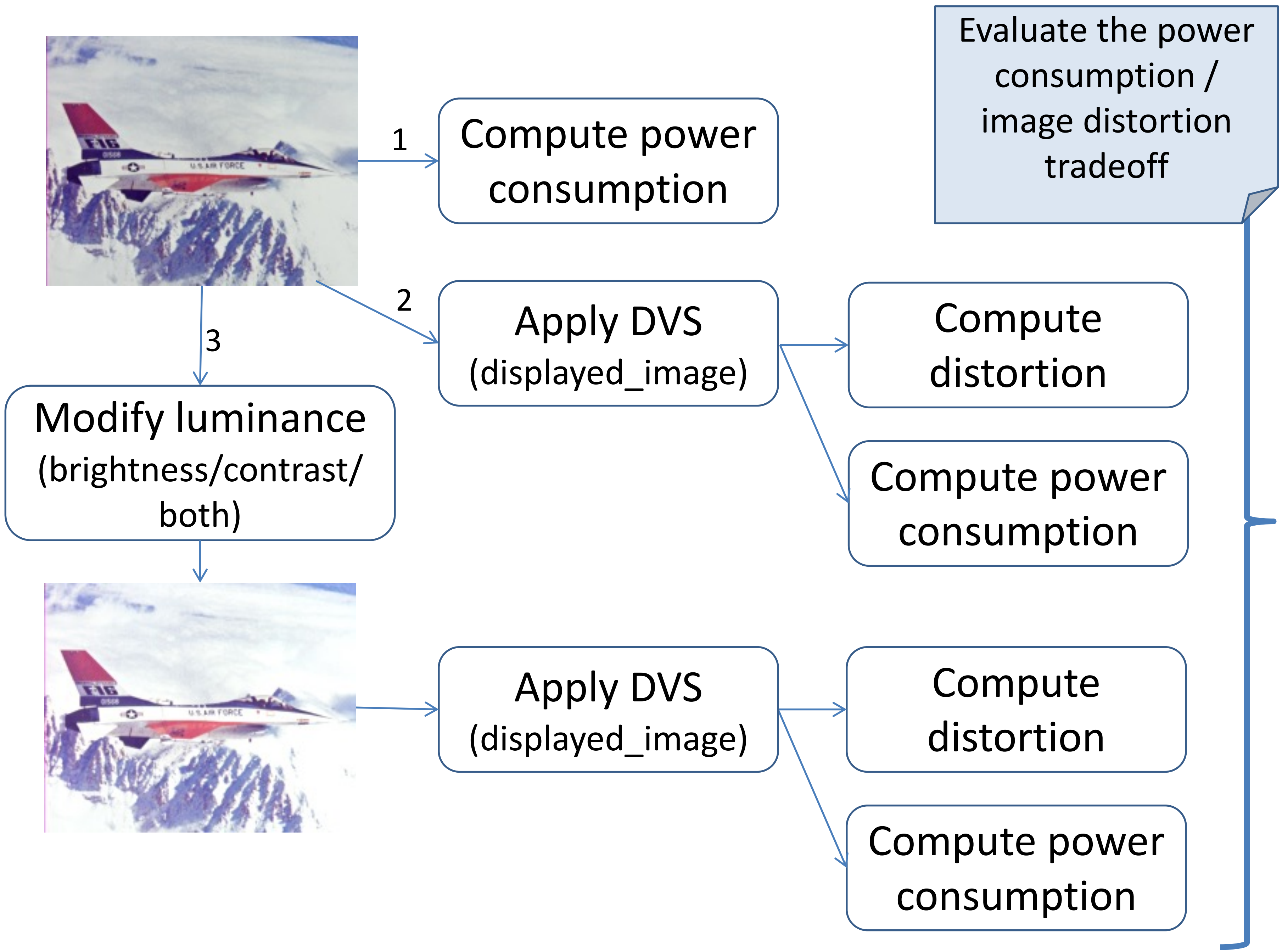




Assignment 2 – Part 2

- **TASK:** Experiment with various **image compensation strategies:**
  - Brightness scaling
  - Contrast enhancement
  - Combined BS + CE
  - Others… (**again, use your creativity!**).





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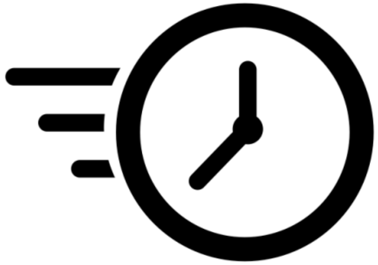
Assignment 2 – Part 2

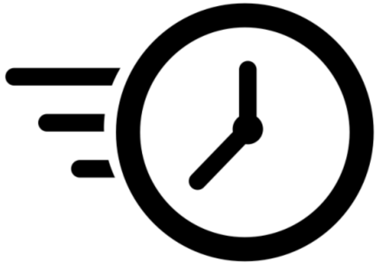
- Compare the different DVS + image compensation strategies
  - With respect to part 1, you have a new «free variable» → **The DVS voltage**



Assignment 2 – Part 2

- The goal becomes *«find optimal supply voltage and compensated image»* to:
  - Minimize power consumption
  - Maximize **perceived visual quality**

  - **Important:** image compensations will typically *increase* the distortion.
    - Remember: **visual quality** is different from **distortion**!
    - But the former is only qualitative…



Assignment 2 – Part 2

- So, what you can do, is:
  - Impose a maximum distortion constraint (e.g., 1%, 2%, 3%), as in Part 1
    - Use the LAB distance for distortion, as in Part 1
  - Among the (V_{DD}, compensation) pairs that meet this constraint, select the one that *in your opinion* yields the *best-quality* images
    - **Of course, this is subjective!!!**

Assignment 2 – Part 2

- Apply the overall flow to all images!
  - Automatically, with a script