

# Can We Get More Than One Pixel Resolution Out of One Pixel?

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# Greetings from HKUST MTrec



# My background

1. B.A. Sc. from Toronto (86), M.A./PhD from Princeton (88/91)
2. Professor, HKUST.
3. Director, Multimedia Technology Center, HKUST.
4. Associate Editor of 6 journals: IEEE TCSVT, IEEE TIP, IEEE TCAS-1, JSPS, JMM, JFI
5. Chairman of IEEE CAS MSATC, Vice Chairman of IEEE SP MMSP TC, member of IEEE CAS VSPC/DSP TC, IEEE SP IVMSP TC, IEEE ComSoC MMTC
6. Steering Committee of IEEE TMM and ICME
7. General Chair, PCM 2007/PV 2010/ICME 2010.
8. Host MPEG in 1/2005.
9. IEEE Senior member.

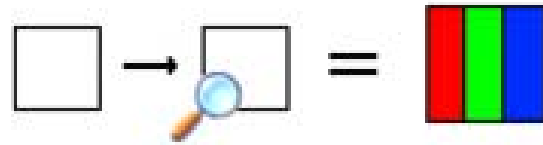
# Outline

- **Background on Subpixel Rendering**
- Application of Subpixel Rendering
  - Subpixel Rendering for Font Display
  - Two-Dimensional Subpixel Geometries
  - Subpixel Rendering for Downsampling
- Optimal subpixel rendering (MinMax)
- Conclusion

# Why more than 1 pixel out of 1 pixel?

- In digital camera or mobile phone, images can be captured with easily 5 or 10 mega-pixels
- The images are to be displayed on a small display with less than 1 mega-pixel.
- Image resolution is not lacking.
- Display resolution IS lacking.
- To solve the problem, we ask – can we get more than 1 pixel resolution out of 1 pixel?

# Why possible? Subpixel!



- pixel = non-separable square capable of displaying 24 bit color? When magnified, a pixel has R, G, B subpixels
- A pixel appears as a single color to the human eye because of the blurring by the optics and spatial integration by nerve cells
- Viewed closely with a magnifying glass, a color LCD is actually composed of individual red, green, and blue
- If we control the subpixel values wisely, we can potentially get 3 times higher resolution.

# Potential of Subpixel Rendering

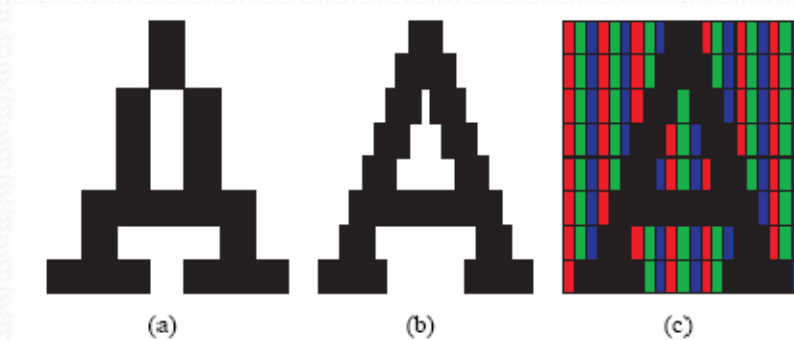


FIGURE: rendering of a character 'A': (a) pixel-based rendering (b) subpixel rendering (conceptual) result (c) subpixel rendering (actual color pattern)

## Potential VS Shortcoming

- Improve the effective resolutions of matrix displays
  - The number of subpixels is three times larger than pixels
  - Reduce staircase artifacts effectively
- Color fringing artifacts can be perceived
  - For some pixels, not all red, green, blue components are turned on

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# Apple II Display

About 20 years ago, the Apple II personal computer used subpixel rendering to display fonts effectively in its high resolution graphics display

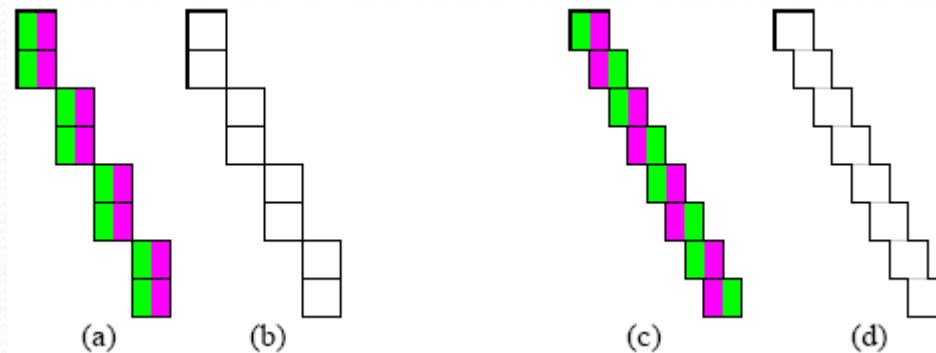


FIGURE: (a) whole-pixel (green-purple) rendering of a line on Apple II display (b) jagged line with whole pixel rendering (c) subpixel rendering of same line on Apple II display (d) smooth line with subpixel rendering

- A line rendered with whole pixel tends to be jagged
- Using subpixel locations or shifts, Apple II can display much smoother edges

# Microsoft

In 1998, Microsoft announced a subpixel based font display technology called 'ClearType' to improve the readability of text on regular LCD



FIGURE: (a) letter 'm' in italic (left) (b) whole-pixel rendered 'm' with jagged edges (middle) (c) subpixel rendered 'm' with smooth edges (right)

- ClearType works by accessing the **individual vertical color stripe elements** in every pixel
  - Features of text as small as a fraction of a pixel in width can be displayed
  - The extra resolution increases the sharpness of the tiny details in text display

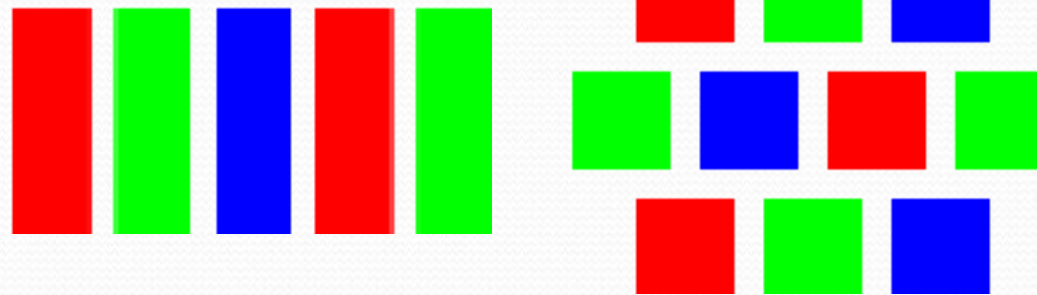
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# Introduction of 2-D Subpixel Geometries

The components of the pixels (red, green and blue) in an image sensor or display can be ordered in different patterns or pixel geometry

- subpixel components in vertical stripes In LCDs
  - display edges or rectangles
- subpixel components in delta (or triangular) patterns
  - display motion pictures



- Currently there are two companies working on displays with special dedicated subpixel rendering technologies
  - VP Dynamics and Clairvoyante

# VP Dynamics-VPX, VPW

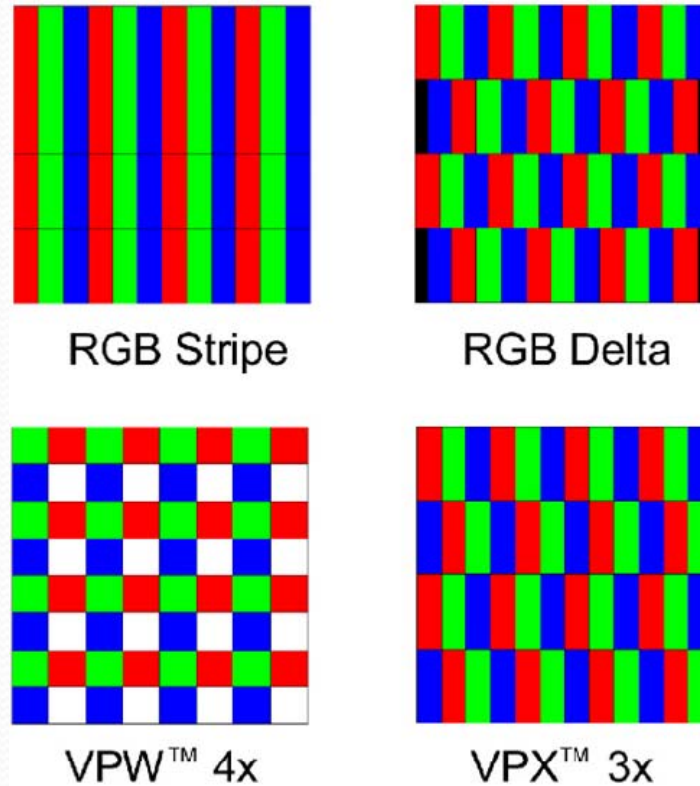


FIGURE: Comparison of pixel geometry of VPW (with 4 subpixel/pixel) and VPX (with 3 subpixel/pixel) with that of RGB strip and RGB delta

- VPX: shift every other line to the right by one subpixel location
- VPW: four square-shaped subpixels with RGBW

# Clairvoyante-PenTile RGBW

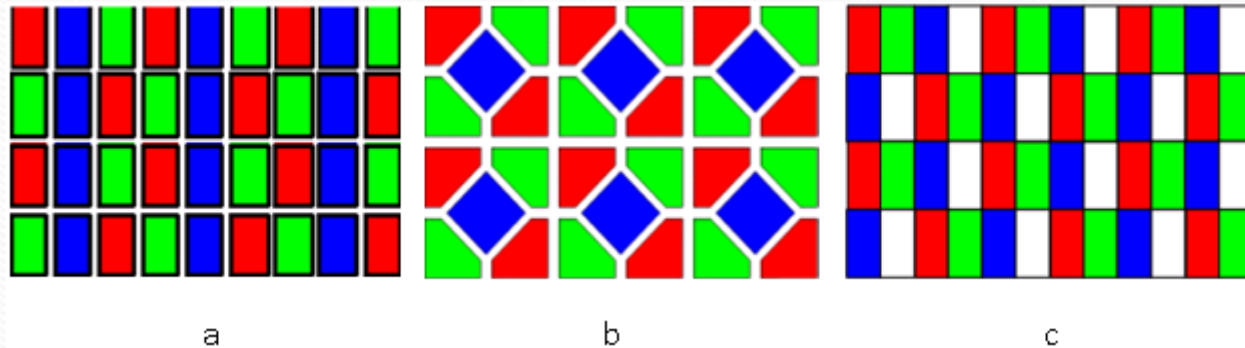
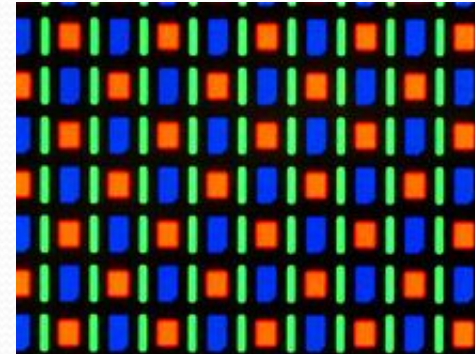


FIGURE: Pixel geometry of PenTile-TM 1A (a) PenTile-TM 2A (b) PenTile-RGBW (c)

- PenTile-TM 1A
  - rectilinear array of subpixels with a six pixel repeating group
- PenTile-TM 2A
  - five pixel array with only one large blue pixel
- PenTile-RGBW
  - one pixel contains two subpixels only
  - every two consecutive pixels have four subpixels RGBW
  - the second row is shifted to the right by 1 pixel location

# Some display products

- Samsung Active Matrix Organic LED (AMOLED)
  - RGBG color configuration
  - Higher resolution
  - Next generation display
  - HTC Nexus One, Samsung Galaxy S, etc.
- Sharp RGBY display
  - 4 color per pixel: R, G, B, Y(yellow)
  - More vivid yellow



# Outline

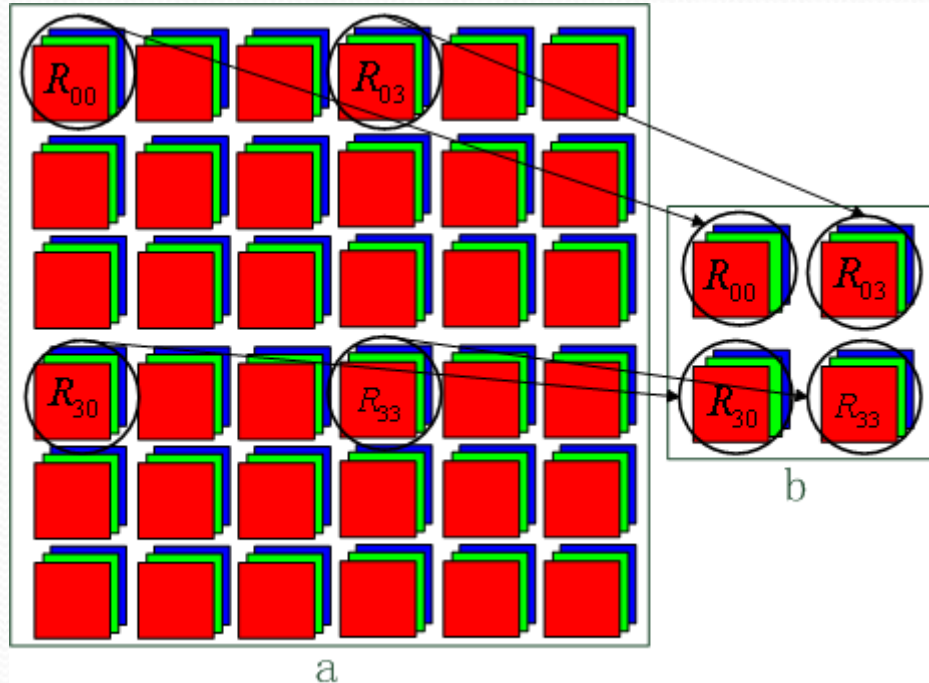
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- To display high resolution image or video on low resolution hand-held devices such as PMPs or PDAs, a **downsampling procedure** is required

Input:  $3M \times 3N$ , Display:  $M \times N$

# Method 1: Direct Pixel-based Downsampling (DPD)



- Pixel-based downsampling: select every third pixel horizontally and vertically
- Details are broken especially in staircase due to severe **aliasing artifacts**

## Method 2: Anti-Aliasing Filter + Pixel-based Downsampling (PDAF)

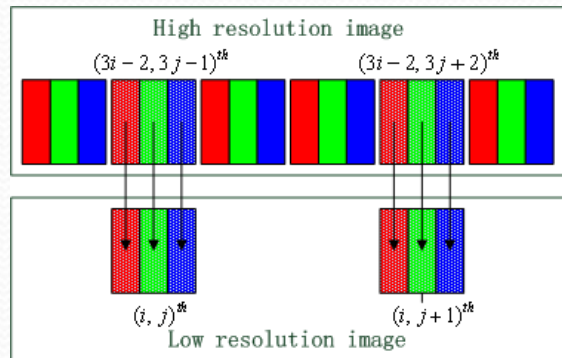
- Method 1 causes aliasing artifacts, so we usually apply an anti-aliasing filter as a prefilter to suppress aliasing artifacts



FIGURE: (a) pixel-based downsampling (left) (b) pixel-based downsampling with anti-aliasing filter (right)

- Method 2 causes unpleasant **blurring artifacts**
  - The cutoff frequency of the anti-aliasing filter is  $\pi/3$
  - Only the low frequency information of the original spectrum is retained

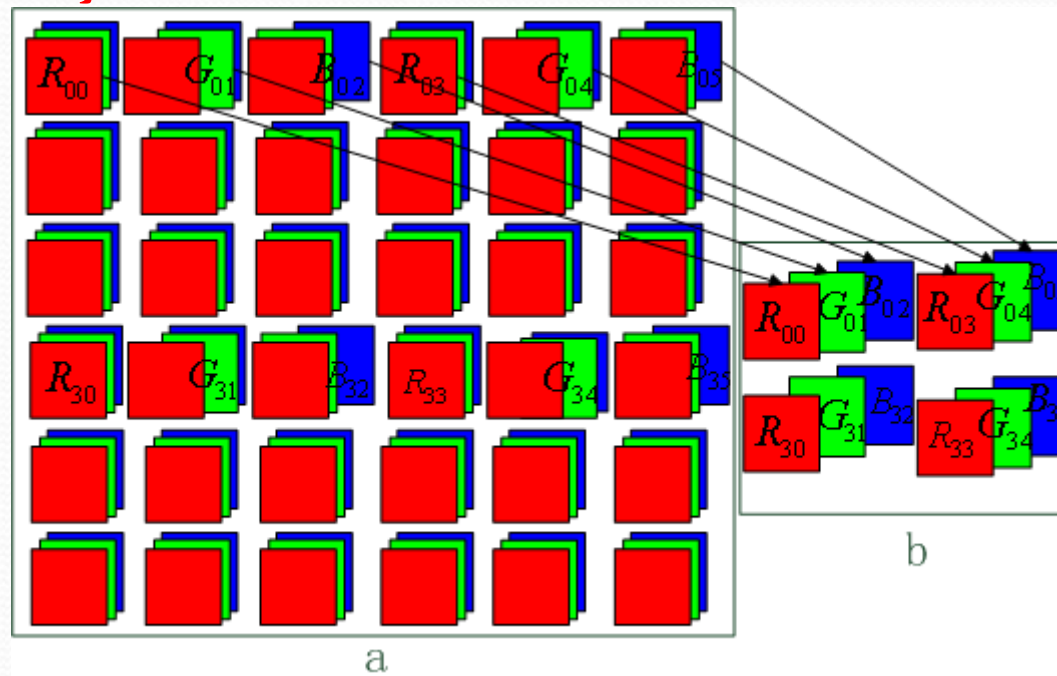
# Pixel-based Down-sampling



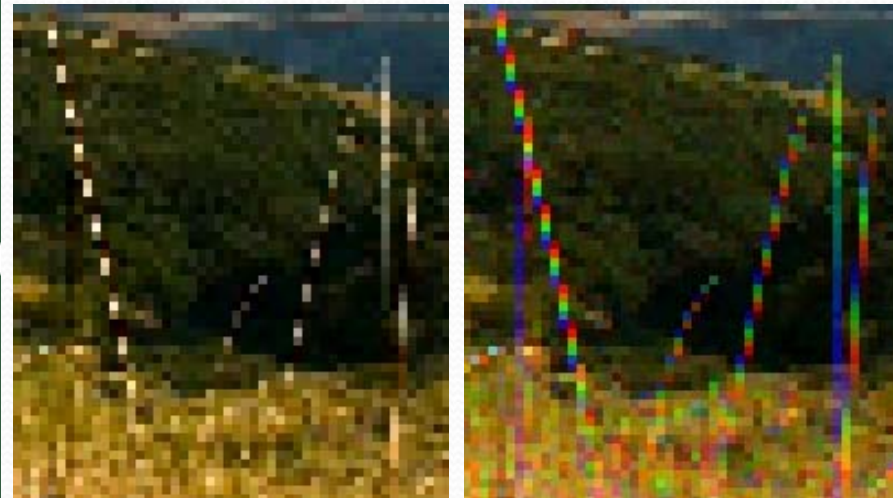
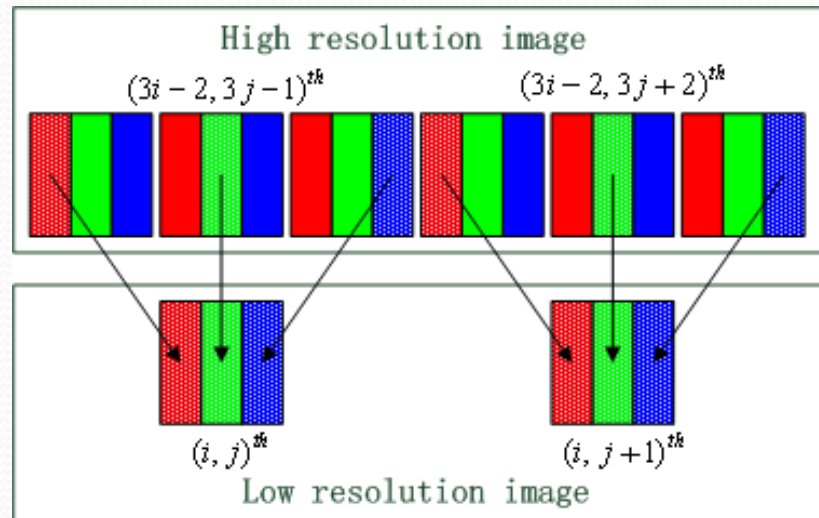
- Method 1 (DPD) selects every third pixel horizontally and vertically
  - **Aliasing artifacts**: broken lines, staircase effect
- Method 2 (PDAF) applies an anti-aliasing filter (ideal low pass filter with cut-off freq. =  $\pi/3$ )
  - **Blurring**, only low frequency is retained

# Method 3: Direction Subpixel-based Downsampling (DSD)

- Application of subpixel rendering in downsampling may lead to improvement in apparent resolution
  - The number of individual reconstruction points can be increased by three times



# Method 3: Direct Subpixel-based Down-sampling (DSD)



- DSD can potentially preserve more high frequency image details
  - Lead to clearer and sharper down-sampled images

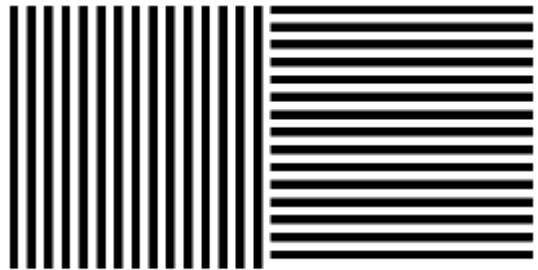
# Method 3: Subpixel-based Downsampling (cont)



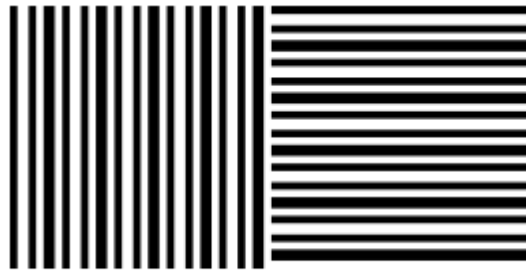
FIGURE: (a) Results of pixel-based downsampling (left)  
(b) Results of subpixel-based downsampling (right)

- Method 3 (DSD) can potentially preserve more high frequency image details leading to clearer and sharper downsampled images

# Advantage of DSD



(a) Original



(b) DPD



(c) DSD

$$\mu = \frac{\sum_{k=1}^m w_k}{m} - \frac{w_0}{3}; \quad \sigma^2 = \frac{\sum_{k=1}^m (w_k - w_0/3)^2}{m}$$

	Subimage-V		Subimage-H	
	DPD	DSD	DPD	DSD
$\mu$	0	0	0	0
$\sigma^2$	2	0	2	2

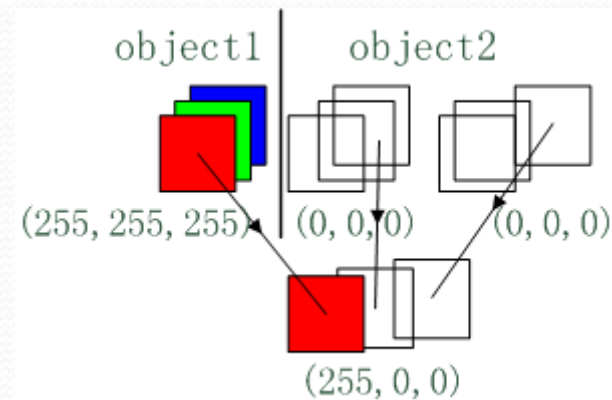


# Color Fringing Artifact



- Applying subpixel techniques to color images/video downsampling is non-trivial
  - each subpixel can signal only red, green or blue information, instead of the original full color
  - direct application of subpixel approach to images/video downsampling would cause the “color fringing” problem

# How Color Fringing Occurs



- a left pixel belonging to object 1 appears white
- the right two pixels belonging to object 2 appear black
- apply SHARP, the pixel in low resolution image would appear **red**

To balance the **increased luminance resolution** against the **color fringing** is the research challenge to be settled

# Experiment Results (Full Color Image)

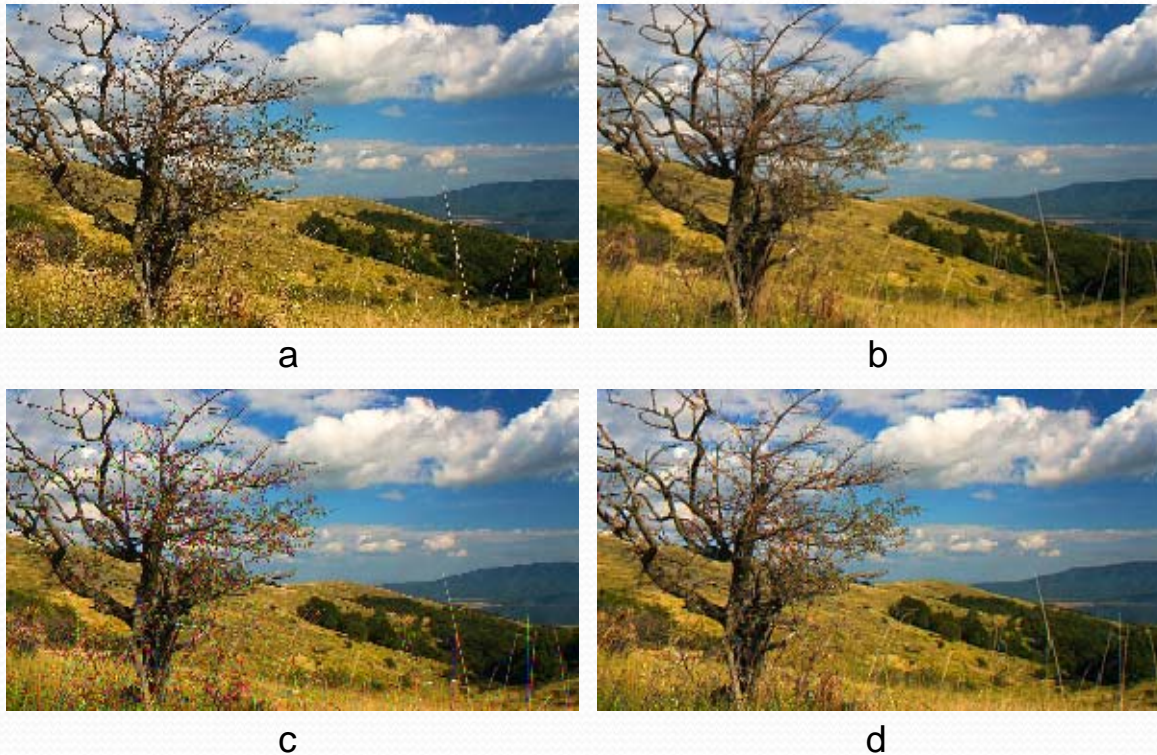


FIGURE: (a) DPD, pixel-based downsampling without filter (b) PDAF, pixel-based downsampling with anti-aliasing filter (c) DSD, subpixel-based downsampling without filter (d) subpixel downsampling with proposed filter



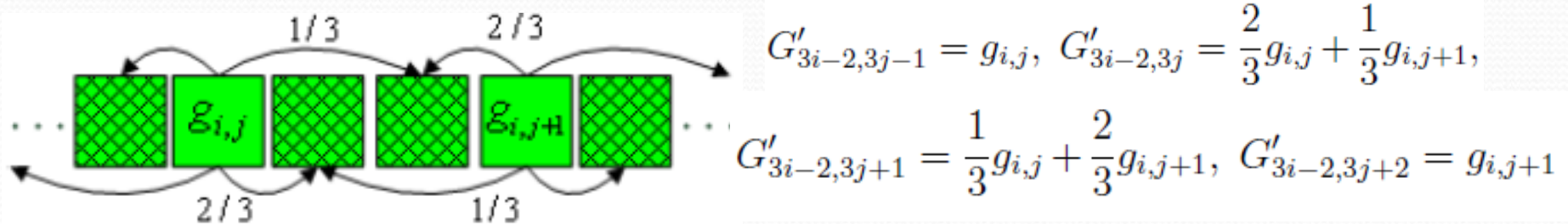
## “Color fringing” artifacts of DSD

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- Lu Fang, O.C. Au, “Subpixel-based Image Down-sampling with Min-Max Directional Error for Stripe Display”, *IEEE Journal of Selected Topics in Signal Processing, Special Issue on Recent Advances in Video Processing for Consumer Displays*, Vol. 5, No. 2, pp. 240-251, Apr. 2011.

# MinMax Directional Error (MMDE) - Problem Formulation(1) in IEEE JSTSP

- Two virtual green components between any two neighboring green components,




- Let  $E_{i,j}^k$  be the directional sum of square error between  $G'$  and  $G$  in the direction  $k$  for those pixels affected by  $g_{i,j}$

$$\begin{aligned}
 E_{i,j}^1 &= \left[ G_{3i-2,3j-3} - \left( \frac{2}{3}g_{i,j-1} + \frac{1}{3}g_{i,j} \right) \right]^2 + \left[ G_{3i-2,3j-2} - \left( \frac{1}{3}g_{i,j-1} + \frac{2}{3}g_{i,j} \right) \right]^2 \\
 &+ \left[ G_{3i-2,3j-1} - g_{i,j} \right]^2 + \left[ G_{3i-2,3j} - \left( \frac{2}{3}g_{i,j} + \frac{1}{3}g_{i,j+1} \right) \right]^2 \\
 &+ \left[ G_{3i-2,3j+1} - \left( \frac{1}{3}g_{i,j} + \frac{2}{3}g_{i,j+1} \right) \right]^2
 \end{aligned}$$

## MMDE-Problem Formulation (2)

- Human eyes tend to be most sensitive to the largest error and more forgiving to the smaller errors
- Min-Max Directional Error (MMDE):

$$\min_{\mathbf{g}} \sum_{i,j} \max \{ E_{i,j}^1, E_{i,j}^2, E_{i,j}^3, E_{i,j}^4 \}$$

$$\begin{aligned} \min_{\mathbf{g}, \mathbf{t}} \quad & \sum_{i,j} t_{i,j} \\ \text{s.t.} \quad & 0 \leq g_{i,j} \leq 255 \\ & t_{i,j} \geq E_{i,j}^1 \\ & t_{i,j} \geq E_{i,j}^2 \\ & t_{i,j} \geq E_{i,j}^3 \\ & t_{i,j} \geq E_{i,j}^4 \end{aligned}$$


## MMDE-VR (Visual Relaxation)

- Consider the case when the  $3 \times 3$  neighborhood for  $g(i,j)$  is dominated by a edge  $D$ :
  - Neighboring components in  $D^\perp$  should belong to two different objects
  - $G'$  tends to be quite different from  $G$
- It is quite probable that the largest value of the four directional errors would be the one **perpendicular** to the current local edge direction.



# MMDE-VR (Visual Relaxation)

- Consider the  $g(i,j)$  for some  $(i,j)$ , determine the local edge direction according to :

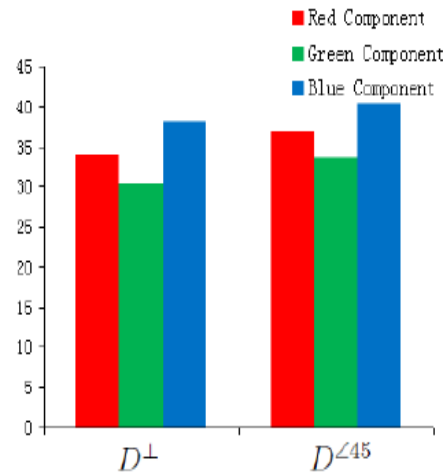
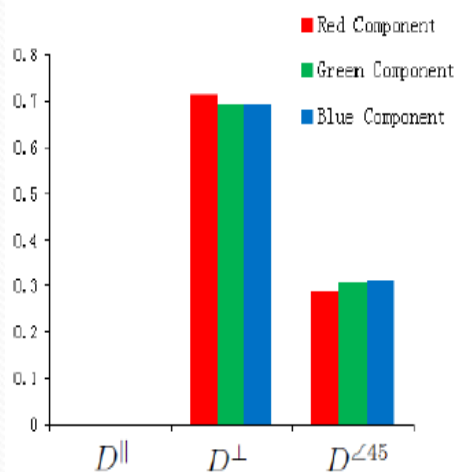
$$\Delta_{i,j}^1 = |Y_{3i-2,3j} - Y_{3i-2,3j-1}| + |Y_{3i-2,3j-1} - Y_{3i-2,3j-2}|$$

$$\Delta_{i,j}^2 = |Y_{3i-1,3j-1} - Y_{3i-2,3j-1}| + |Y_{3i-2,3j-1} - Y_{3i-3,3j-1}|$$

$$\Delta_{i,j}^3 = |Y_{3i-1,3j} - Y_{3i-2,3j-1}| + |Y_{3i-2,3j-1} - Y_{3i-3,3j-2}|$$

$$\Delta_{i,j}^4 = |Y_{3i-1,3j-2} - Y_{3i-2,3j-1}| + |Y_{3i-2,3j-1} - Y_{3i-3,3j}|$$

$$Dir(g_{i,j}) = \begin{cases} \text{Horizontal,} & \text{if } \min_k \Delta_{i,j}^k = \Delta_{i,j}^1 \\ \text{Vertical,} & \text{if } \min_k \Delta_{i,j}^k = \Delta_{i,j}^2 \\ \text{Diagonal,} & \text{if } \min_k \Delta_{i,j}^k = \Delta_{i,j}^3 \\ \text{Anti-Diagonal,} & \text{if } \min_k \Delta_{i,j}^k = \Delta_{i,j}^4 \end{cases}$$



- 70% of maximum errors occur in direction  $D^{\perp}$ , and the other 30% in  $D^{<45}$

# MMDE-VR (Visual Relaxation)

- Approximate the maximization operation by directly choosing the direction in  $D^\perp$ :

$$\begin{aligned} \min_{\mathbf{g}} \quad & \sum_{i,j} (w_1 \times E_{i,j}^1 + w_2 \times E_{i,j}^2 + w_3 \times E_{i,j}^3 + w_4 \times E_{i,j}^4) \\ \text{s.t.} \quad & w_k \in \{0, 1\}, k = 1, 2, 3, 4 \\ & \sum_{k=1}^4 w_k = 1 \end{aligned}$$

- $(w_1, w_2, w_3, w_4)$  are determined adaptively by local edge directions

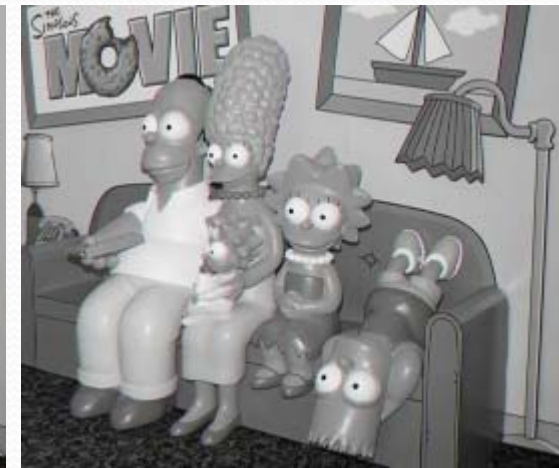
$$(w_1, w_2, w_3, w_4) = \begin{cases} (1, 0, 0, 0), & \text{if } Dir(g_{i,j}) = \text{Vertical} \\ (0, 1, 0, 0), & \text{if } Dir(g_{i,j}) = \text{Horizontal} \\ (0, 0, 1, 0), & \text{if } Dir(g_{i,j}) = \text{Anti-Diagonal} \\ (0, 0, 0, 1), & \text{if } Dir(g_{i,j}) = \text{Diagonal} \end{cases}$$

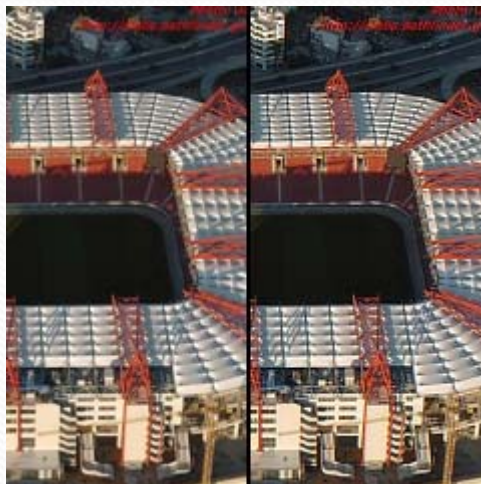
# Outline

- Background on Subpixel-based Image Down-sampling
- Proposed MMDE (Min-Max Directional Error)
  - MMDE-VR (Visual Relaxation)
- **Experiment Results**
- Conclusion









## Demo video

Demo1:

<http://ihome.ust.hk/~fanglu/MMSE-SD.htm>

Demo2:

<http://ihome.ust.hk/~fanglu/MMSE-SD2.htm>



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# Conclusion

- We reviewed some little known results on subpixel rendering and its application to downsampling
  - Subpixel-based downsampling can lead to better perceptual quality compared to conventional downsampling approaches
  - However, subpixel rendering provides apparent higher resolution at the price of annoying color artifacts
- Unsettled Issue
  - Develop theoretical results and analytical models to characterize subpixel-based downsampling of color images/video to be displayed on terminals of any pixel geometries

# References

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- [2] Jun-Seong Kim, Chang-Su Kim, "A filter design algorithm for subpixel rendering on matrix displays" in EUSIPCO, 2007
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- [7] Lu Fang, O.C. Au, "Subpixel-based Image Down-sampling with Min-Max Directional Error for Stripe Display", IEEE Journal of Selected Topics in Signal Processing, Special Issue on Recent Advances in Video Processing for Consumer Displays, Vol. 5, No. 2, pp. 240-251, Apr. 2011.



Thank you!  
Q & A