High Dynamic Range Photography

Computational Photography (CSCI 3240U)

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High Dynamic Range (HDR) Photography

- Human eyes have high visual range
  - It can differentiate and see structure between very bright and very dark regions in a scene
- An image is taken at a particular exposure setting, which determines whether it contains more visible structure in brighter or darker regions

Images taken at various exposure settings

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HDR techniques combine multiple images of the same scene to emulate the high visual range of human eyes

Images taken at various exposure settings

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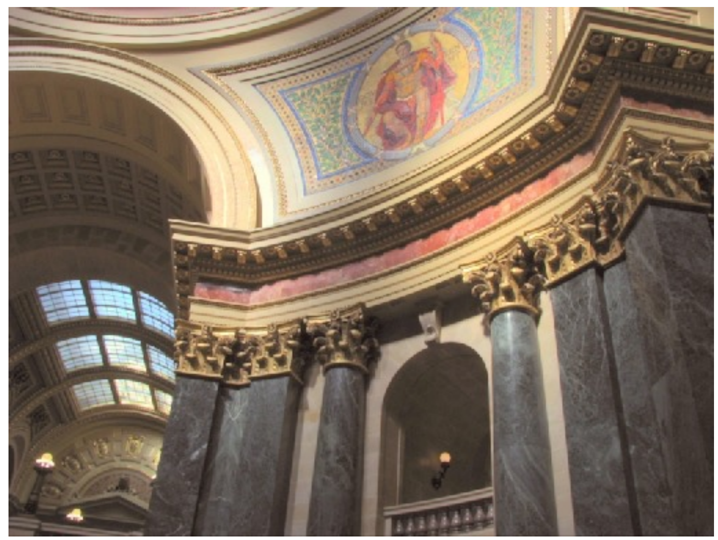
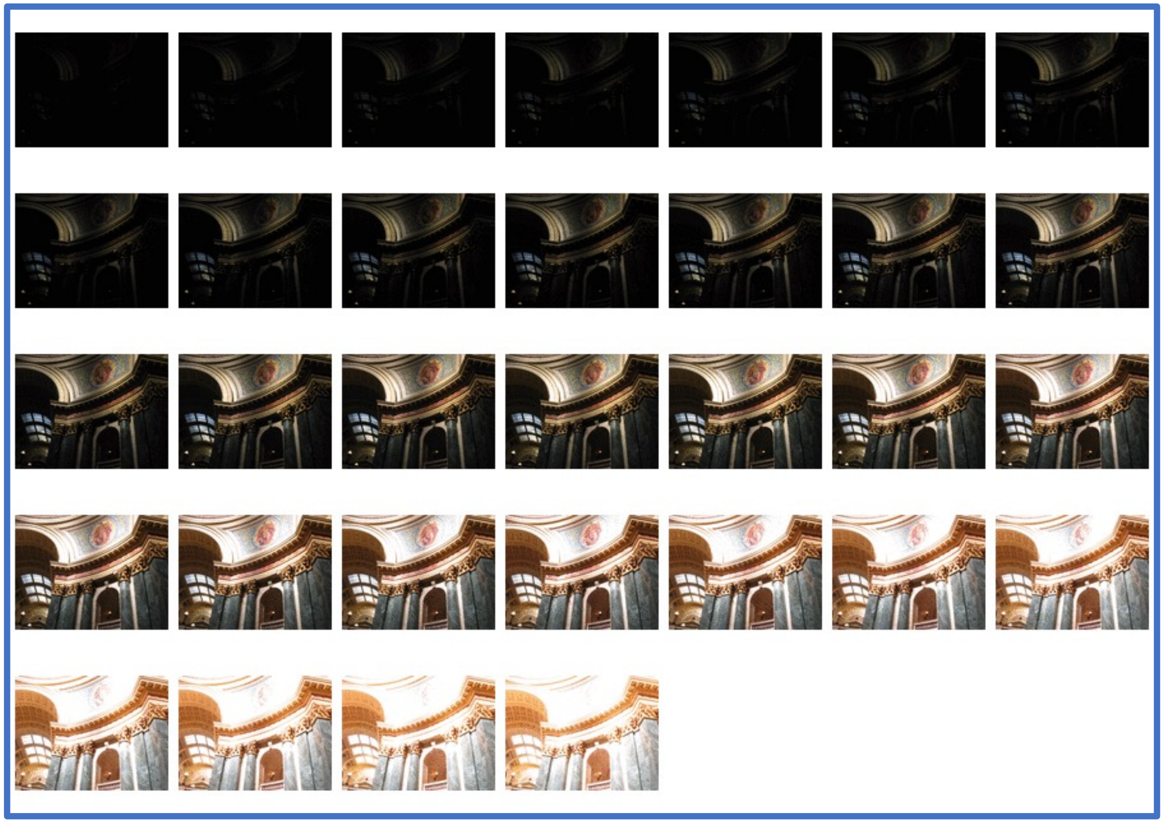
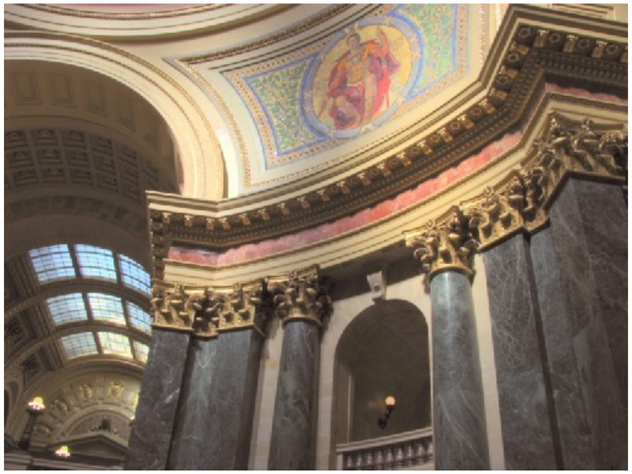


HDR image

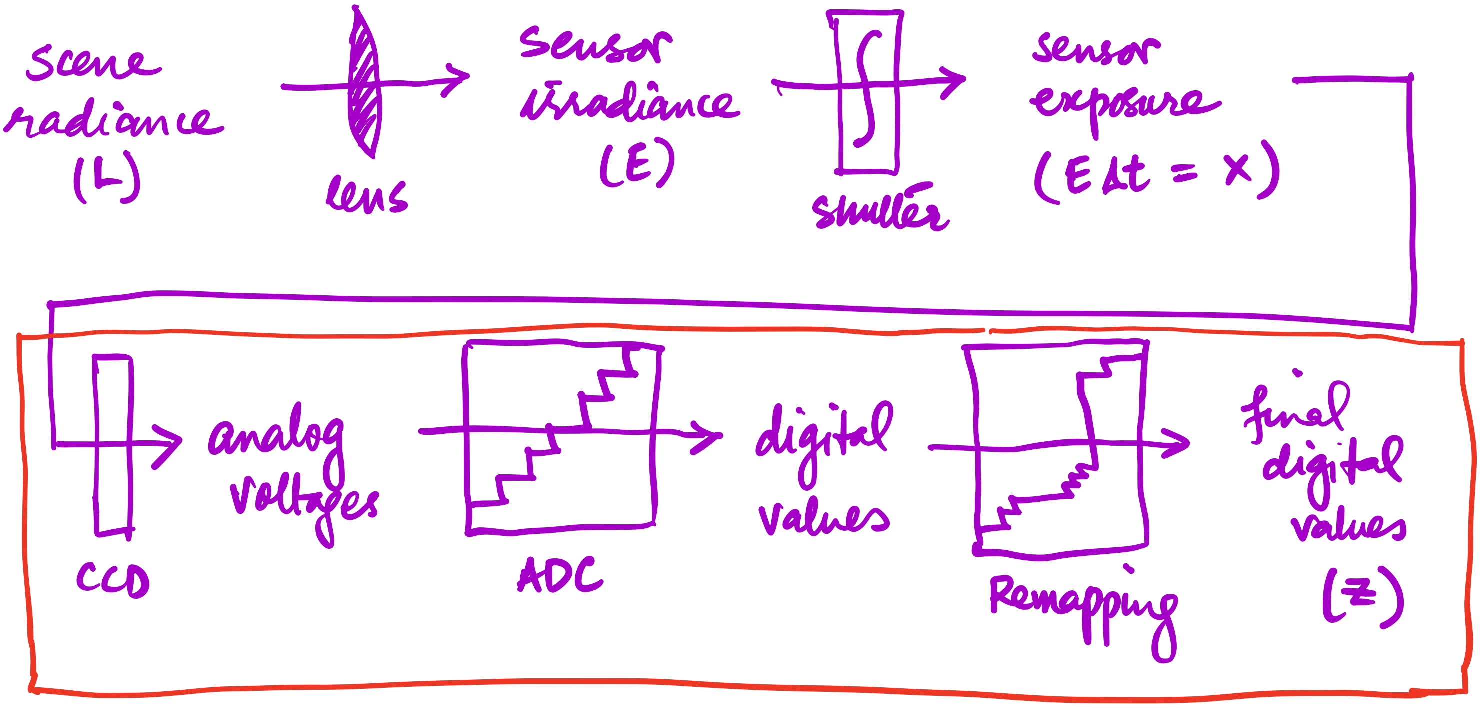
High Dynamic Range (HDR) Photography



Images taken at various exposure settings



HDR image



$$Z = f(E\Delta t)$$

observed pixels

camera response function

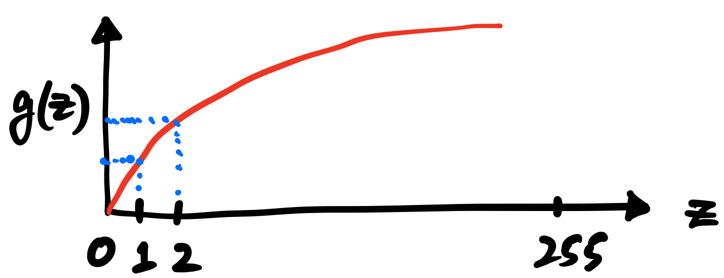
Goal: Compute the camera response function (f).

$$Z = f(E\Delta t)$$

$$f^{-1}(Z) = E\Delta t$$

$$\underbrace{\log f^{-1}(Z)} = \log E + \log \Delta t$$

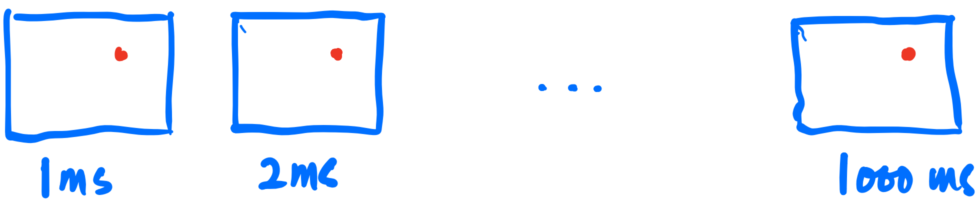
$$g(Z) = \log E + \log \Delta t \quad \text{--- (1)}$$

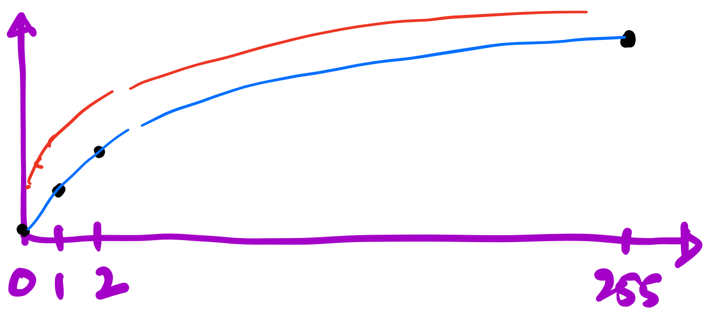


We need to compute $g(z)$: $\underbrace{g(0), g(1), g(2), \cdots, g(255)}_{256 \text{ values}}$.

Approach 1

- One pixel and many many images
- Images are taken by finely adjusting Δt
- Plot $\underline{\log \Delta t}$ as a function of pixel intensity.





Drawbacks: need to acquire too many images.
how to control Δt to hit all possible z values between 0 and 255.
what if you store 16-bit pixels. Here possible values are between 0 and $2^{16}-1$.
Does not scale!!

What happens $\log E$?

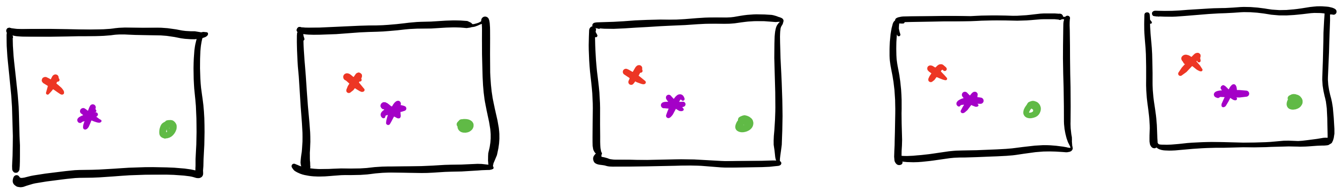
$$g(z) = \boxed{\log E} + \log \Delta t \rightsquigarrow g(z) \approx \log \Delta t$$

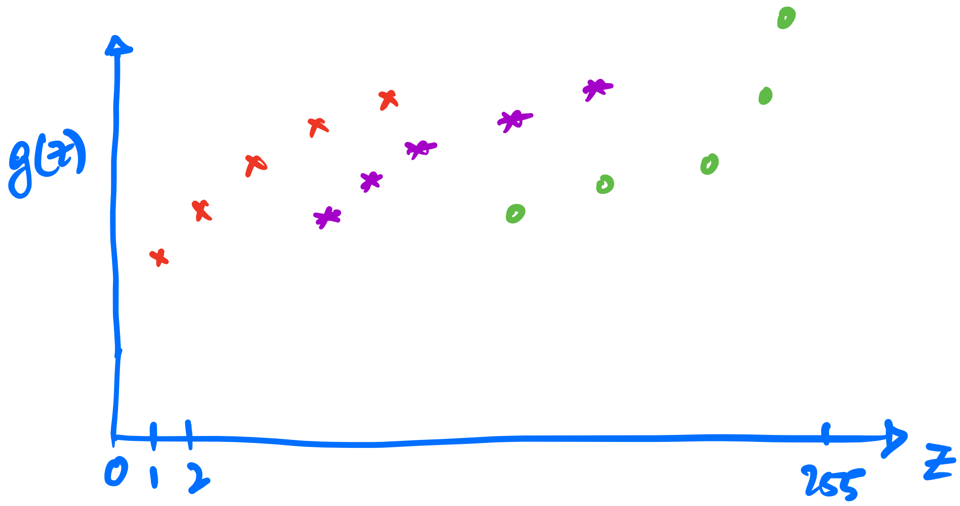
simplified

same value for all the images

Approach 2

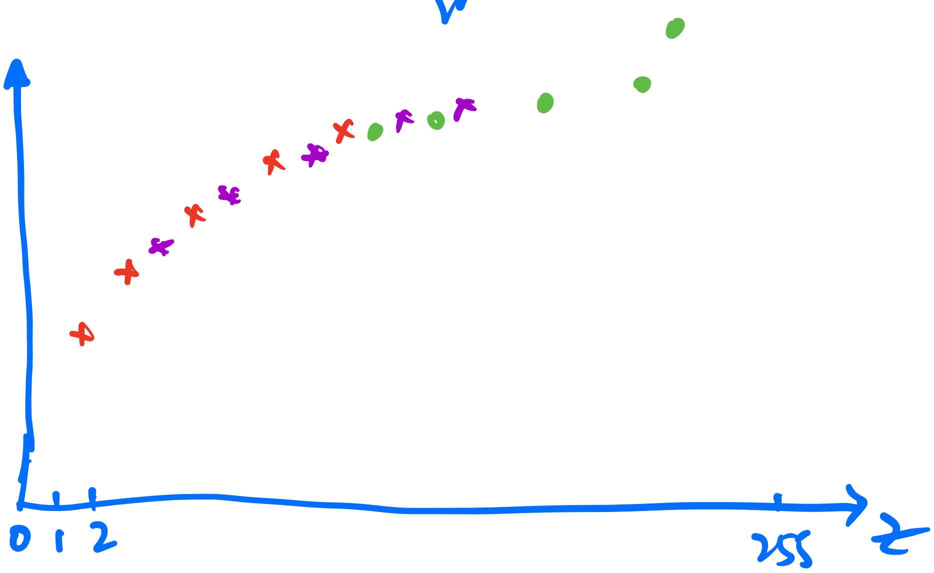
- Few pixels and a few images.





Plot of g(z) from three images.

Computed g(z)



Benefit over approach 1:

we need far far fewer images.

Approach 2 (mathematics).

N pixels

P images.

Example:

$N = 3$

$P = 5$

$$g(z_{ij}) = \log E_i + \log \Delta t_j \qquad (2)$$

i^{th} pixel

in j^{th} image

irradiance for i^{th} pixel

exposure interval of j^{th} image.

Unknowns: $g(0), \dots, g(255)$ [256]

E_i [N]

$x_{ij} \in [0, 255]$

Given Δt_j

\# of unknowns = $256 + N$

\# of equations = NP

Simplified notation:

$$g(z_{ij}) = g_{ij}$$

$$\log E_i = e_i$$

$$\log \Delta t_j = \delta_j$$

Re-write (2)

$$g_{ij} = e_i + \delta_j$$

$$\Rightarrow \quad g_{ij} - e_i = s_j \quad \text{—③}$$

I want to express this as $Ax = b$

$$x = \begin{bmatrix} g_0 \\ g_1 \\ \vdots \\ g_{255} \\ e_1 \\ \vdots \\ e_N \end{bmatrix} \in \mathbb{R}^{(256+N)\times 1}$$

$g_0 = g(0)$

$\vdots$

$g_{255} = g(255)$

Express ③ as $Ax = b$

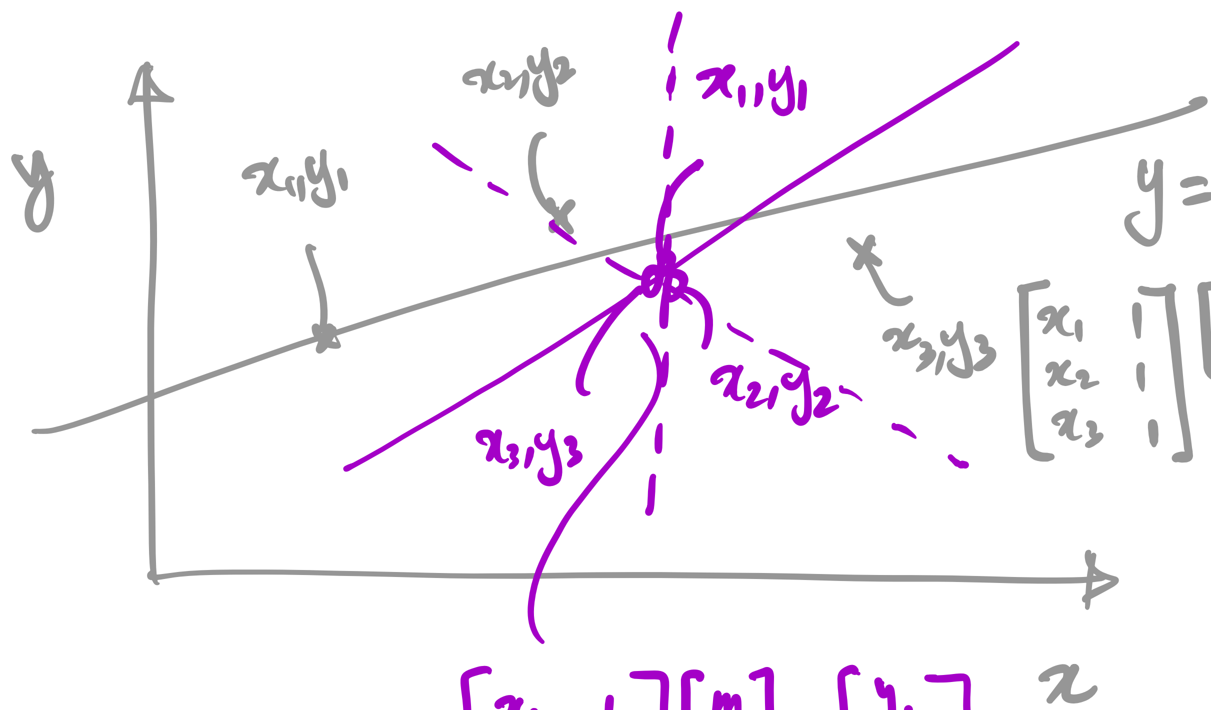
$$\begin{array}{c} \overset{256}{\longleftrightarrow} \qquad\qquad \overset{N}{\longleftrightarrow} \\ \left[\, 0 \;\cdots\; 0 \;\; \underset{z_{ij}^{\text{th}} \text{ column}}{1} \;\; 0 \;\cdots\; 0 \;\; 0 \cdots 0 \;\; \underset{256+i \text{ column}}{-1} \;\; 0 \;\cdots\; 0 \,\right] \end{array} \begin{bmatrix} g_0 \\ g_1 \\ \vdots \\ g_{255} \\ e_1 \\ \vdots \\ e_N \end{bmatrix} = [s_j]$$

co-efficients of $g_0 \cdots g_{255}$

co-efficients of $e_1 \cdots e_N$

$$
\begin{array}{c|c}
 & \text{column } z_{ij} \qquad\qquad \text{column } 256+i \\
\hline
ij^{\text{th}} \text{ row} & \left[\begin{array}{cccccccccccc} 0 & \cdots & 0 & 1 & 0 & \cdots & 0 & 0 & \cdots & 0 & -1 & 0 \;\cdots\; 0 \end{array}\right]
\end{array}
\begin{bmatrix} g_0 \\ \vdots \\ g_{255} \\ e_1 \\ \vdots \\ e_N \end{bmatrix}
=
\begin{bmatrix} \\ \\ \delta_j \\ \\ \\ \end{bmatrix}
$$

$$
A \in \mathbb{R}^{NP\times(256+N)} \qquad x \in \mathbb{R}^{256+N} = b \in \mathbb{R}^{NP}
$$



$y = mx + c$

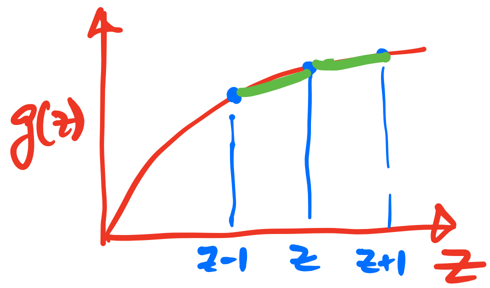
$$
\begin{bmatrix} x_1 & 1 \\ x_2 & 1 \\ x_3 & 1 \end{bmatrix}
\begin{bmatrix} m \\ c \end{bmatrix}
=
\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix}
$$

$$
\begin{bmatrix} x_1 & 1 \\ x_2 & 1 \\ x_3 & 1 \end{bmatrix}
\begin{bmatrix} m \\ c \end{bmatrix}
=
\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix}
$$

Consider $Ax = b$. What if A is ill-conditioned? How do we address this issue?

$\rightarrow$ "Regularize"

Real camera response curves (functions) varies smoothly.



Add more equations to enforce smoothness

$$g(z) - g(z-1) = g(z+1) - g(z) \quad *$$

Re-write this as

$$2g(z) - g(z-1) - g(z+1) = 0$$

$$\begin{array}{c} \left[\begin{array}{ccc|c|c|c|ccc} 0 & \cdots & 0 & -1 & 2 & -1 & 0 & \cdots & 0 \end{array}\right] \\ \begin{array}{ccc} \hspace{3em} z \text{ column} & z+1 \text{ column} & z+2 \text{ column} \hspace{3em} \end{array} \end{array} \begin{bmatrix} g_0 \\ g_1 \\ \vdots \\ g_{z-1} \\ g_z \\ g_{z+1} \\ \vdots \\ g_{255} \end{bmatrix} = [0]$$

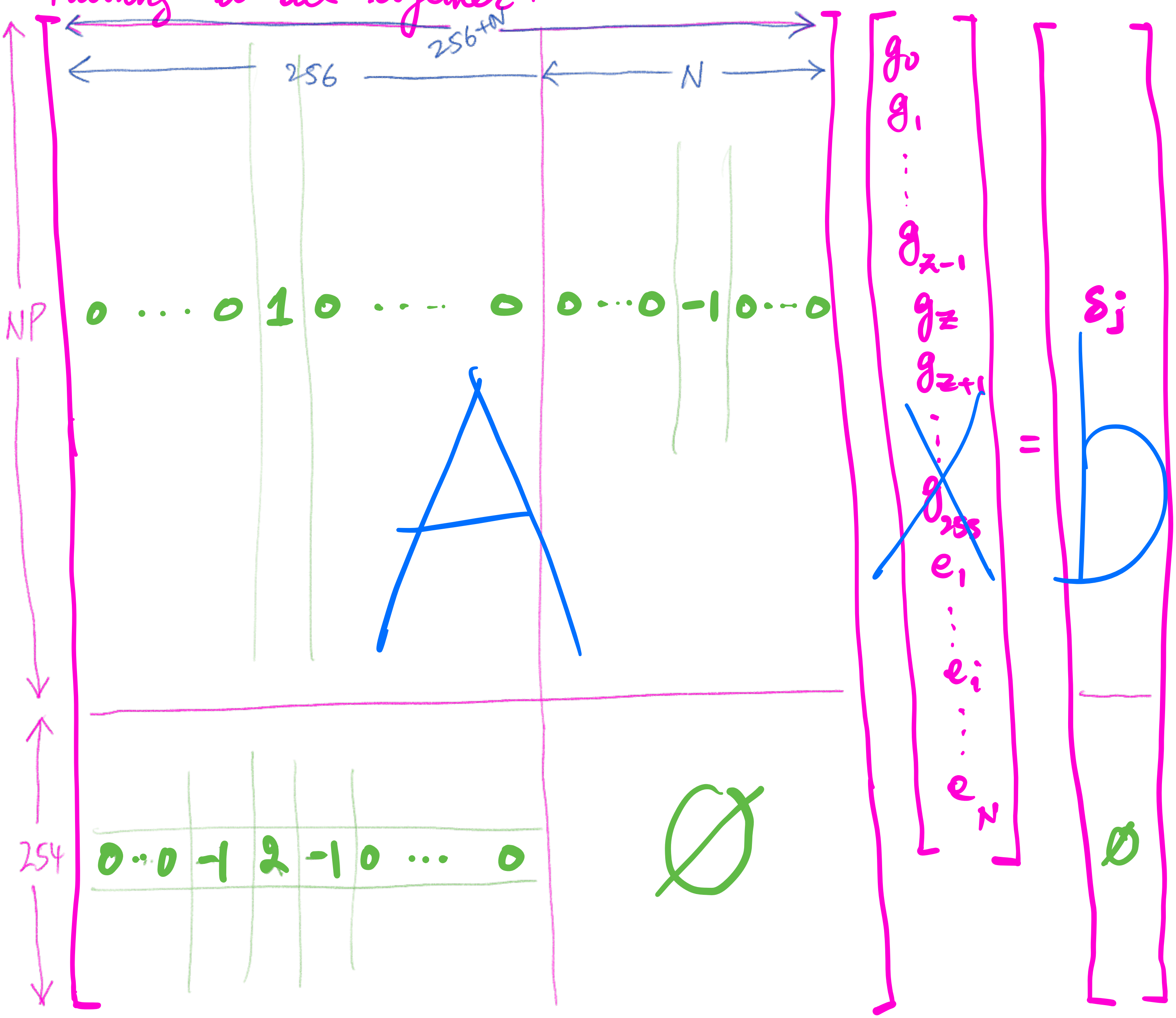
For a particular g_z, g_{z-1}, g_{z+1}

We have $g_0, \dots, g_{255}$. We extend the idea to all possible values of $z \in [0, 255]$.

We get 254 more equations:

$$\left.\begin{aligned}
2g_1 - g_0 - g_2 &= 0 \\
2g_2 - g_1 - g_3 &= 0 \\
&\vdots \\
2g_{254} - g_{253} - g_{255} &= 0
\end{aligned}\right\} 254$$

Putting it all together:



$$g(z) = \log E + \log \Delta t$$

$$\Rightarrow \log E = g(z) - \log \Delta t.$$

irradiance of that pixel.

shutter speed

While $z \in [0, 255]$, $E \in [0, \infty]$ (HDR)

$\boxed{\text{tone-mapping}}$ because irradiances can not be displayed on a standard display.

Process of compressing a range to the available range.

For HDR logarithmic tone-mapping:

- Given an image I.
- $I' = \log(1+\alpha I) / \log(1+\alpha)$
  - $\rightarrow \alpha = 0.1$, controls the strength of tone-mapping. smaller results in stronger compression.
- $I'' = [I' - \min(I')] / [\max(I') - \min(I')]$
  - $\rightarrow$ remapping pixel values between 0 and 1.
- $R = (I'' \times 255.0) \rightarrow$ int8

result.

High Dynamic Range (HDR) Photography

- Collect images at different exposure settings
  - Align images if needed
- Estimate response curve
  - Set up the system of linear equations and solve for unknowns
- Use response curve to compute pixel irradiance values
- Perform tone mapping to construct the final HDR image that can displayed on a device with limited dynamic range

Reference

- https://pages.cs.wisc.edu/~csverma/CS766_09/HDRI/hdr