Color Interpolation for Single-CCD Color Camera

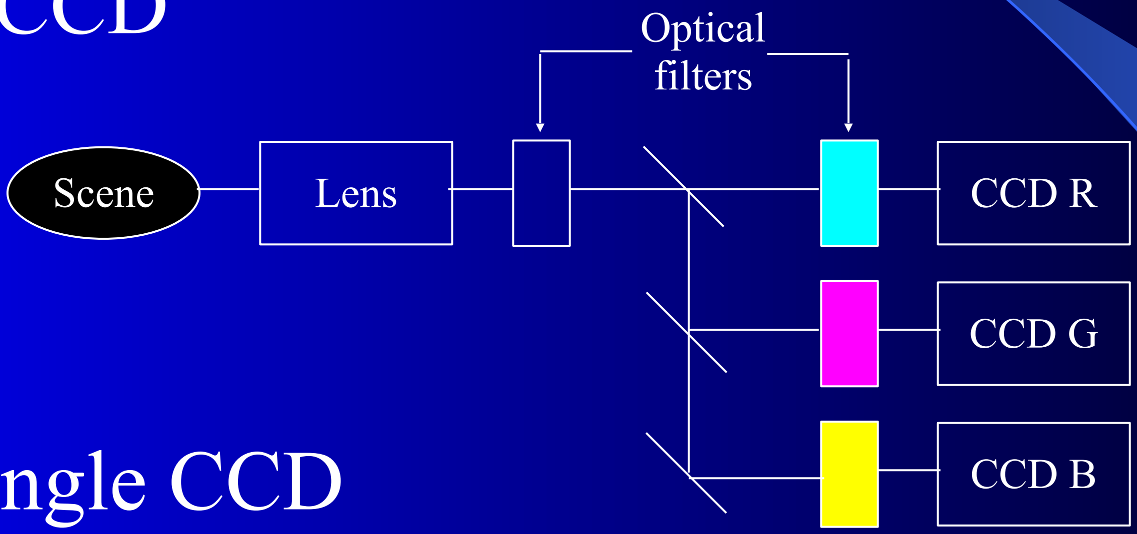
Outline

- Introduction
- Brief review of traditional interpolation techniques
- Our proposed methods
- Experiment results
- Conclusion and future work

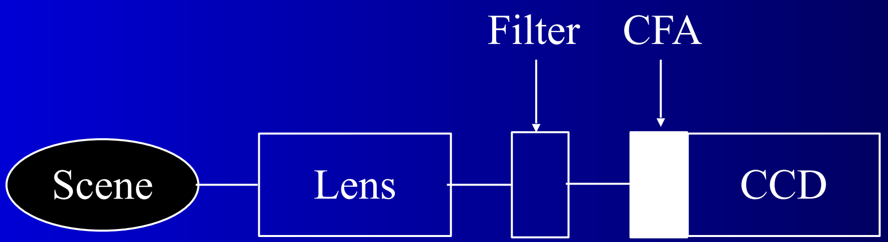
Introduction

3 CCD versus Single CCD

- 3 CCD



- Single CCD



Color Filter Array (CFA)

- Mosaic RGB type
  - Consists of red, green, and blue color filters.
  - B. E. Bayer, “Color Image Array,” U.S. Patent 3971065, 1976.

R	G	R	G
G	B	G	B
R	G	R	G
G	B	G	B

Color Filter Array *(Continued)*

- Other mosaic types

Cy	W	Ye	G
Ye	G	Cy	W
Cy	W	Ye	G
Ye	G	Cy	W

G	Mg	G	Mg
Cy	Ye	Cy	Ye
Mg	G	Mg	G
Cy	Ye	Cy	Ye

- Stripe types

R	G	B	G
R	G	B	G
R	G	B	G
R	G	B	G

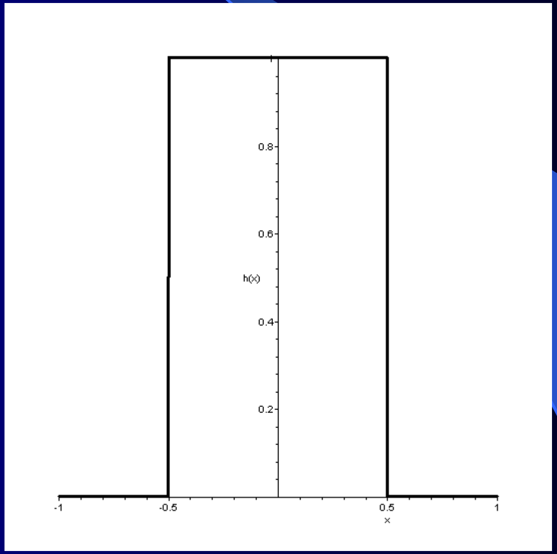
Ye	G	Cy	G
Ye	G	Cy	G
Ye	G	Cy	G
Ye	G	Cy	G

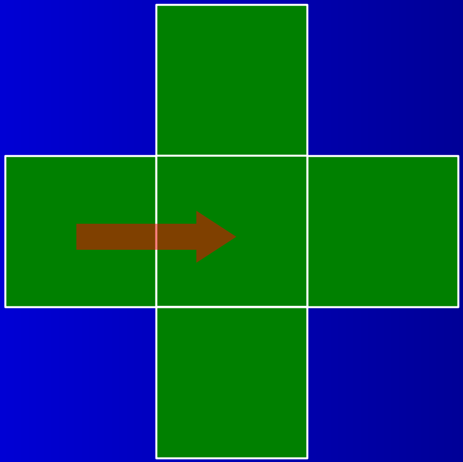
Brief Review of Traditional Interpolation Techniques

Nearest Neighbor Interpolation

- Interpolation function

$$h(x) = \begin{cases} 1 & 0 \le |x| < 0.5 \\ 0 & 0.5 \le |x| \end{cases}$$

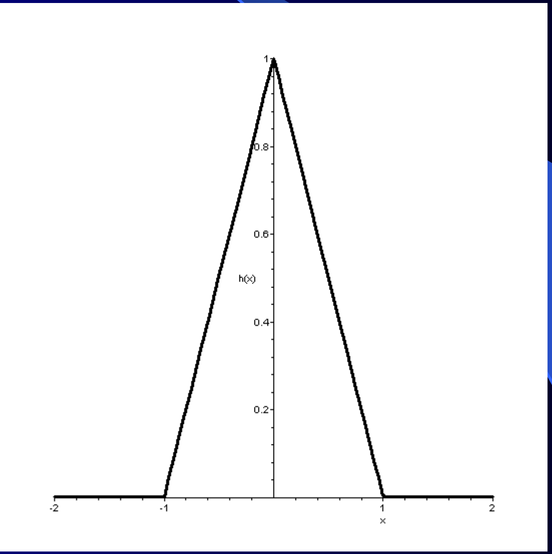


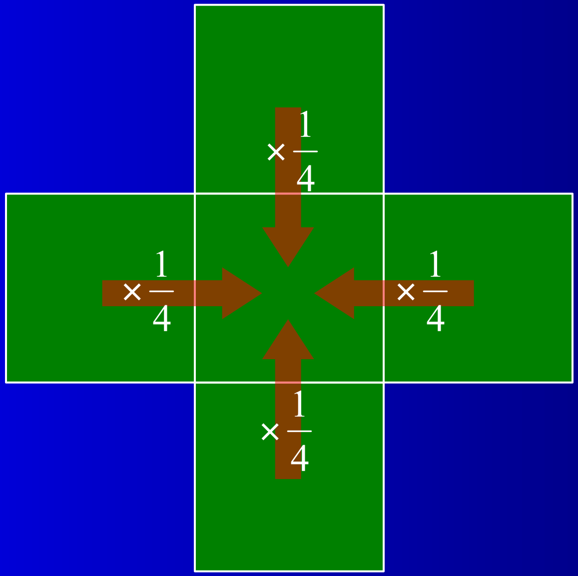


Bilinear Interpolation

- Interpolation function

$$h(x)=\begin{cases}1-|x| & 0\le |x|<1\\ 0 & 1\le |x|\end{cases}$$

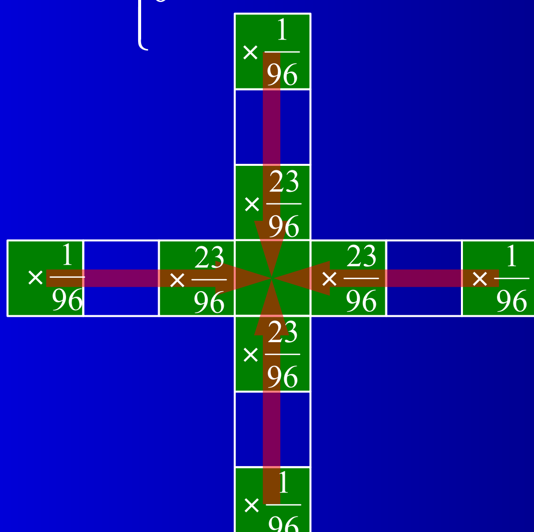


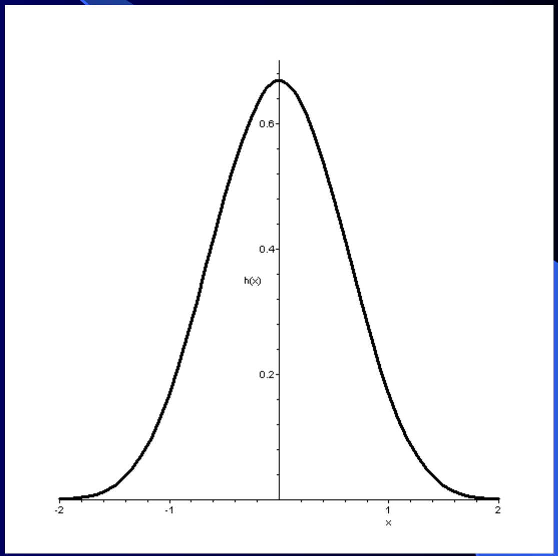


Cubic B-Spline Interpolation

- Interpolation function

$$h(x)=\begin{cases}\frac{1}{2}|x|^3-|x|^2+\frac{2}{3} & 0\le |x|<1\\ -\frac{1}{6}|x|^3+|x|^2-2|x|+\frac{4}{3} & 1\le |x|<2\\ 0 & 2\le |x|\end{cases}$$

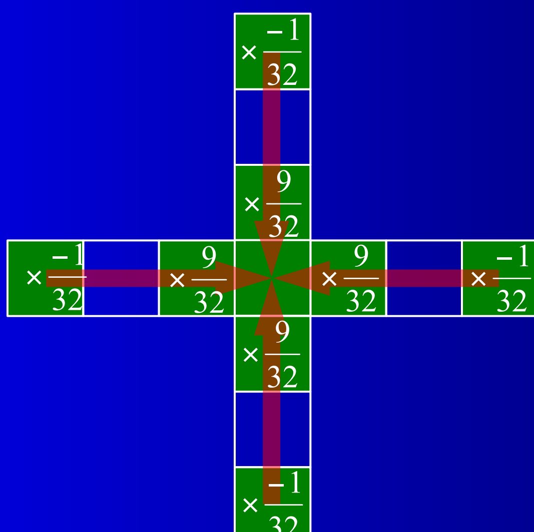


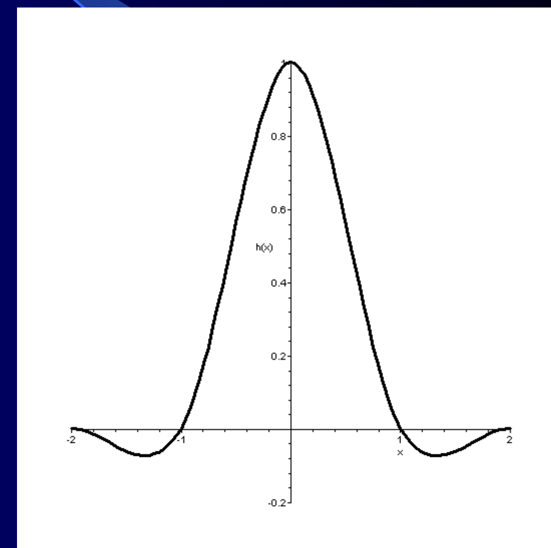


Cubic Convolution Interpolation

- Interpolation function

$$h(x)=\begin{cases}(a+2)|x|^3-(a+3)|x|^2+1 & 0\le|x|<1\\ a|x|^3-5a|x|^2+8a|x|-4a & 1\le|x|<2\\ 0 & 2\le|x|\end{cases}$$

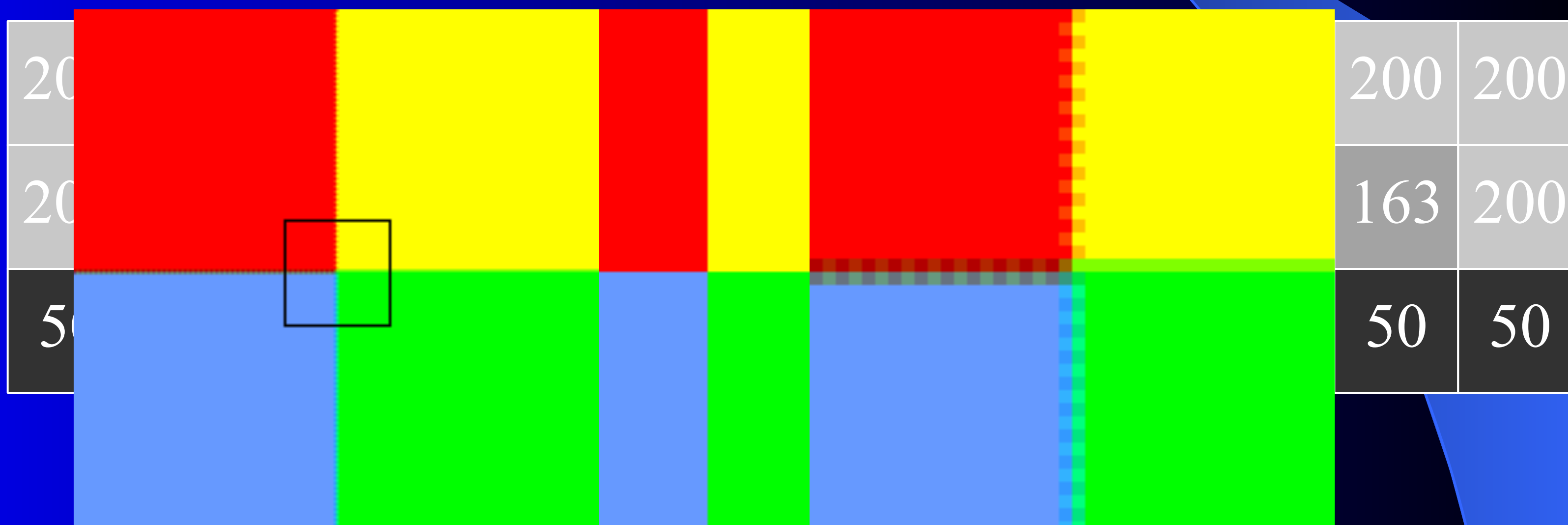




a = -0.5

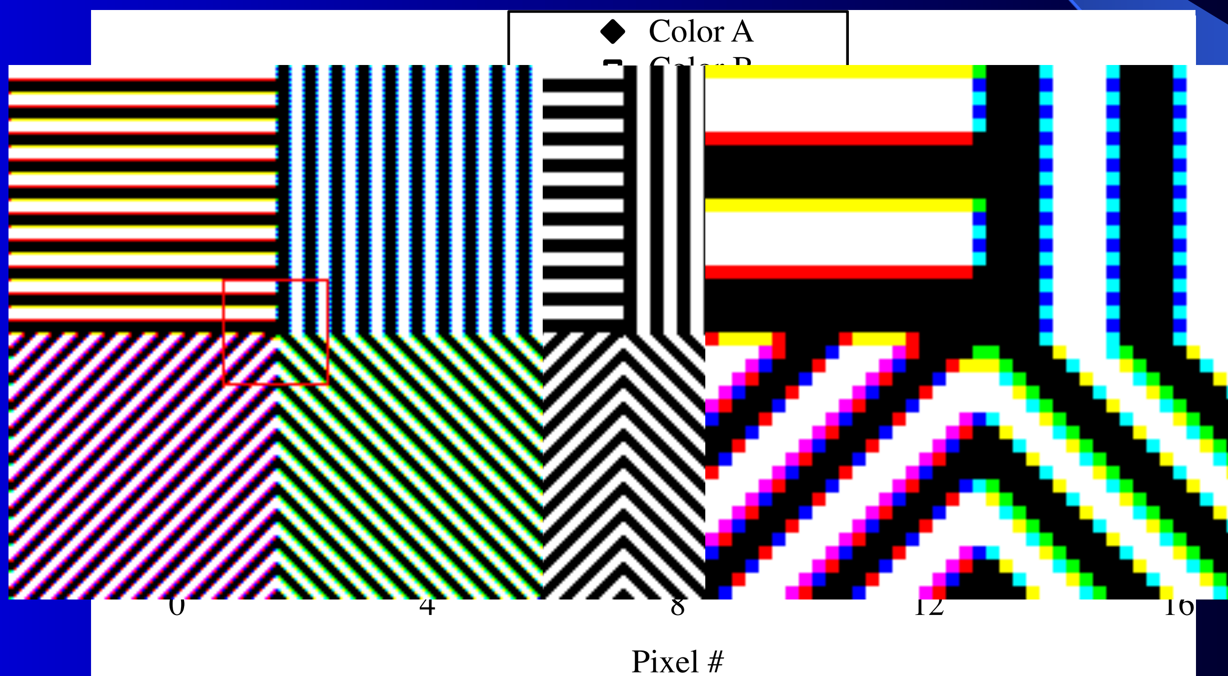
Traditional Interpolation Problems

- Blurred-edge effect



Traditional Interpolation Problems
(Continued)

- Color-alias effect



Our Proposed Methods

Horizontal and Vertical Edge-Filters

- Gradient magnitude

$$\Delta H = \left| G_{x+1,y} - G_{x-1,y} \right|$$

$$\Delta V = \left| G_{x,y+1} - G_{x,y-1} \right|$$

- Laplacian magnitude

$$\Delta \hat{H} = \left| 2R_{x,y} - R_{x-2,y} - R_{x+2,y} \right|$$

$$\Delta \hat{V} = \left| 2R_{x,y} - R_{x,y-2} - R_{x,y+2} \right|$$

- Composite edge-filters

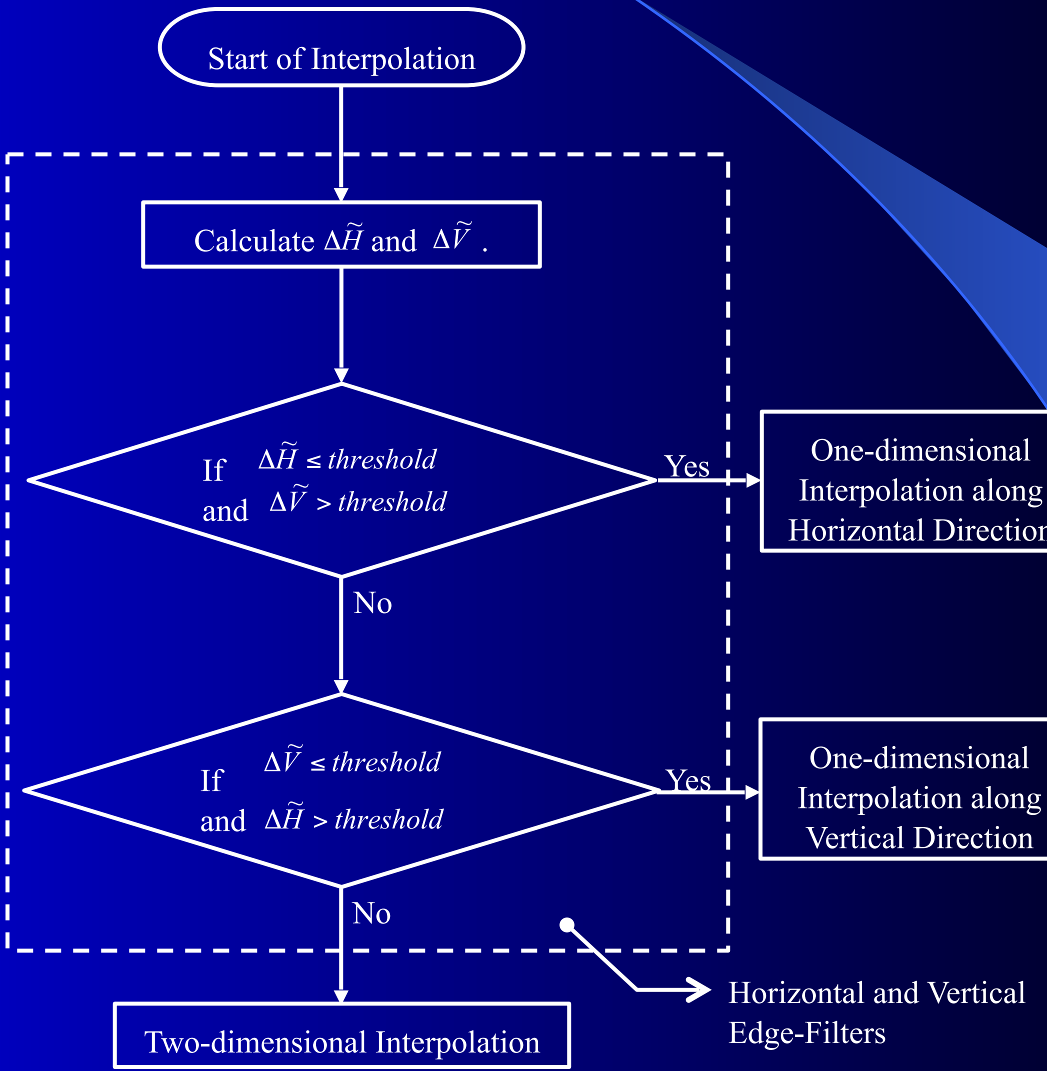
$$\Delta \tilde{H} = \Delta H + \Delta \hat{H} \qquad \Delta \tilde{V} = \Delta V + \Delta \hat{V}$$

x

y

$R_{x-2,y-2}$	$G_{x-1,y-2}$	$R_{x,y-2}$	$G_{x+1,y-2}$	$R_{x+2,y-2}$
$G_{x-2,y-1}$	$B_{x-1,y-1}$	$G_{x,y-1}$	$B_{x+1,y-1}$	$G_{x+2,y-1}$
$R_{x-2,y}$	$G_{x-1,y}$	$R_{x,y}$	$G_{x+1,y}$	$R_{x+2,y}$
$G_{x-2,y+1}$	$B_{x-1,y+1}$	$G_{x,y+1}$	$B_{x+1,y+1}$	$G_{x+2,y+1}$
$R_{x-2,y+2}$	$G_{x-1,y+2}$	$R_{x,y+2}$	$G_{x+1,y+2}$	$R_{x+2,y+2}$

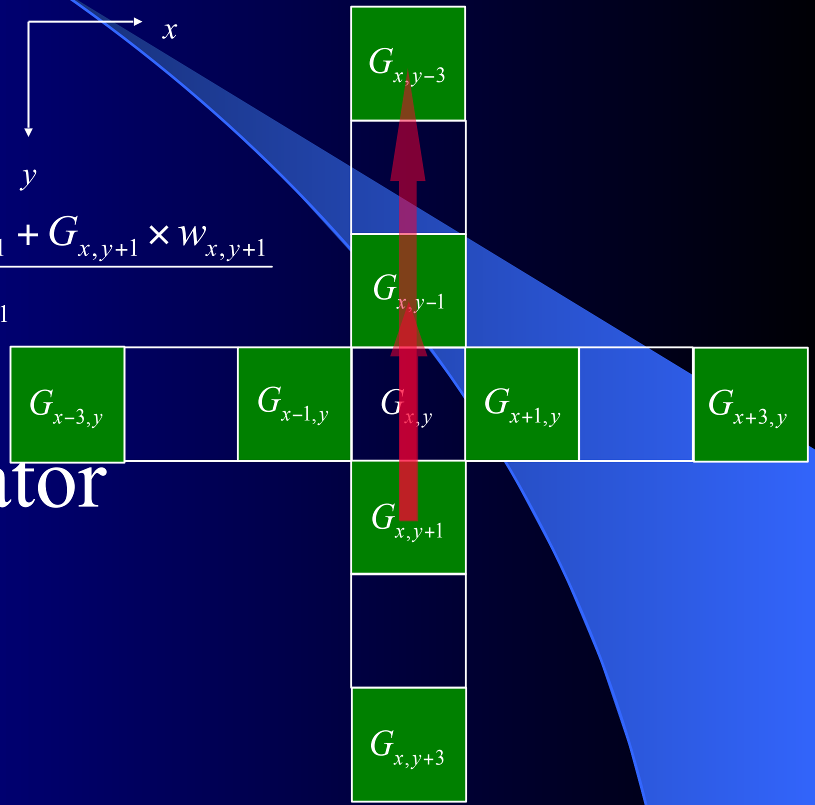
Edge-Filtered Interpolation



Weighting-Based Interpolation

- Interpolation

$$G_{x,y} = \frac{G_{x-1,y} \times w_{x-1,y} + G_{x+1,y} \times w_{x+1,y} + G_{x,y-1} \times w_{x,y-1} + G_{x,y+1} \times w_{x,y+1}}{w_{x-1,y} + w_{x+1,y} + w_{x,y-1} + w_{x,y+1}}$$



- Weighting by edge indicator

$$DG_y(y+1, y-1) = \frac{G_{x,y+1} - G_{x,y-1}}{2}$$

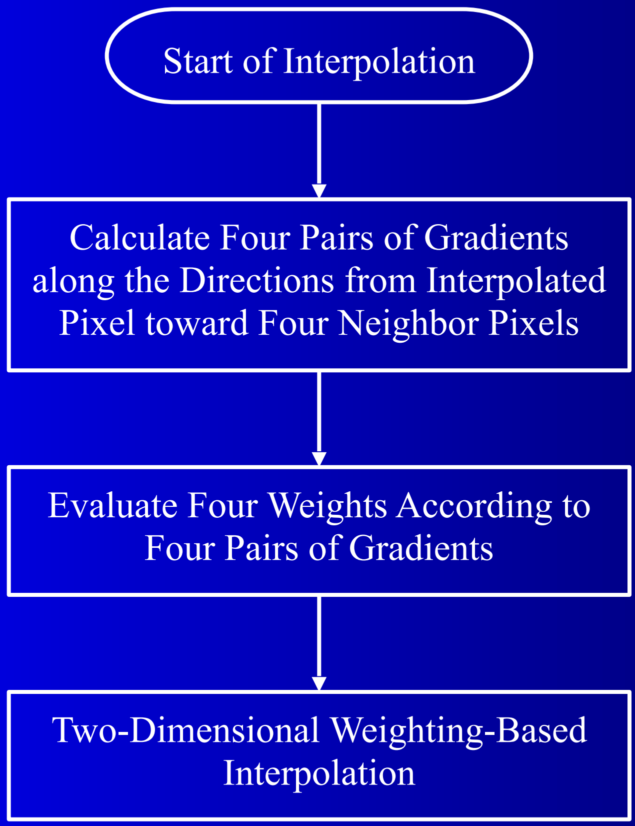
$$DG_y(y+1, y-3) = \frac{G_{x,y+1} - G_{x,y-3}}{4}$$

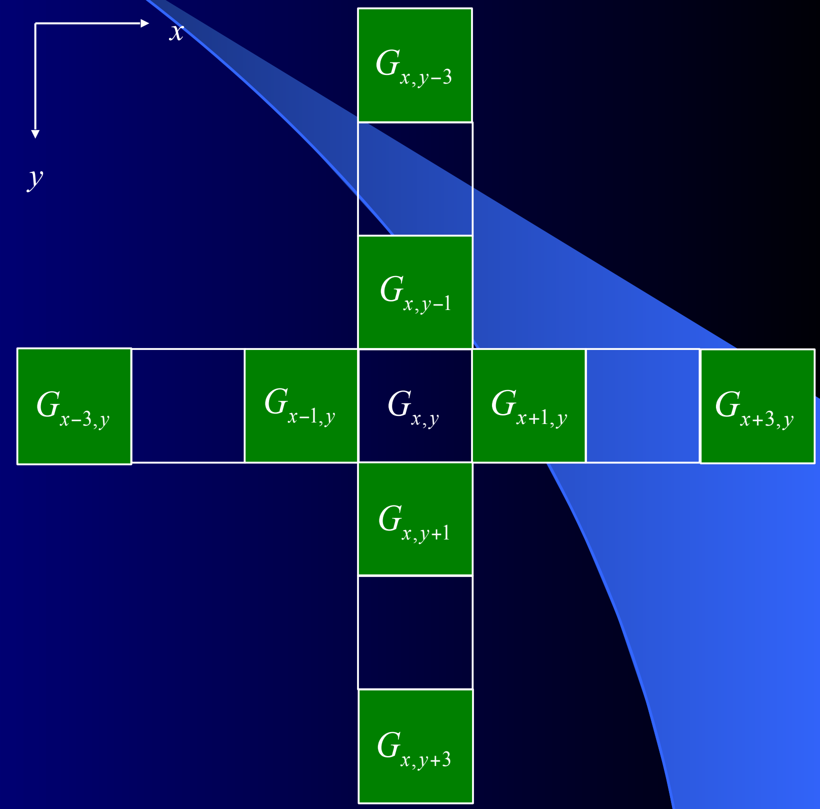
$$w_{x,y-1} = \left(1 + \left(DG_y(y+1, y-1)\right)^2 + \left(DG_y(y+1, y-3)\right)^2\right)^{-\frac{1}{2}}$$

simplif

$$w_{x,y-1} = \left(1 + \left|DG_y(y+1, y-1)\right| + \left|DG_y(y+1, y-3)\right|\right)^{-1}$$

Weighting-Based Interpolation
(Continued)





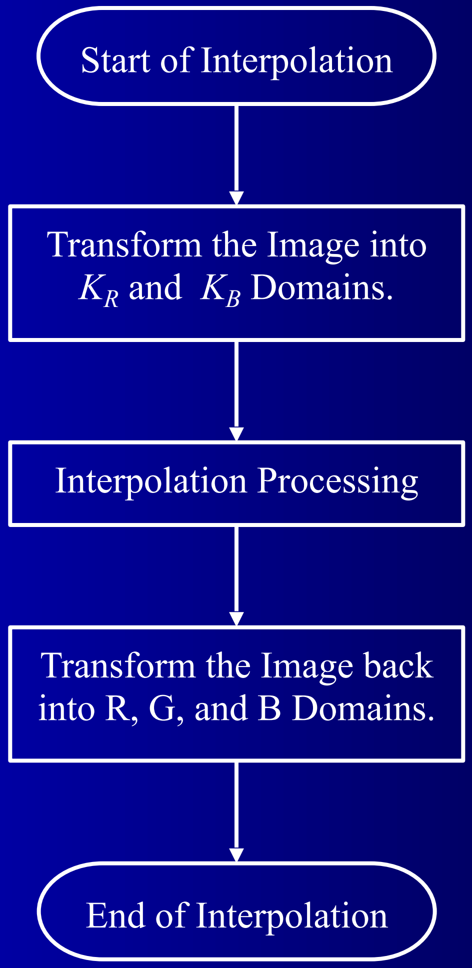
Color-Difference Domain

- Col
  - T pixel are pe offset, th
- Col
  - K
  - K

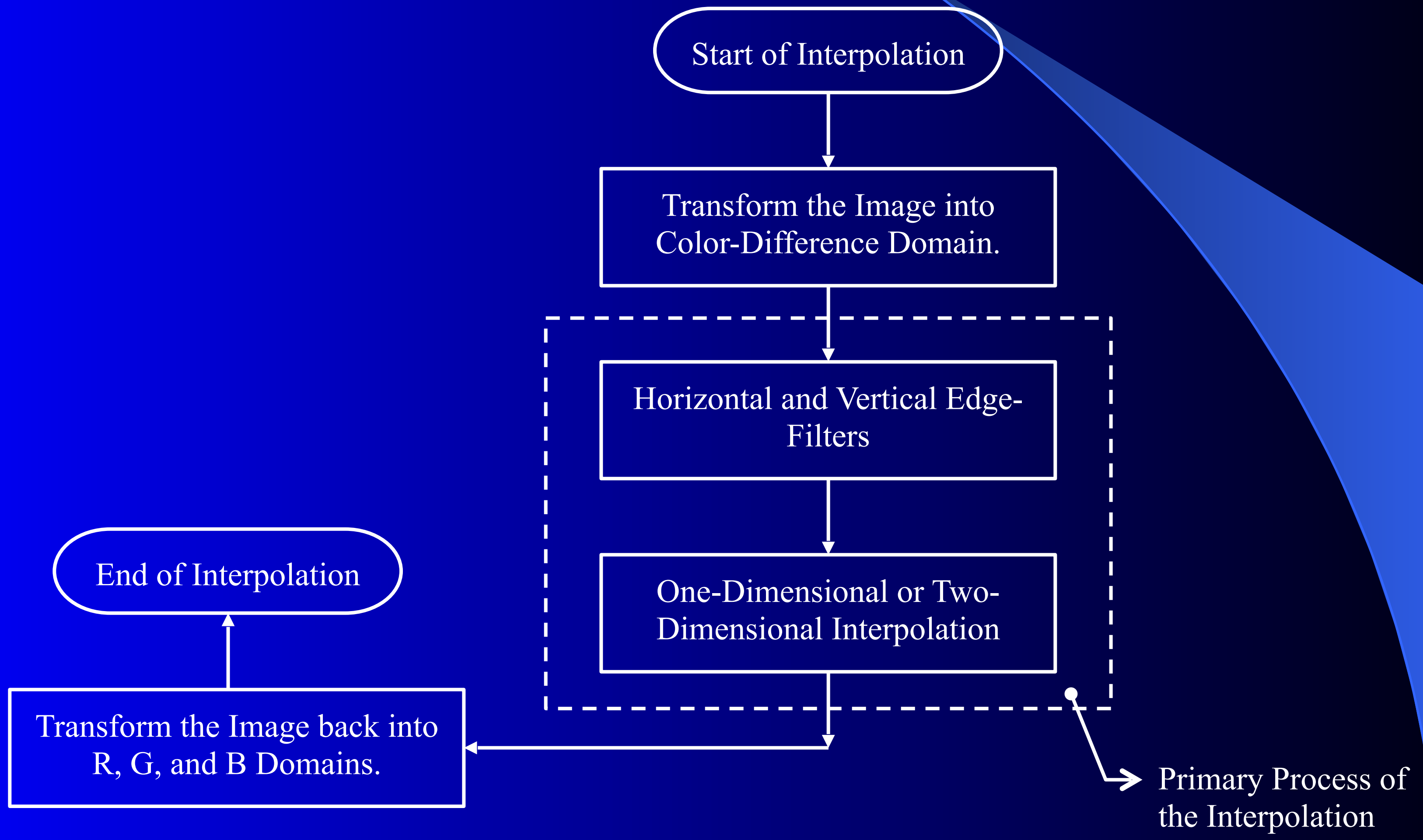
An example of G channel of the image.

The K_R channel of the image.

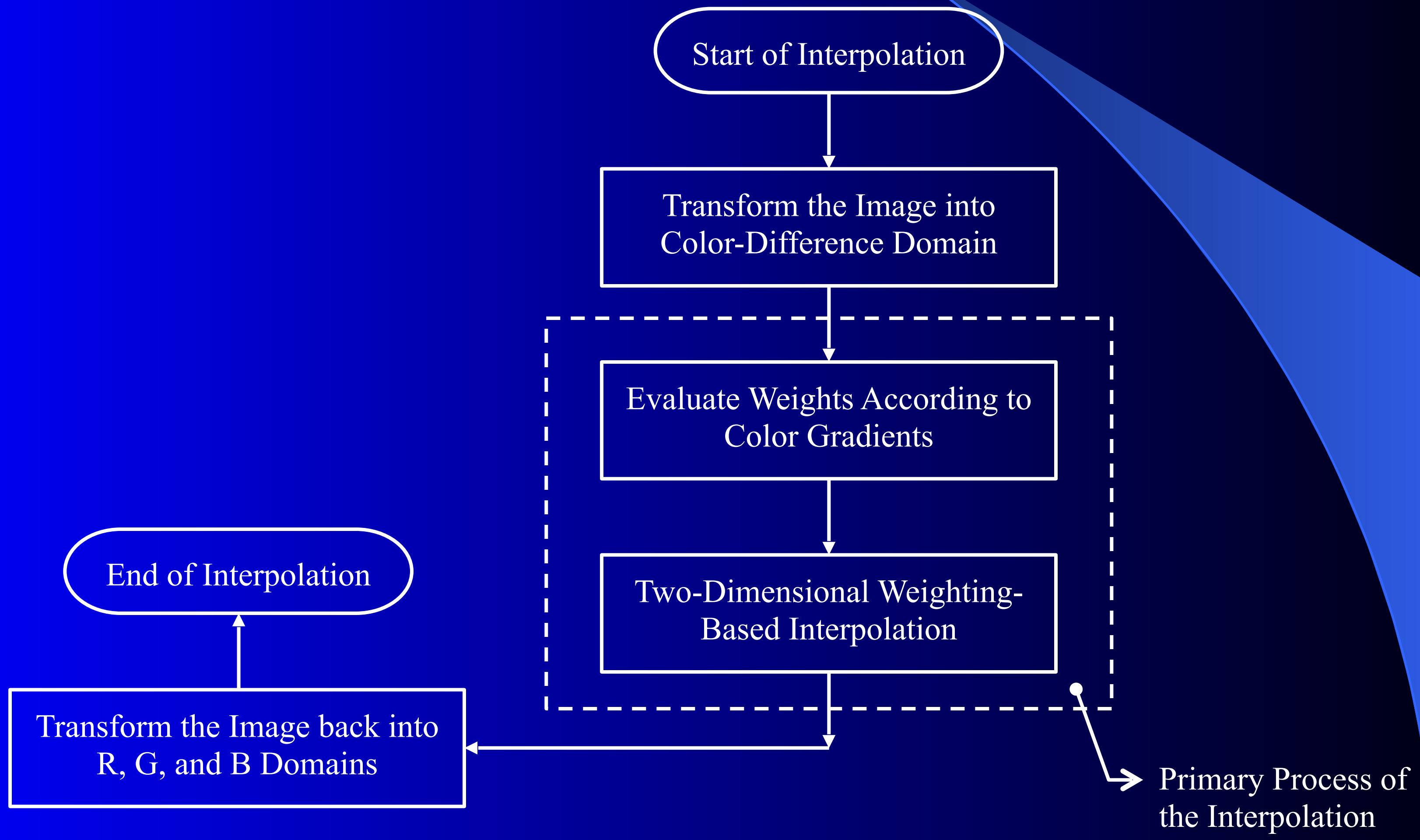
Color-Difference Interpolation



Edge-Filtered Color-Difference Interpolation



Weighting Color-Difference Interpolation



Interpolation of Green Color Components

$$K_R(x-1,y) = G_{x-1,y} - R_{x-1,y} \approx G_{x-1,y} - \left(R_{x-2,y} + R_{x,y}\right)/2$$

$$K_R(x+1,y) = G_{x+1,y} - R_{x+1,y} \approx G_{x+1,y} - \left(R_{x,y} + R_{x+2,y}\right)/2$$

$$K_R(x,y-1) = G_{x,y-1} - R_{x,y-1} \approx G_{x,y-1} - \left(R_{x,y-2} + R_{x,y}\right)/2$$

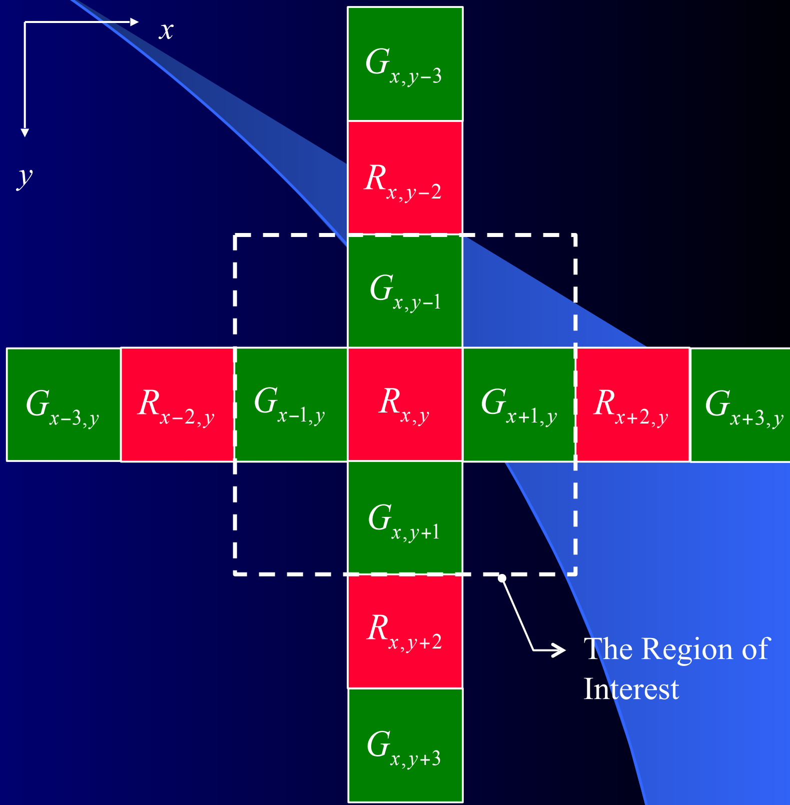
$$K_R(x,y+1) = G_{x,y+1} - R_{x,y+1} \approx G_{x,y+1} - \left(R_{x,y} + R_{x,y+2}\right)/2$$

$$w_{x-1,y} = \left(1 + \left(\frac{G_{x+1,y} - G_{x-1,y}}{2}\right)^2 + \left(\frac{G_{x+1,y} - G_{x-3,y}}{4}\right)^2\right)^{-\frac{1}{2}}$$

$$w_{x+1,y} = \left(1 + \left(\frac{G_{x-1,y} - G_{x+1,y}}{2}\right)^2 + \left(\frac{G_{x-1,y} - G_{x+3,y}}{4}\right)^2\right)^{-\frac{1}{2}}$$

$$w_{x,y-1} = \left(1 + \left(\frac{G_{x,y+1} - G_{x,y-1}}{2}\right)^2 + \left(\frac{G_{x,y+1} - G_{x,y-3}}{4}\right)^2\right)^{-\frac{1}{2}}$$

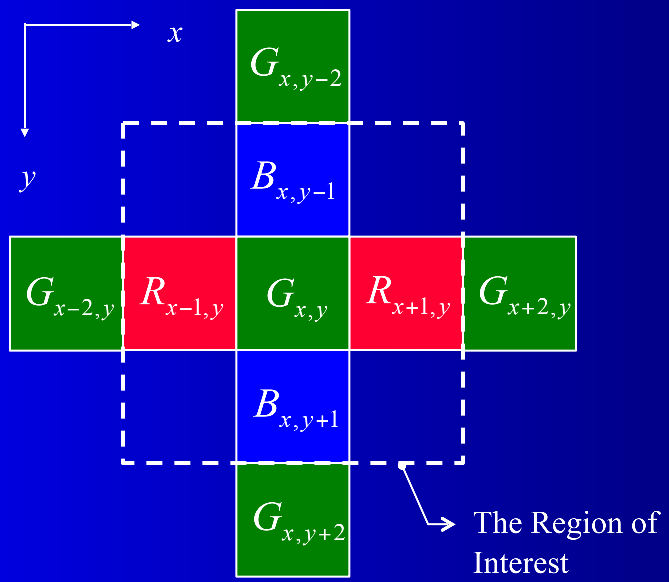
$$w_{x,y+1} = \left(1 + \left(\frac{G_{x,y-1} - G_{x,y+1}}{2}\right)^2 + \left(\frac{G_{x,y-1} - G_{x,y+3}}{4}\right)^2\right)^{-\frac{1}{2}}$$

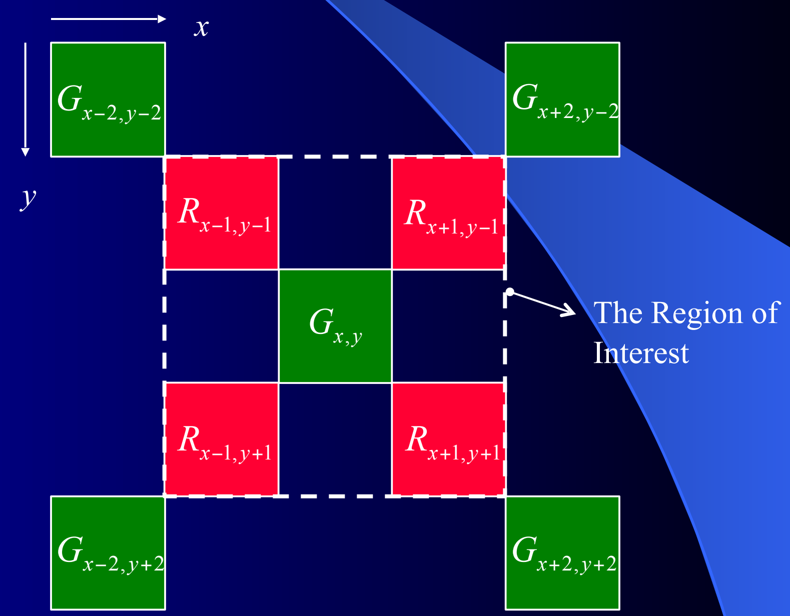


$$K_R(x,y) = \frac{K_R(x-1,y)\times w_{x-1,y} + K_R(x+1,y)\times w_{x+1,y} + K_R(x,y-1)\times w_{x,y-1} + K_R(x,y+1)\times w_{x,y+1}}{w_{x-1,y} + w_{x+1,y} + w_{x,y-1} + w_{x,y+1}}$$

$$G_{x,y} = K_R(x,y) + R_{x,y}$$

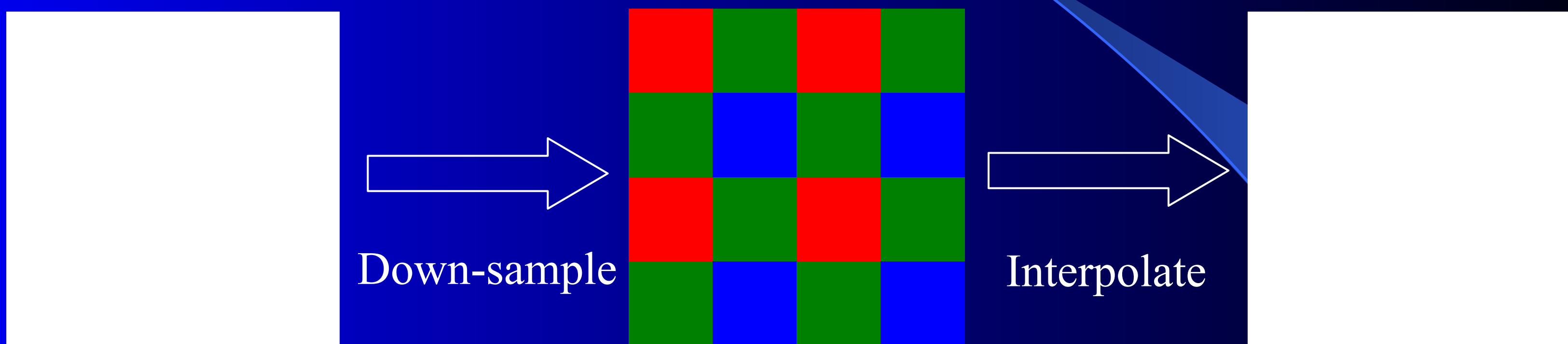
Interpolation of Red and Blue Color Components





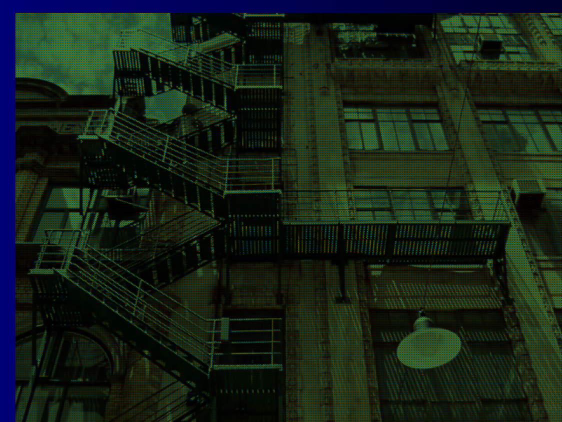
Experimental Results

Simulation of Color Interpolation



Scene Raw data Result

The original image.



The result of the down-sampled image.

Evaluation

- Visualization results
- Peak signal-to-noise ratio (PSNR)

$$PSNR = 10 \times \log_{10}\left(\frac{255^2}{MSE}\right)$$

$$MSE = \frac{1}{XY}\sum_{l=0}^{X-1}\sum_{m=0}^{Y-1}\left(o(l,m) - i(l,m)\right)^2$$

- Processing time

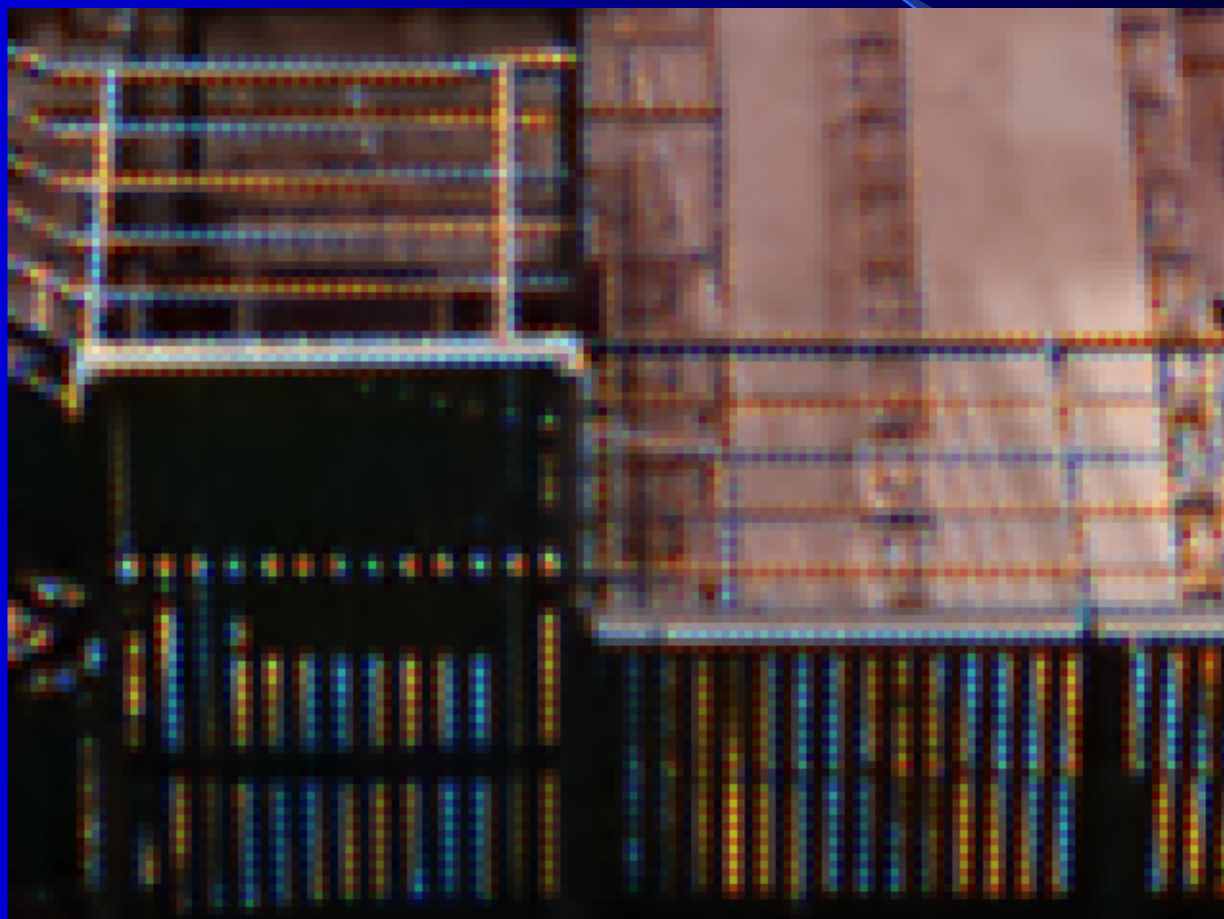
Environment

- Machine:
  - Pentium III 650Mhz Notebook
  - 256MB SDRAM
- OS: MS Windows 2000 Professional
- Image:
  - 640 x 480 pixels
  - 24 bit Bitmap
  - 100 images

Apartment (Original)

The original image.

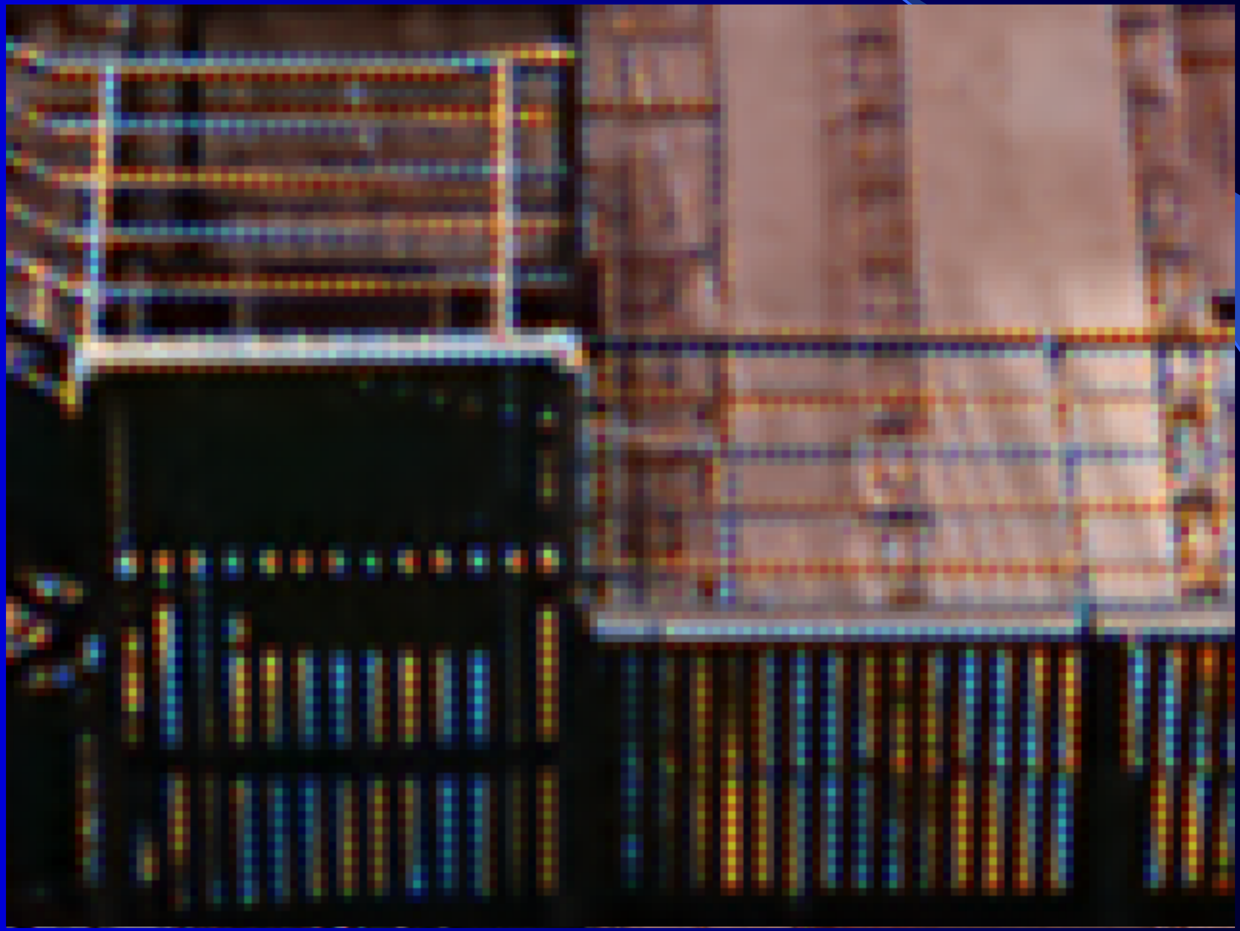
Apartment
(Bilinear Interpolation)



The result with bilinear interpolation, where PSNR is 25.21 dB

The scale-up image

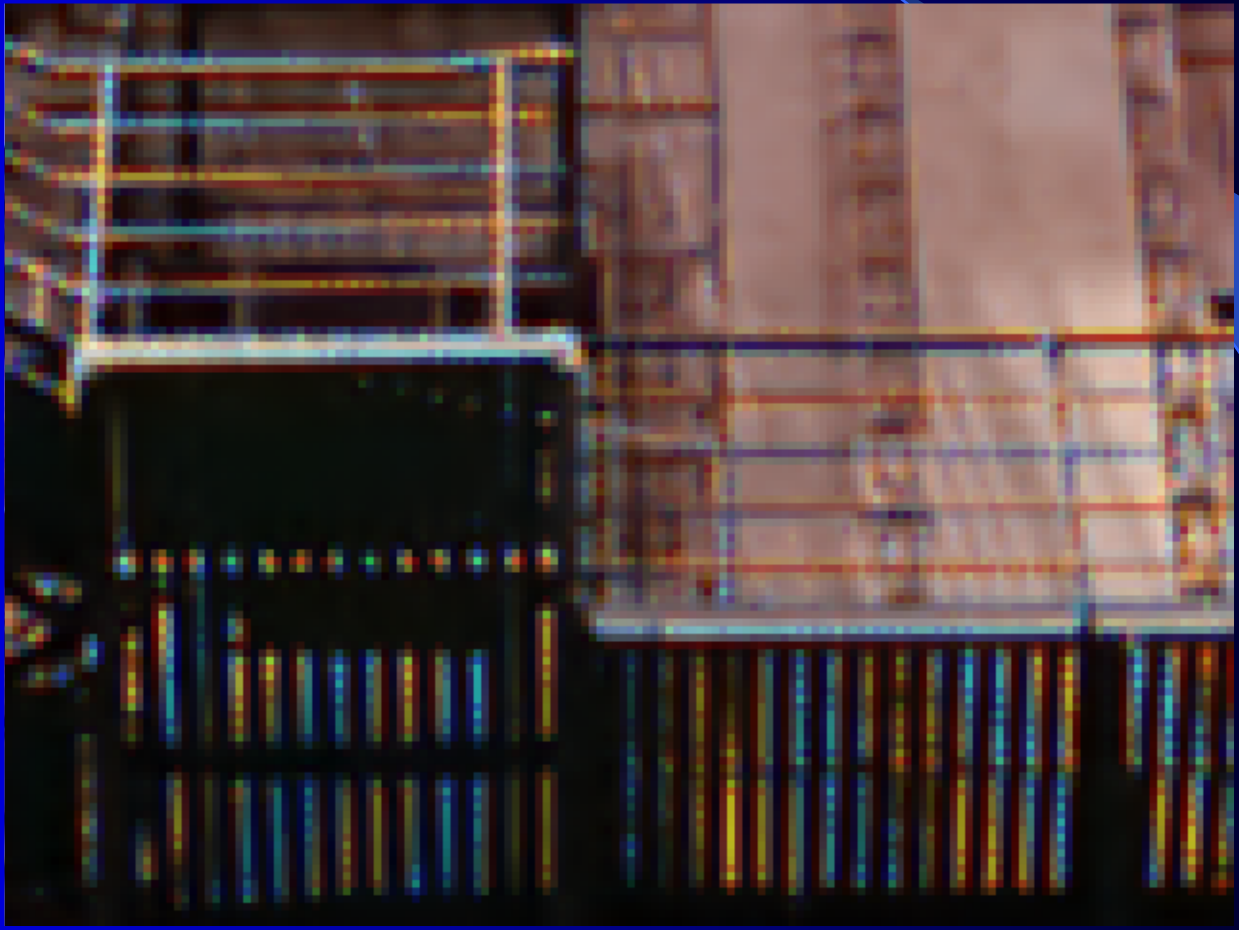
Apartment
(Cubic Convolution Interpolation)



The result with cubic convolution interpolation, where PSNR is 25.4 dB

The scale-up image

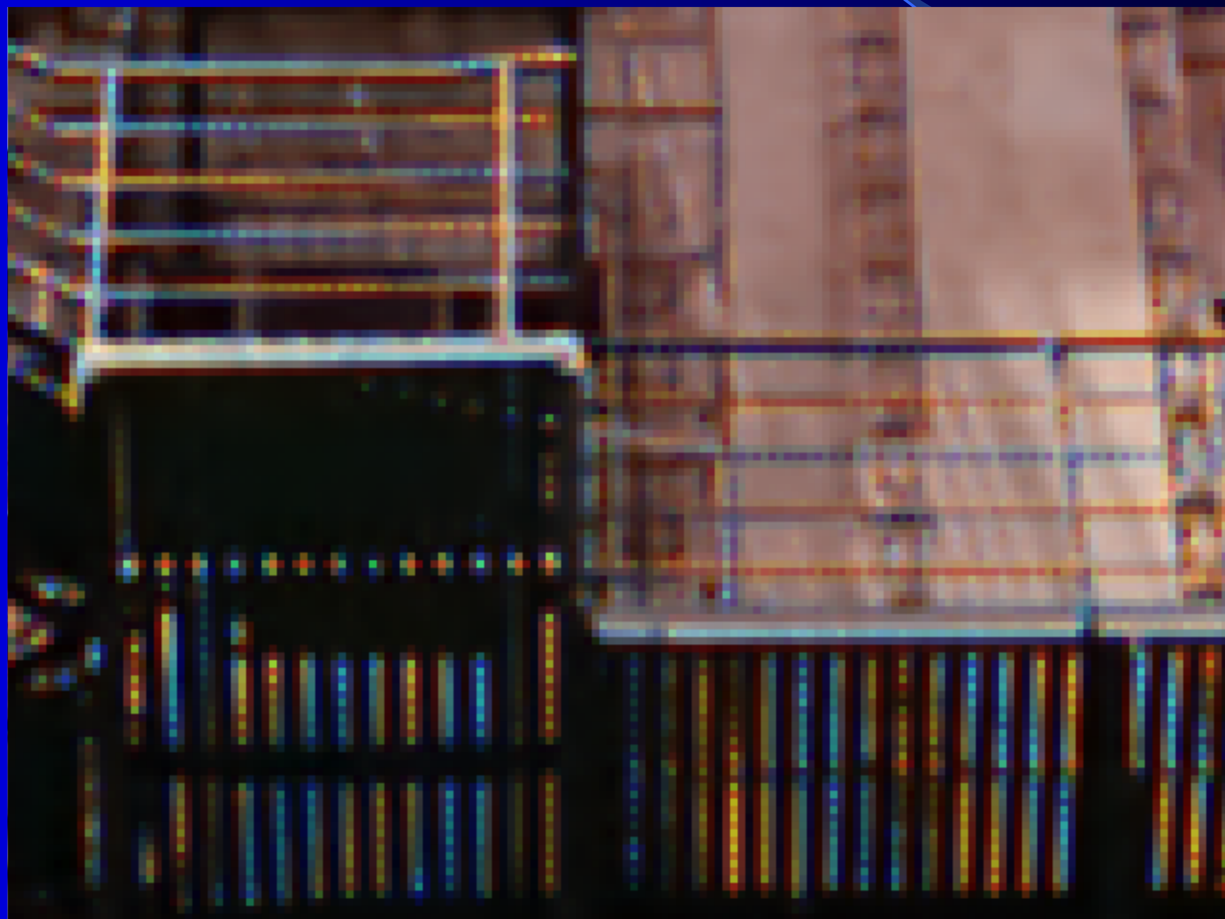
Apartment
(Edge-Filtered Interpolation)



The result with edge-filters, where PSNR is 25.46 dB

The scaled-up image

Apartment (Weighting-Based Interpolation)



The scale-up image

The result with weighting-based interpolation, where PSNR is 25.54 dB

Apartment
(Edge-Filtered Color-Difference Interpolation)

The result with edge-filtered color-difference interpolation, where PSNR is 34.52 dB

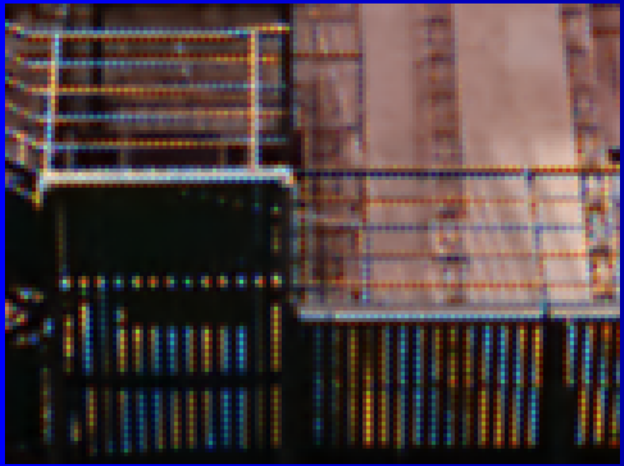
The scale-up image

Apartment
(Weighting Color-Difference Interpolation)

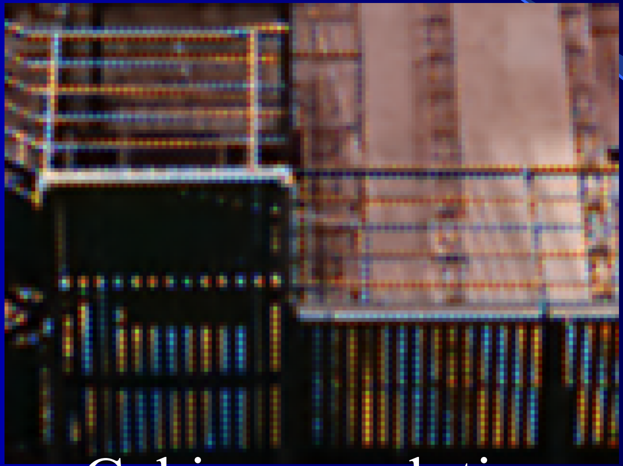
The result with weighting color-difference interpolation, where PSNR is 35.72 dB

The scale-up image

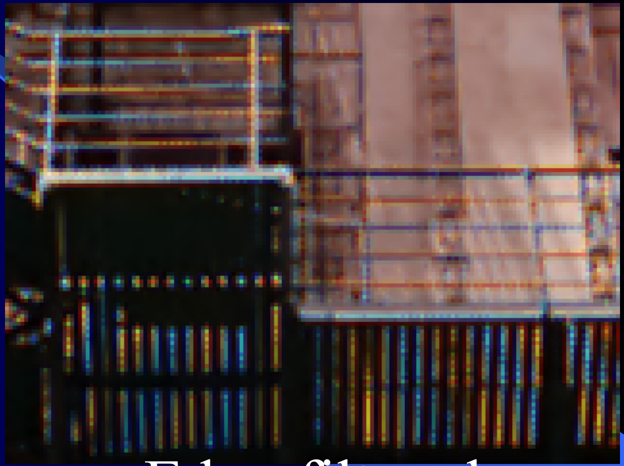
Apartment (Comparison)



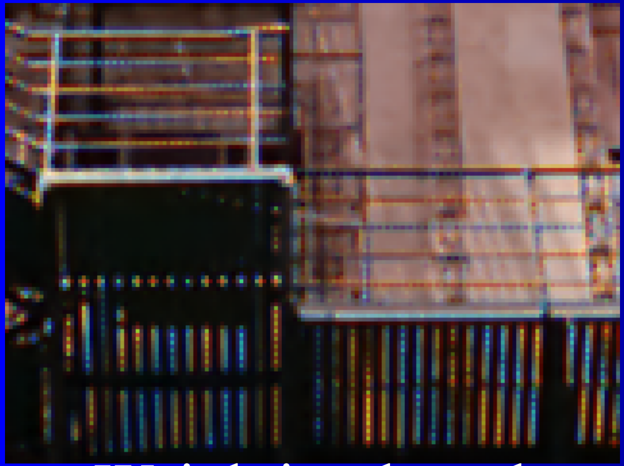
Bilinear



Cubic convolution

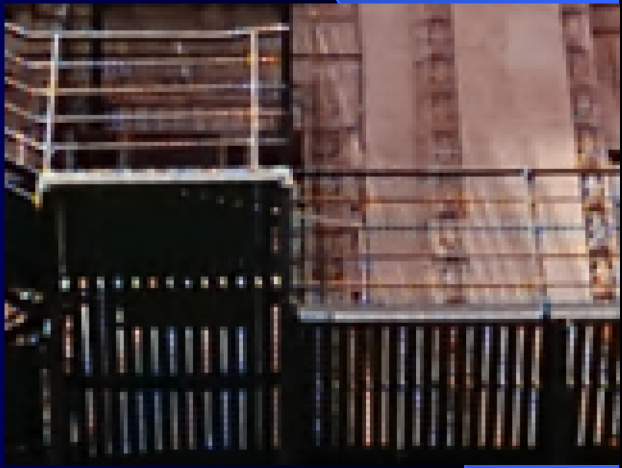


Edge-filtered



Weighting-based

Edge-filtered color-difference



Weighting color-difference

PSNR Results

Image No.	Nearest Neighbor	Bilinear	Cubic B-spline	Cubic Convolution	Edge-Filtered	Weighting-Based	Edge-filtered Color-Difference	Weighting Color-Difference	Simplified Weighting Color-Difference
001 ~ 090	90	290	193	414	402	508	658	791	703
091 ~ 100	10	35	24	38	51	52	72	83	85
001 ~ 100	100	325	217	452	453	560	730	874	788

Processing Time Results

Image No.	Nearest Neighbor	Bilinear	Cubic B-spline	Cubic Convolution	Edge-Filtered	Weighting-Based	Edge-Filtered Color-Difference	Weighting Color-Difference	Simplified Weighting Color-Difference
001	0.050	0.090	0.210	0.210	0.200	0.701	0.250	[illegible]	0.531
002	0.050	0.080	0.210	0.210	0.210	0.681	0.250	0.791	0.581
003	0.050	0.090	0.210	0.210	0.200	0.691	0.240	[illegible]	0.591
004	0.050	0.080	0.210	0.200	0.210	0.781	0.250	[illegible]	0.590
005	0.050	0.080	0.210	0.210	0.210	0.701	0.250	[illegible]	0.601
006	0.050	0.080	0.210	0.200	0.210	0.701	0.250	[illegible]	0.681
007	0.050	0.090	0.210	0.210	0.200	0.741	0.250	0.871	0.560
008	0.050	0.090	0.210	0.210	0.210	0.701	0.250	0.891	0.690
009	0.050	0.080	0.210	0.210	0.200	0.701	0.250	[illegible]	0.521
010	0.050	0.080	0.210	0.210	0.210	0.791	0.250	0.891	0.581
011	0.050	0.080	0.210	0.201	0.200	0.471	0.250	[illegible]	0.581
012	0.050	0.090	0.210	0.210	0.200	0.591	0.250	0.691	0.581
013	0.050	0.090	0.210	0.200	0.200	0.461	0.250	[illegible]	0.581
014	0.050	0.080	0.210	0.200	0.200	0.690	0.250	0.721	0.581
015	0.050	0.080	0.210	0.200	0.210	0.631	0.250	0.761	0.551
016	0.050	0.080	0.210	0.210	0.200	0.691	0.250	[illegible]	0.521
017	0.050	0.090	0.210	0.210	0.200	0.691	0.250	0.701	0.590
018	0.050	0.080	0.210	0.210	0.200	0.701	0.240	0.801	0.591
019	0.050	0.080	0.210	0.200	0.200	0.401	0.240	0.801	0.591
020	0.050	0.080	0.210	0.200	0.210	0.701	0.250	0.812	0.591

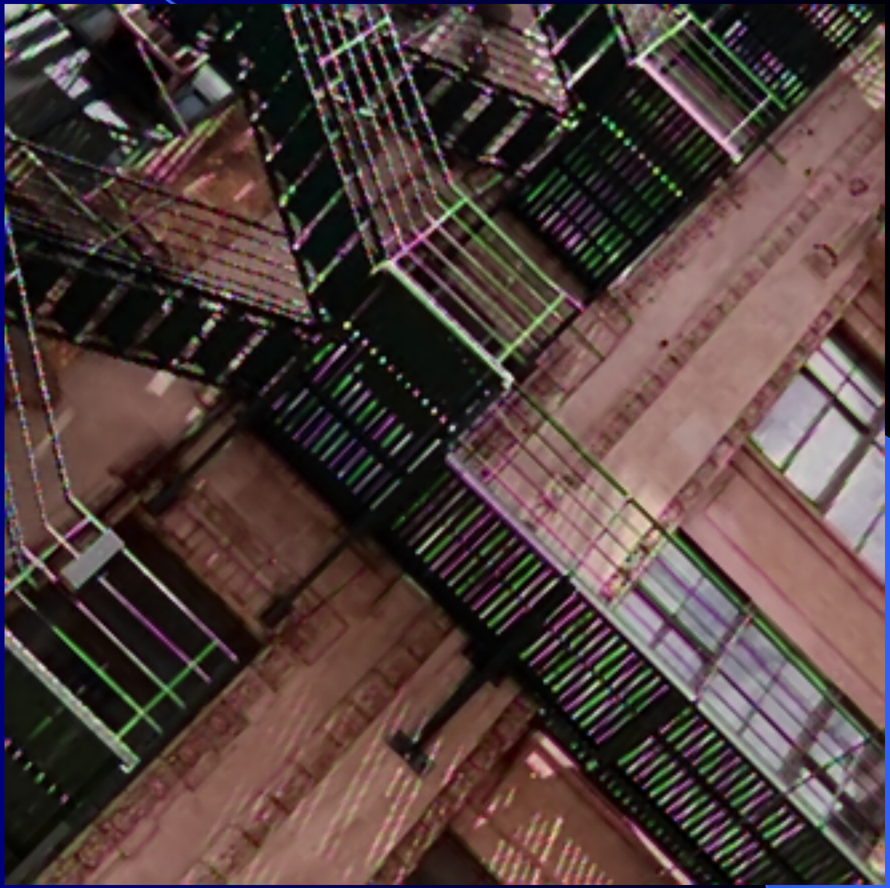
Conclusion and Future Work

Conclusion

- Traditional interpolation methods
  - Advantage: simplicity.
  - Disadvantage: blurred-edge and color-alias effects.
- Proposed composite interpolation scheme
  - Advantage: reducing blurred-edge and color-alias effects both.
  - Disadvantage: complex and slightly slow.

Unsolved Problem

The original image

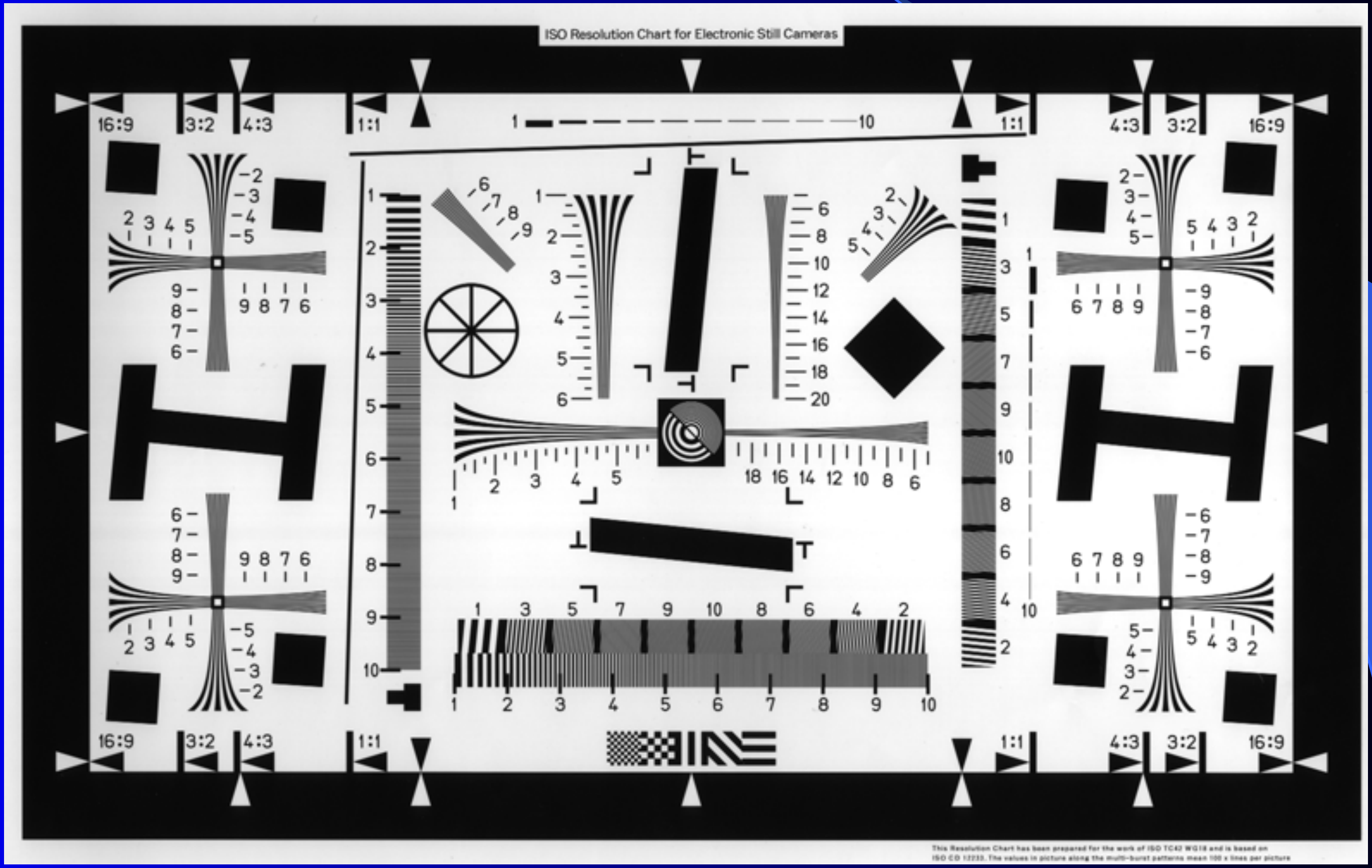


The result with the weighting color-difference interpolation, where PSNR is 28.39 dB

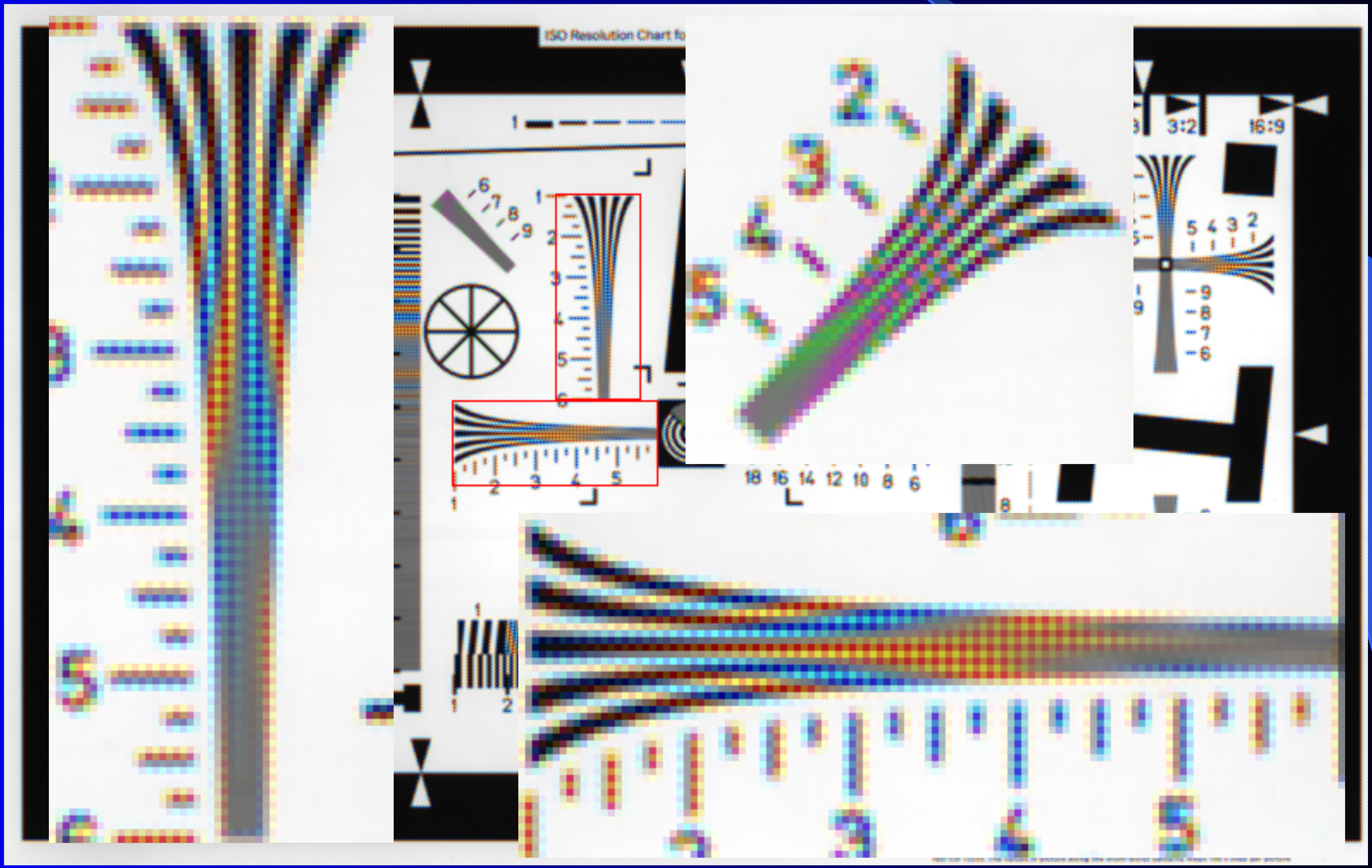
Future Work

- Keep improving our proposed interpolation method.
- Speeding up our algorithm.
- Extend our proposed scheme to suit other types of the CFA such as Fujifilm Super CCD.

ISO Resolution Chart (Original)

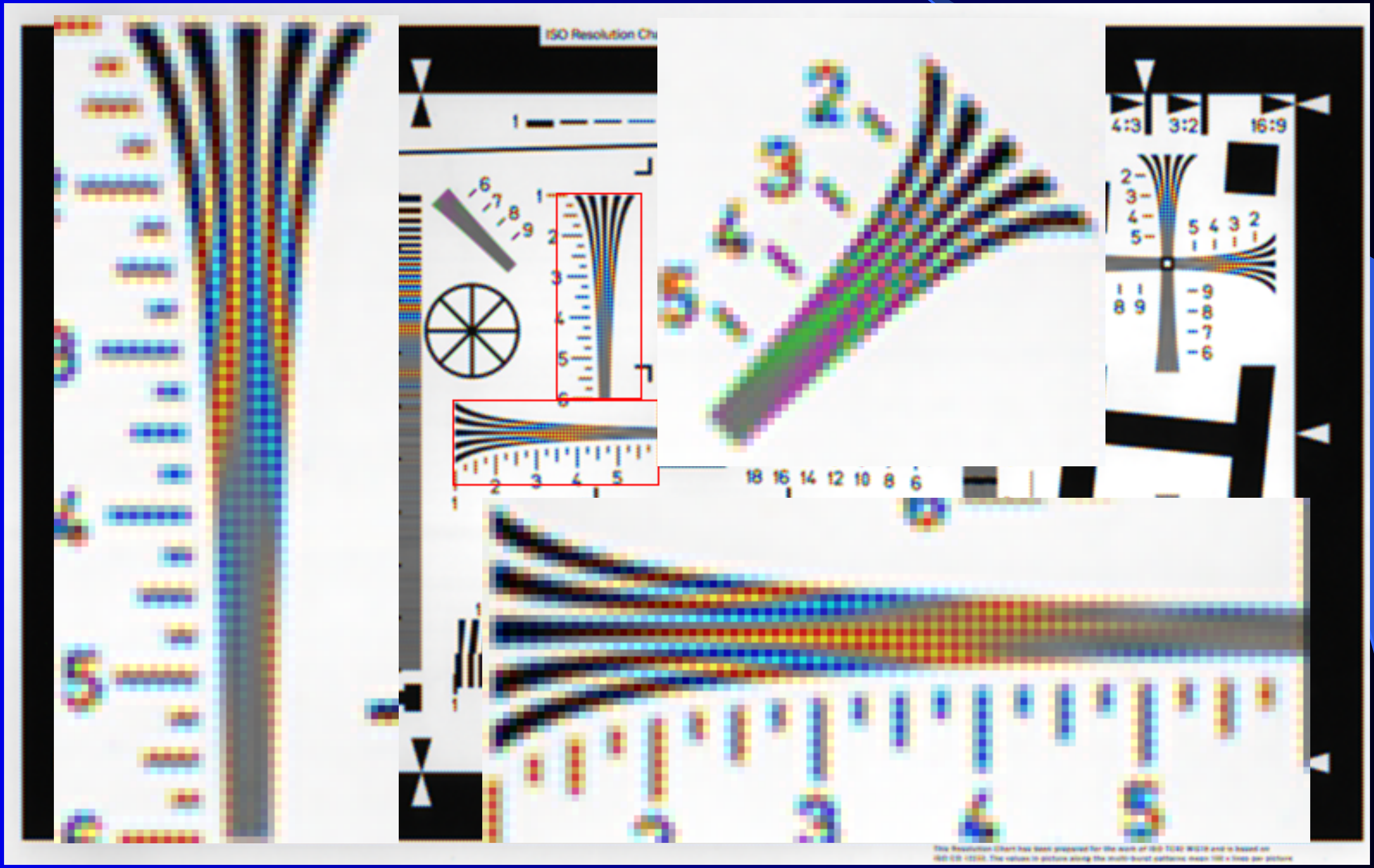


ISO Resolution Chart (Bilinear Interpolation)



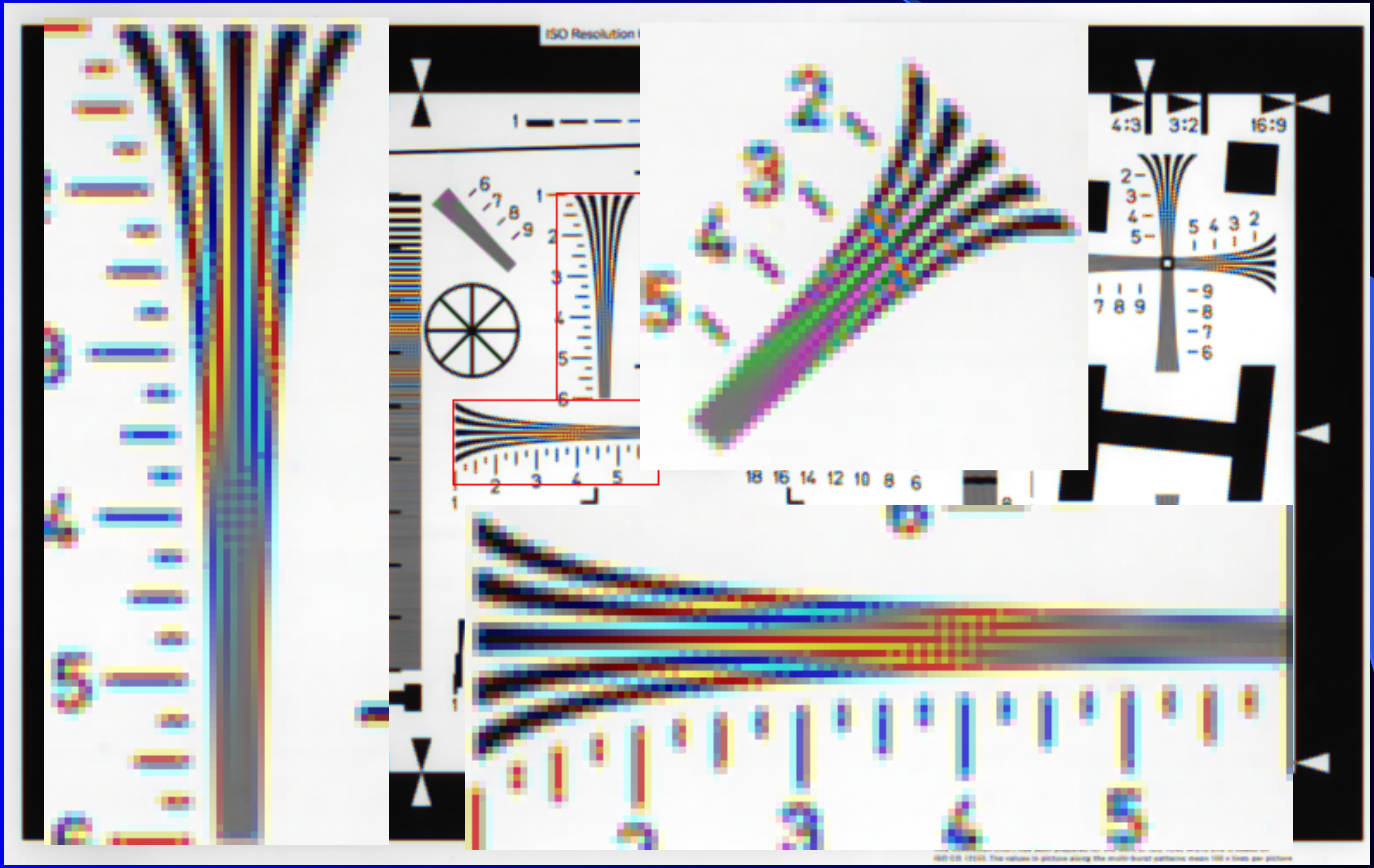
PSNR = 22.95 dB

ISO Resolution Chart
(Cubic Convolution Interpolation)



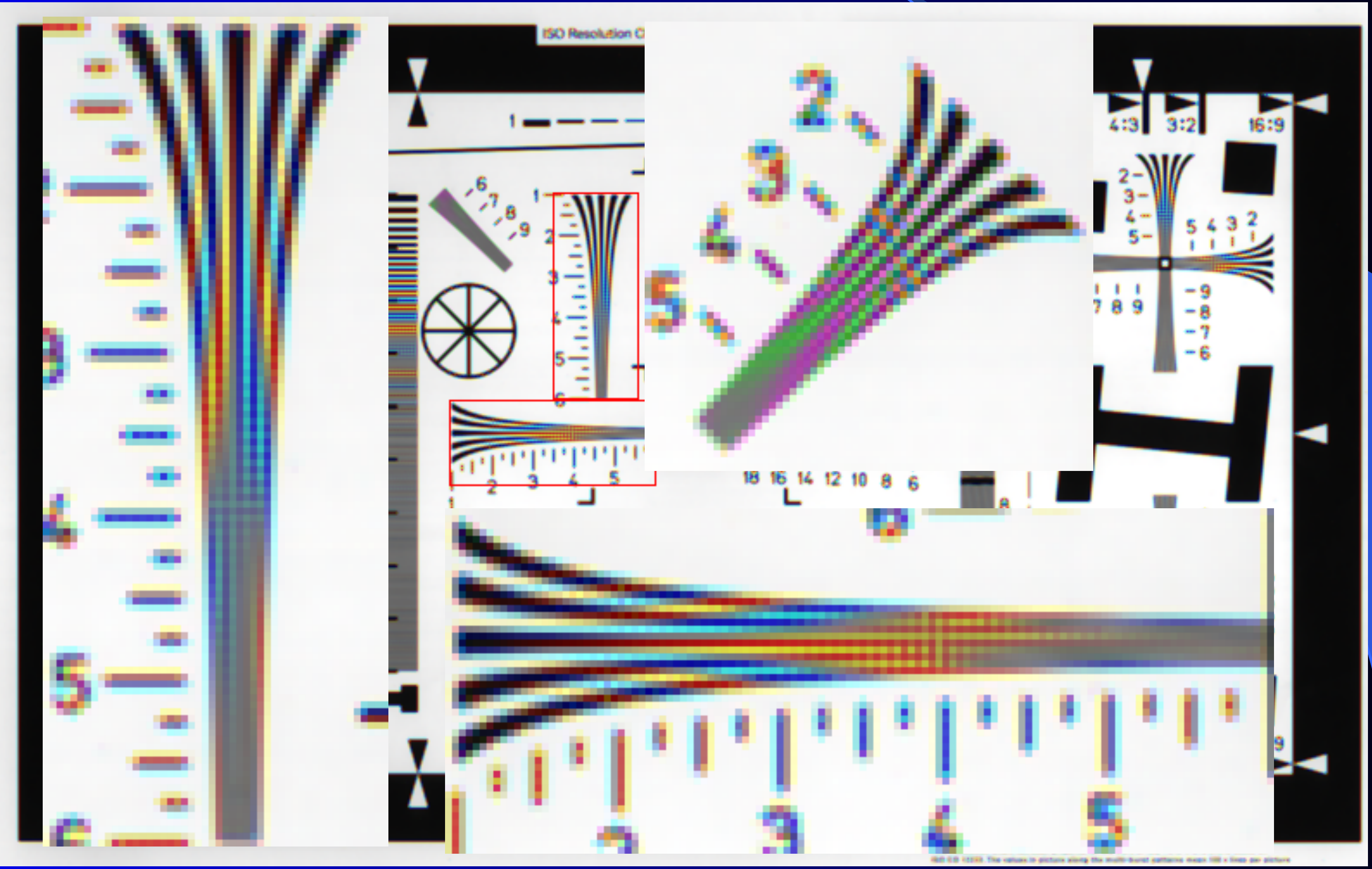
PSNR = 23.03 dB

ISO Resolution Chart (Edge-Filtered Interpolation)



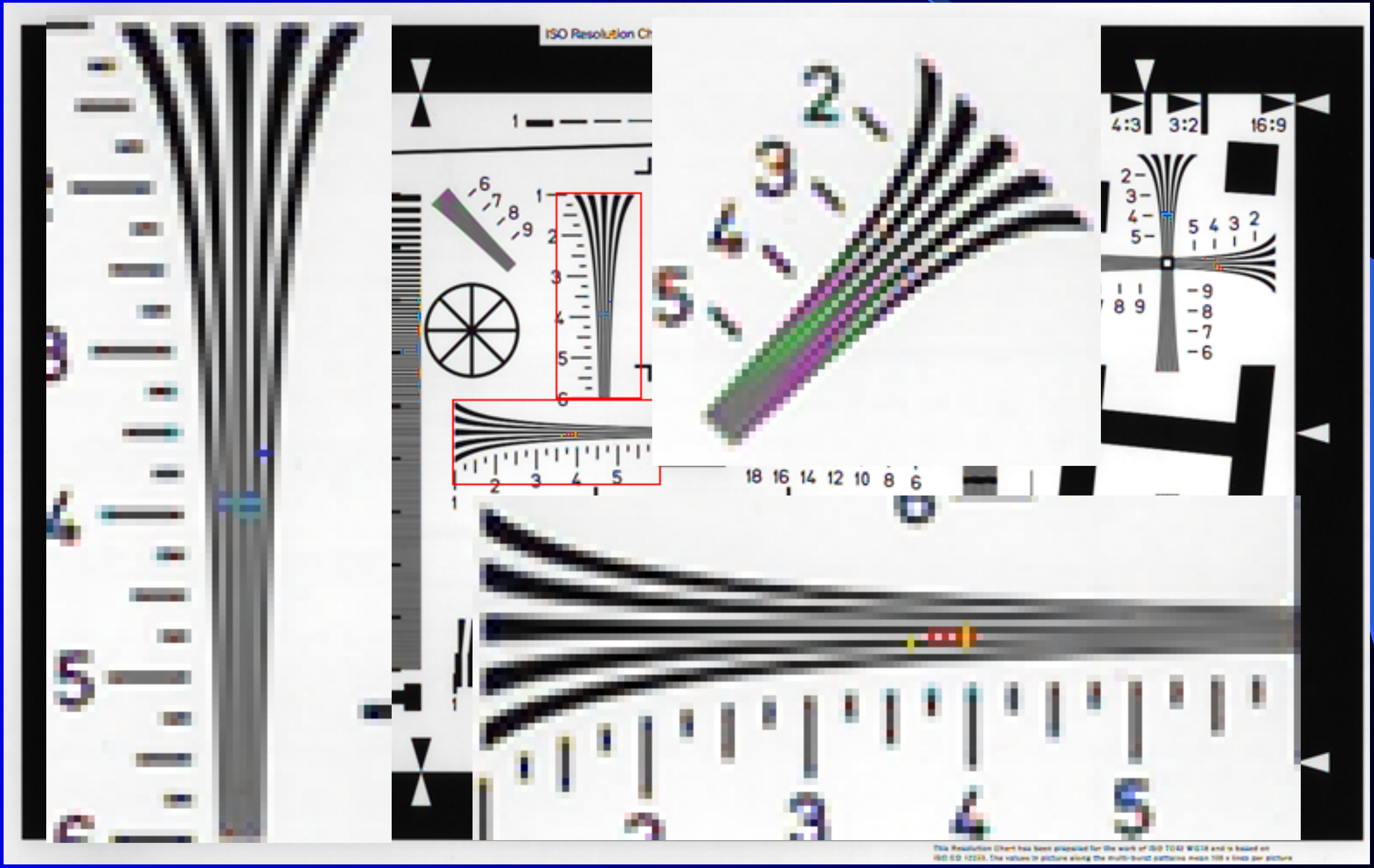
PSNR = 23.59 dB

ISO Resolution Chart (Weighting-Based Interpolation)



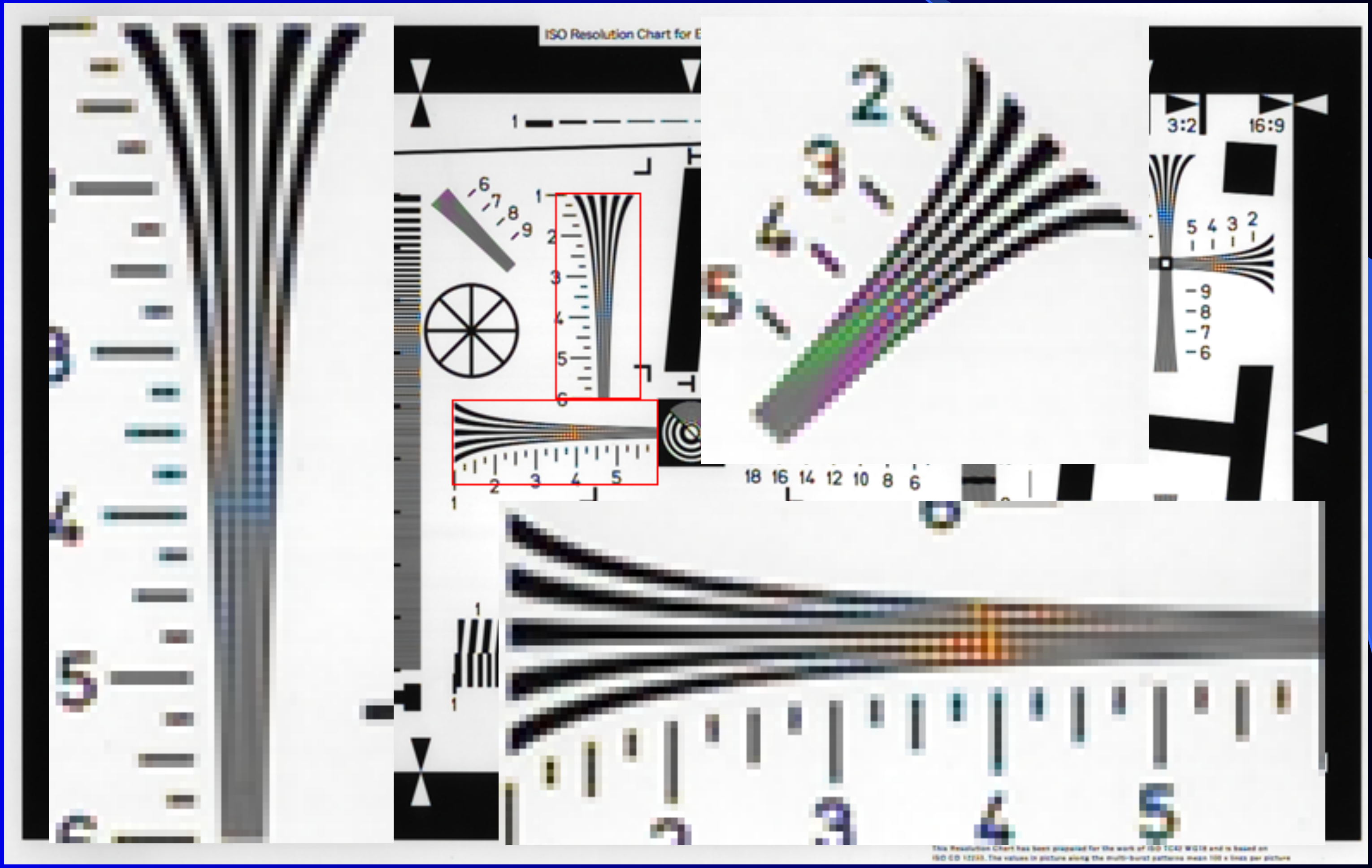
PSNR = 23.93 dB

ISO Resolution Chart
(Edge-Filtered Color-Difference Interpolation)



PSNR = 32.86 dB

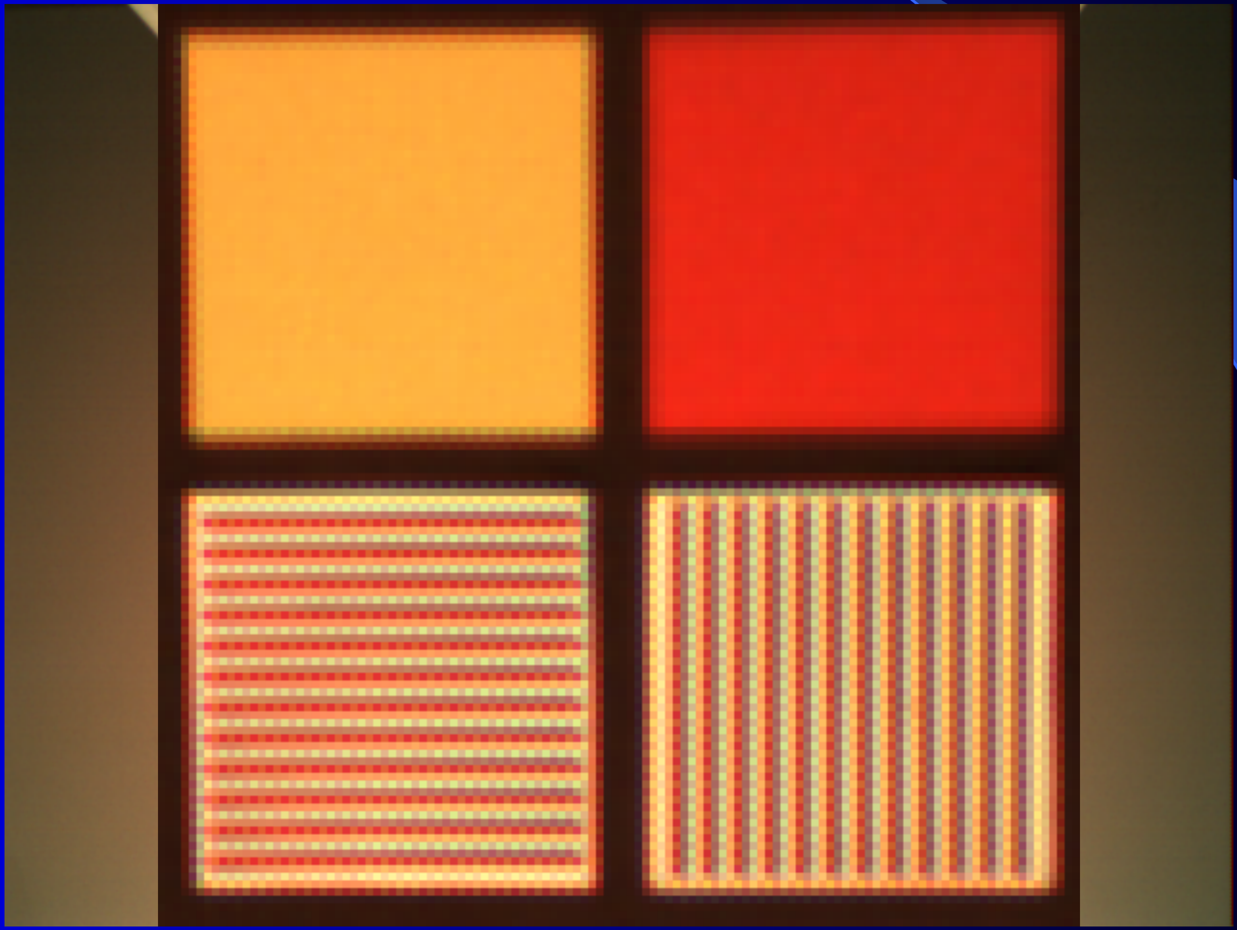
ISO Resolution Chart
(Weighting Color-Difference Interpolation)



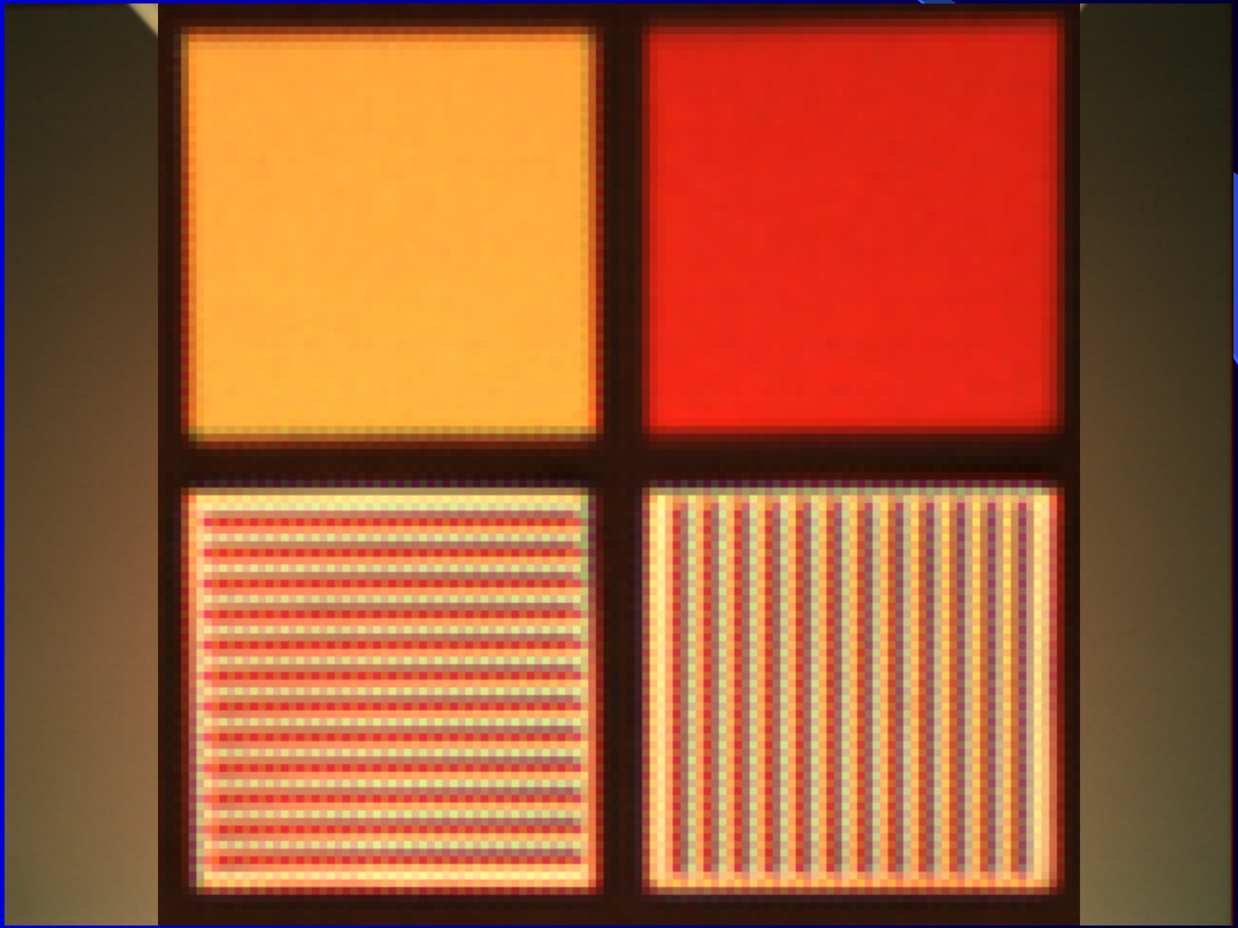
PSNR = 33.92 dB

Color Checker (Raw Data)

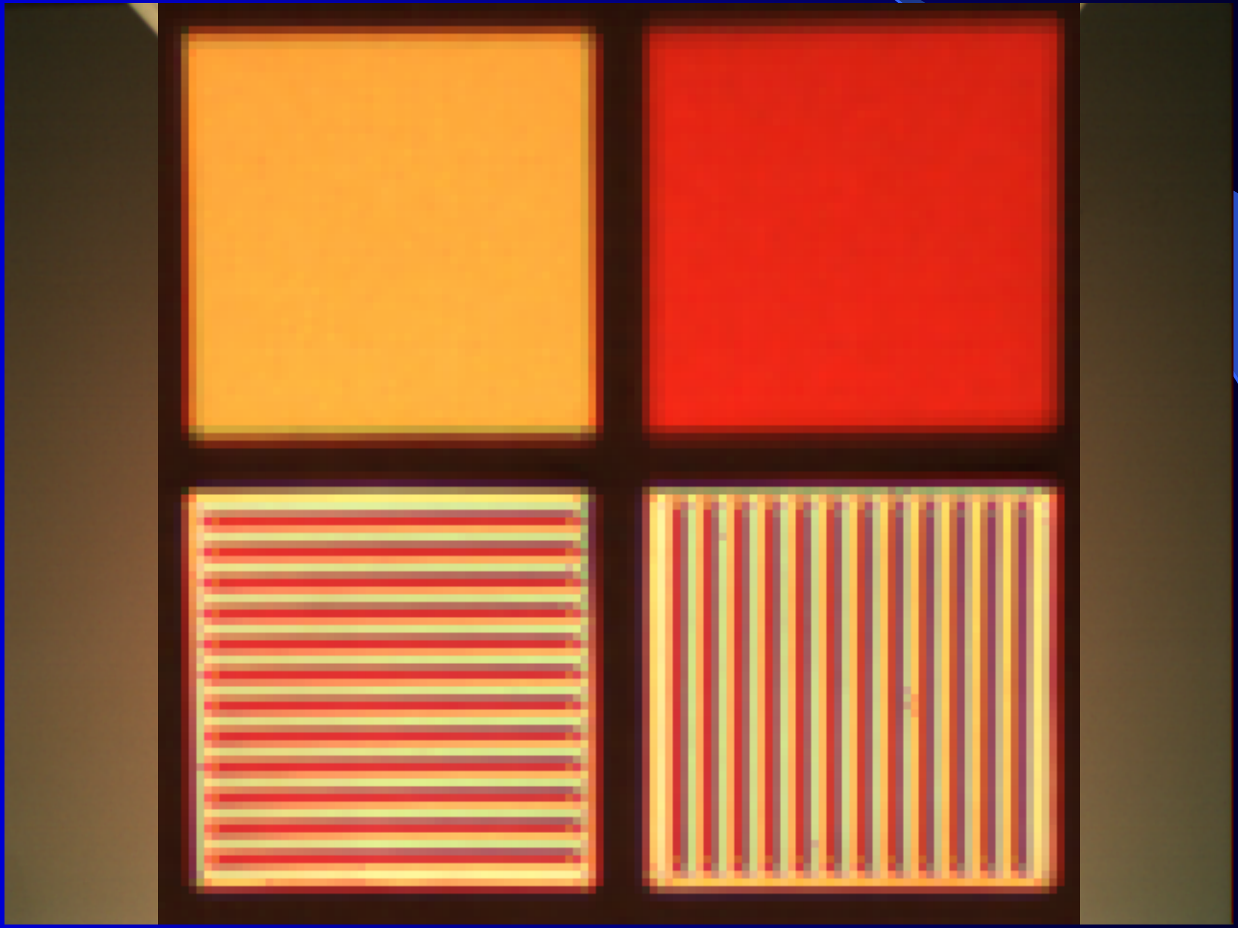
Color Checker
(Bilinear Interpolation)



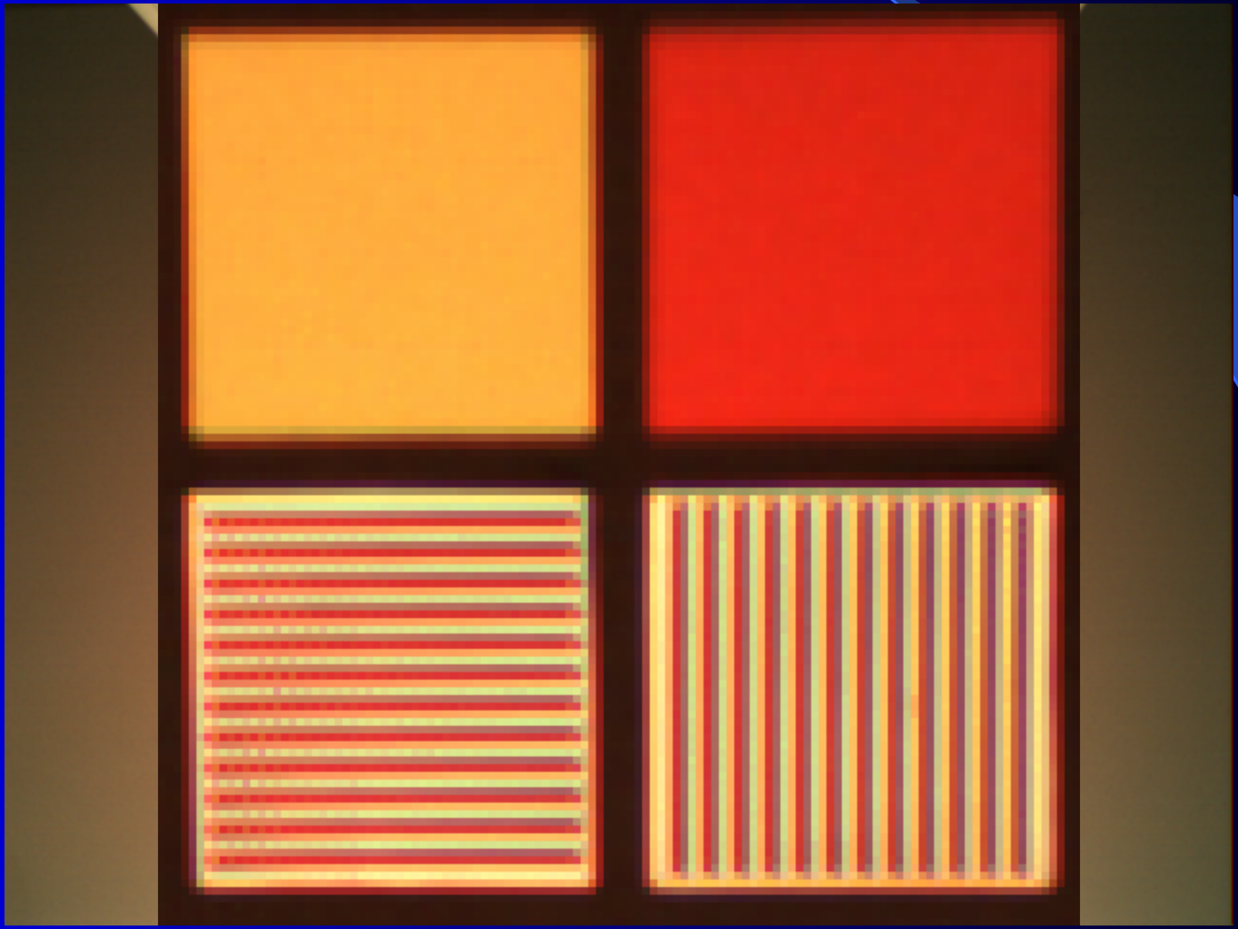
Color Checker
(Cubic Convolution Interpolation)



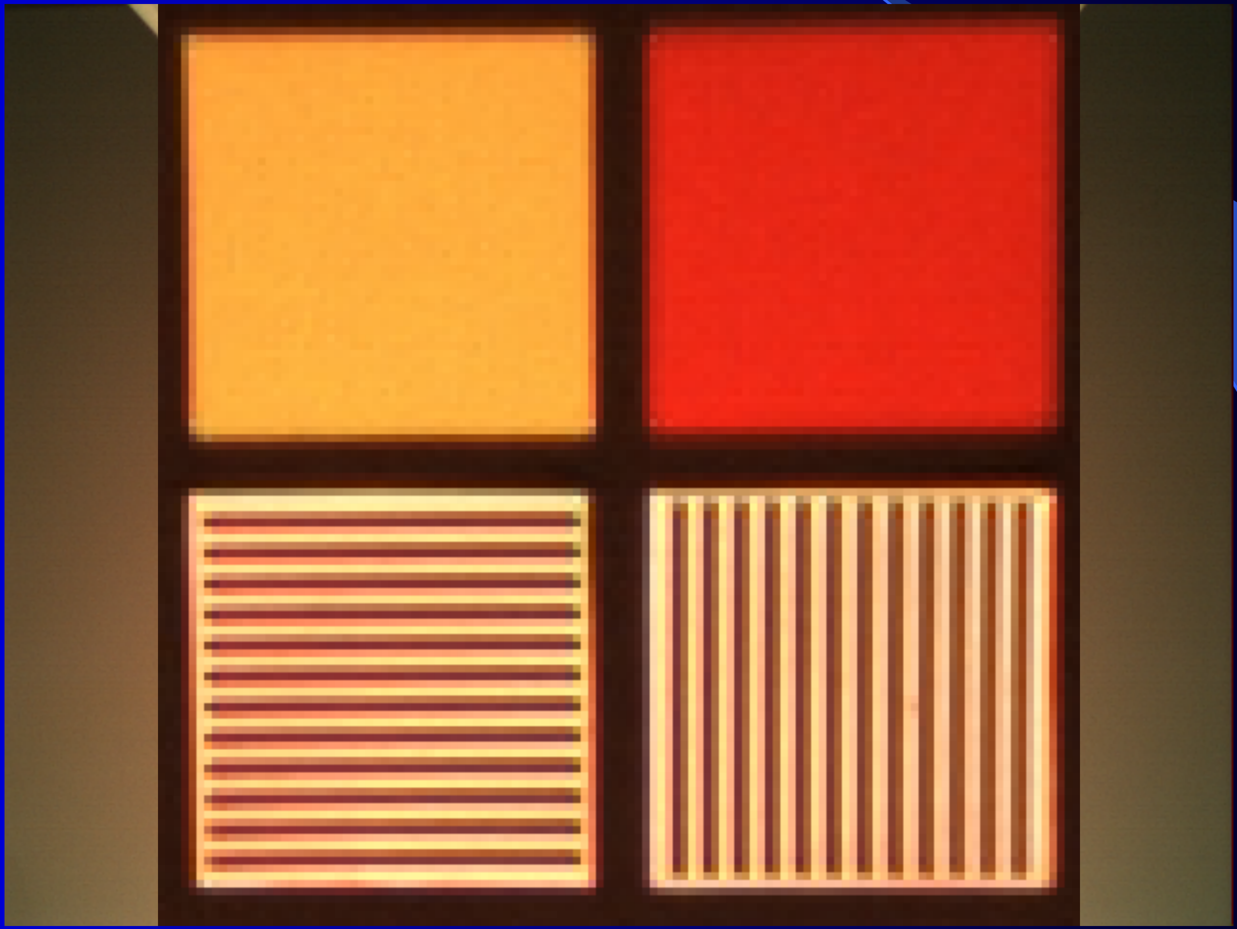
Color Checker (Edge-Filtered Interpolation)



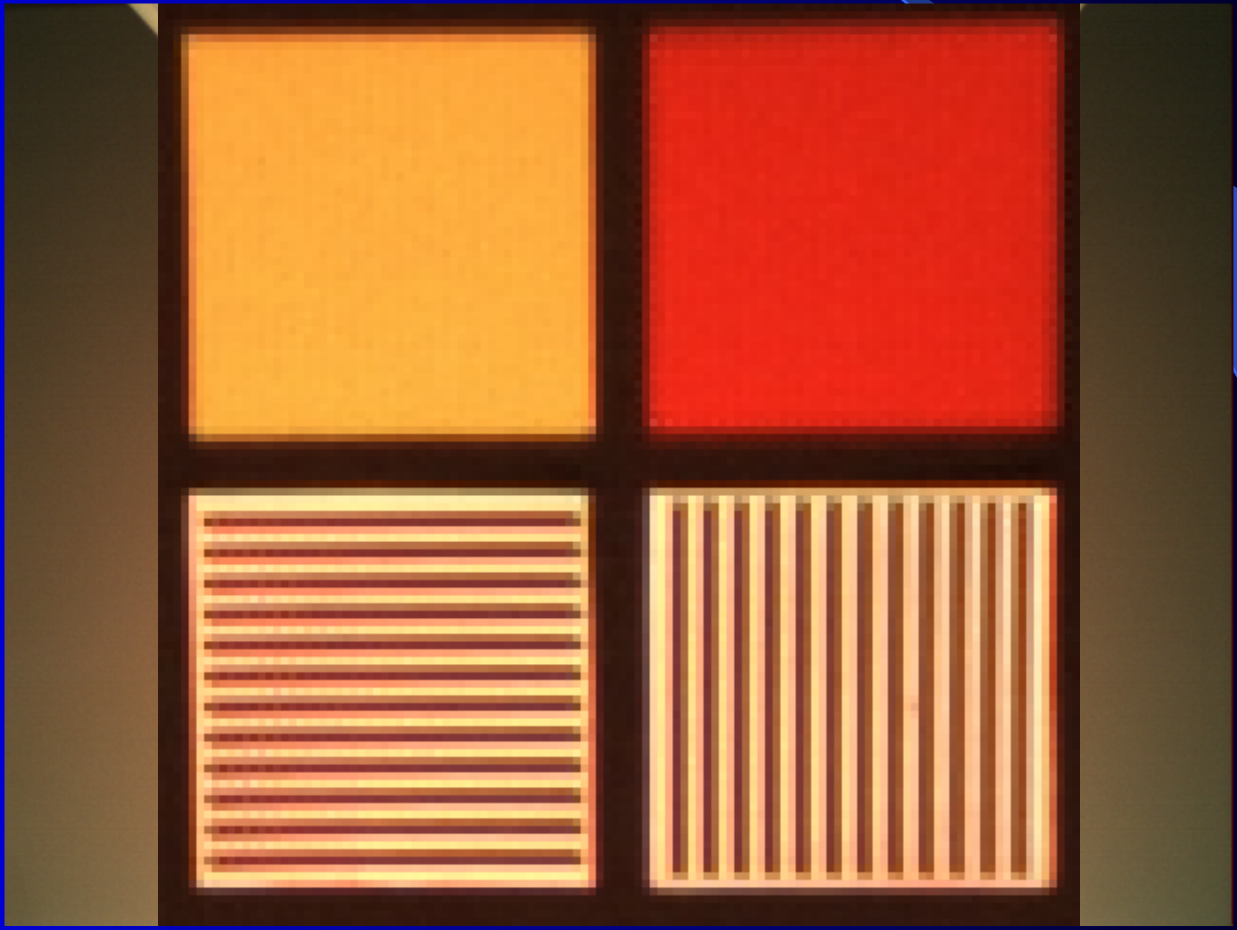
Color Checker
(Weighting-Based Interpolation)



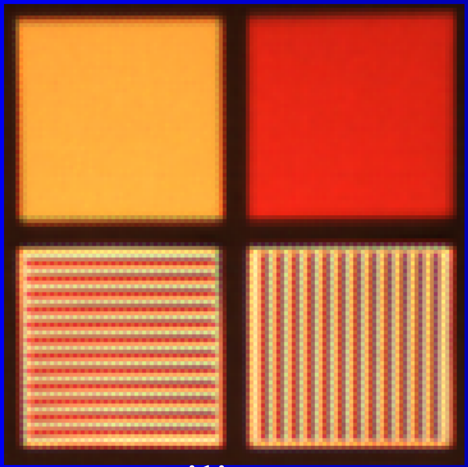
Color Checker
(Edge-Filtered Color-Difference Interpolation)

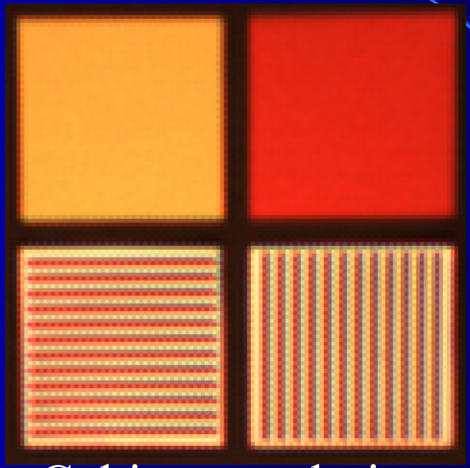


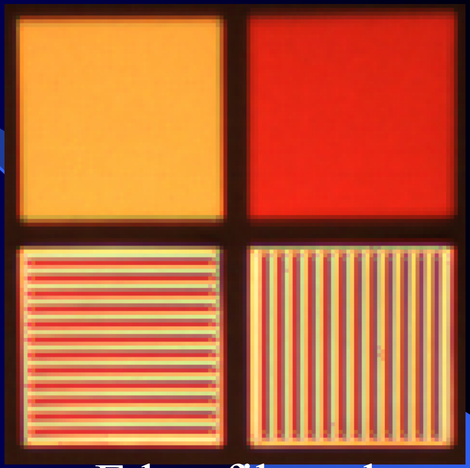
Color Checker (Weighting Color-Difference Interpolation)

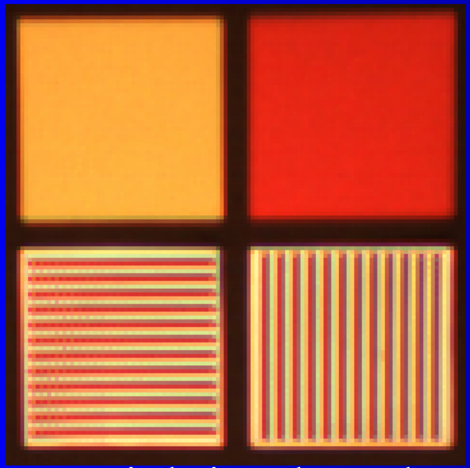


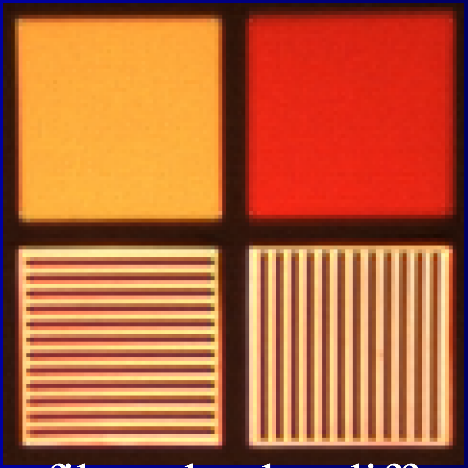
Color Checker (Comparison)

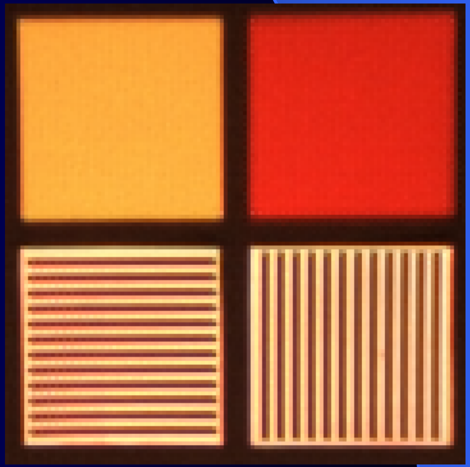

Bilinear


Cubic convolution


Edge-filtered


Weighting-based


Edge-filtered color-difference


Weighting color-difference