SIGGRAPHASIA2008
NEW HORIZONS

Extracting Depth and Matte using a Color-Filtered Aperture

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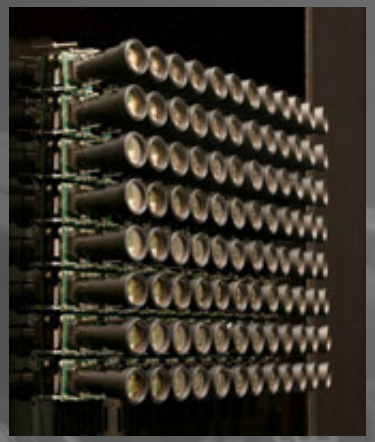
The University of Tokyo

Outline

- Background
- Related Work
- Our Method
- Results
- Conclusion

Computational Cameras

- **Capture various scene properties**
  - High dynamic range, high resolution,
  - Large field of view, reflectance, depth,
  - … and more
- **With elaborate imaging devices**
  - Camera arrays
  - Additional optical elements



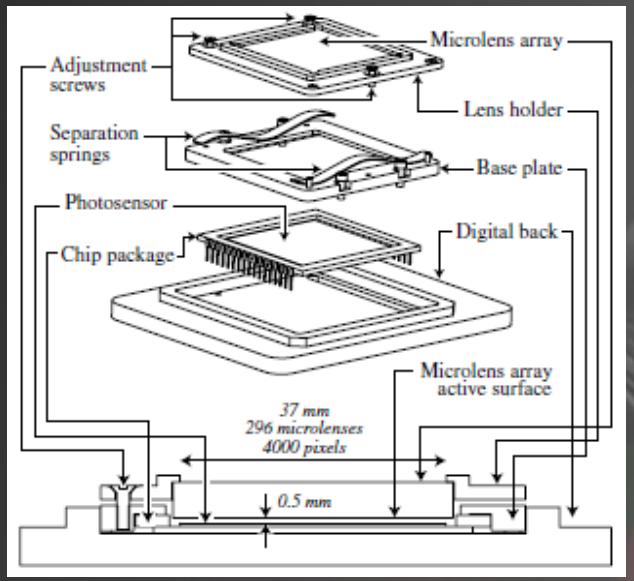
[Wilburn 2005]

[Nayar 1997]

Compact Computational Cameras

- Small devices
- Simple optical elements

[Ng 2005]



[Levin 2007]

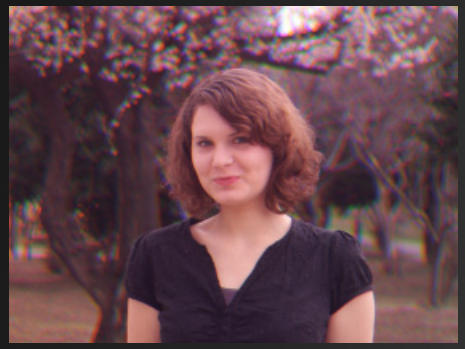
Our Goal

- Capture scene properties

- With minimal modification to the camera

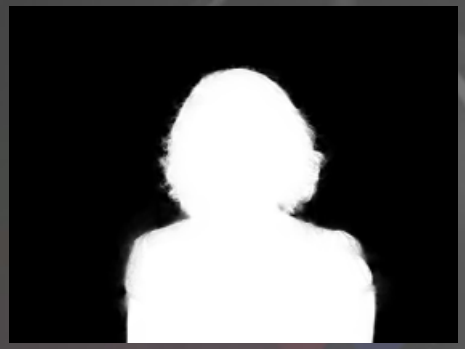
Our Goal

- Capture scene properties
  - Depth maps
  - Alpha mattes
- With minimal modification to the camera



Captured image

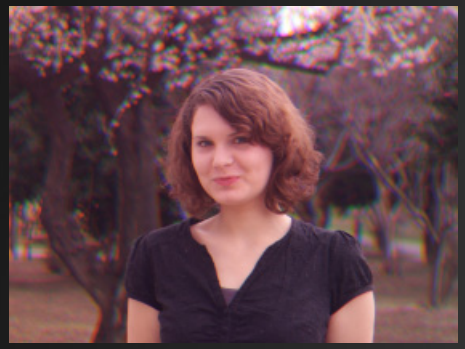
Depth



Matte

Our Goal

- Capture scene properties
  - Depth maps
  - Alpha mattes
- With minimal modification to the camera
  - Put color filters in a camera lens aperture



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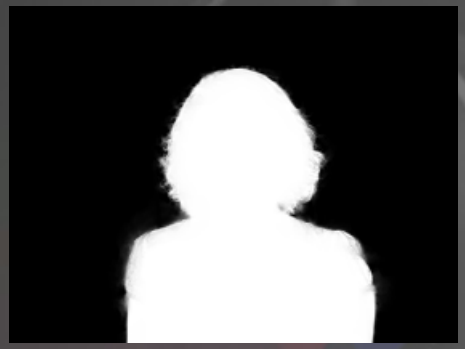
Depth

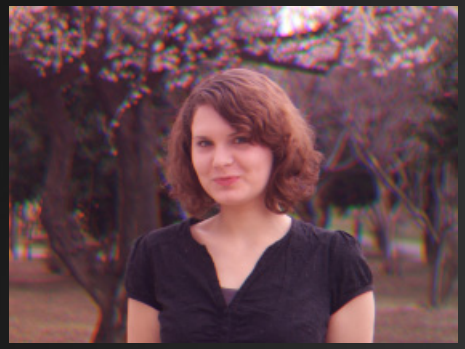


Matte

Lens with color filters

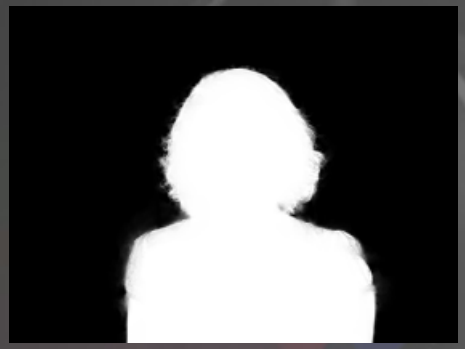
Our Goal

- Capture scene properties
  - Depth maps
  - Alpha mattes
- With minimal modification to the camera
  - Put color filters in a camera lens aperture
  - This idea itself is not new



Captured image

Depth



Matte

Lens with color filters

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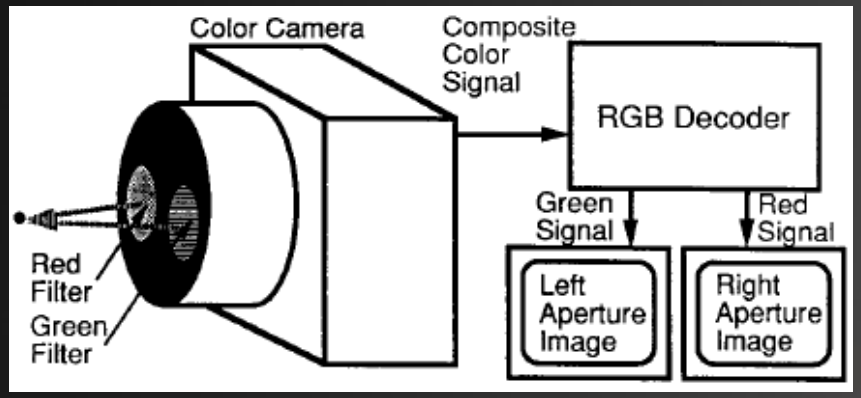
Previous Color-Filter Methods

- Extract (only) depth maps
  - With low precision
  - Or, a specialized flashbulb is used
    - Spoils the visual quality of captured images



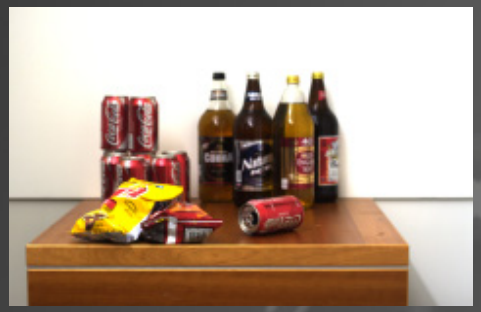
[Amari 1992]

[Chang 2002]

Coded Aperture

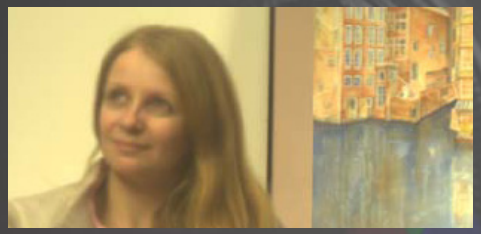
- **Patterned mask in the aperture**
  - Changes frequency characteristics of defocus
  - Facilitates blur identification/removal

[Levin 2007]

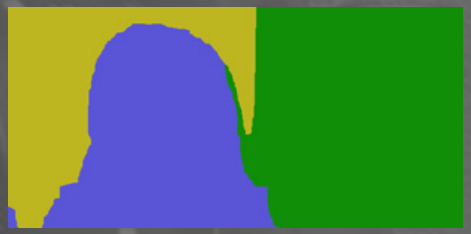


[Veeraraghavan 2007]

Lens with a mask



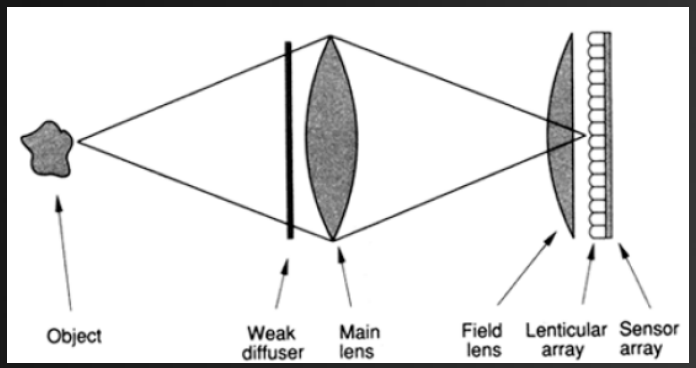
Captured image



Amount of defocus blur (≈ depth)

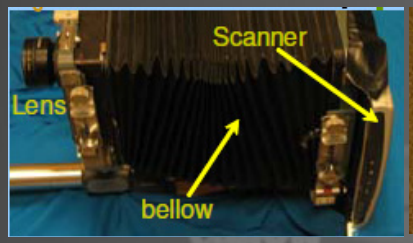
Single-Lens Multi-View Capture

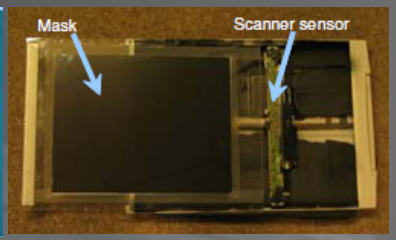
- Records light rays separately depending on their incident angle
  - Enables light field rendering



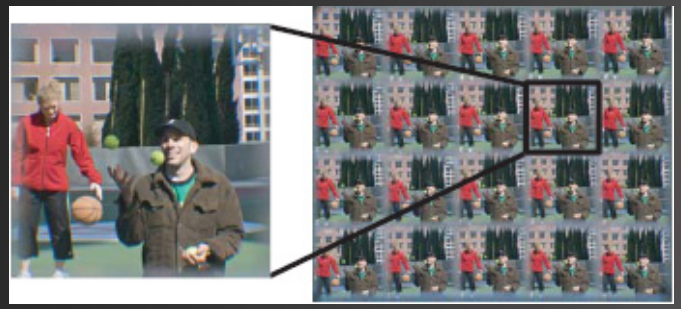
[Adelson 1992]

[Ng 2005]

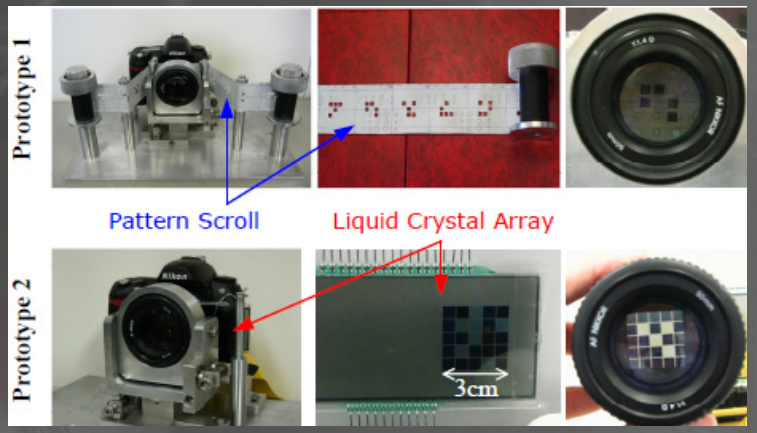




[Veeraraghavan 2007]



[Georgeiv 2006]

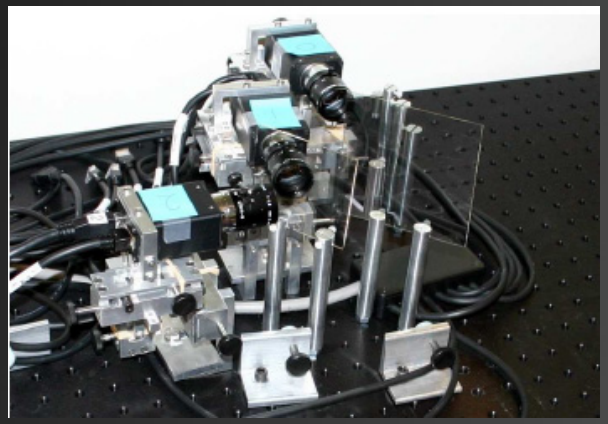


[Liang 2008]

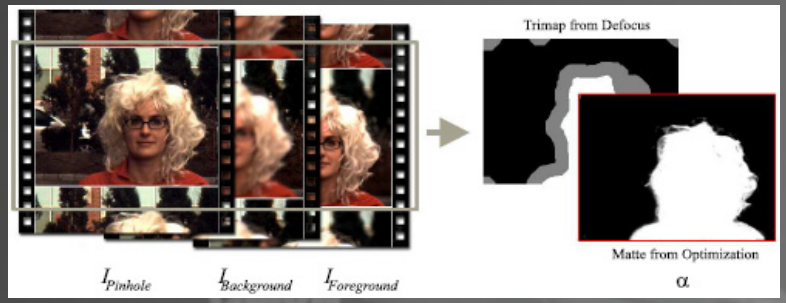
Matting

- Automatic matting by multiple cameras

[McGuire 2005]



3 cameras with half mirrors



Video matting

[Joshi 2006]

Array of 8 cameras

Video matting

Our Method

- **Features**
  - Automatic depth and matte extraction
  - Single hand-held camera
  - Single shot

- **Contributions**
  1. Improved depth estimation
  2. Novel matting algorithm
  for images captured thru a color-filtered aperture

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Our Method

- Color-filtered aperture
- Depth estimation
- Matting

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Our Prototype Camera Lens

Canon EF 50mm
f/1.8 II lens

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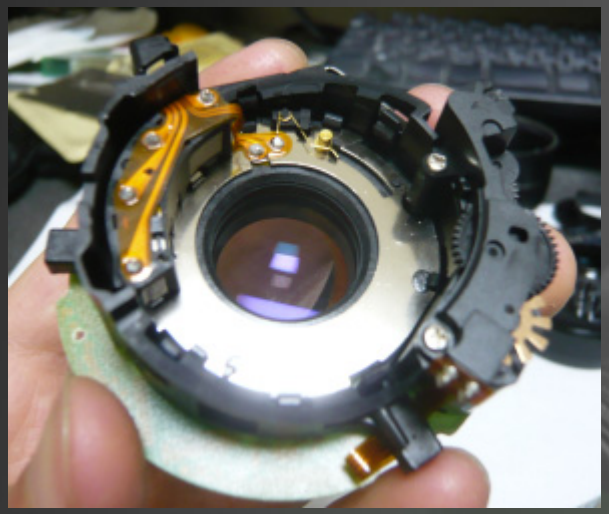
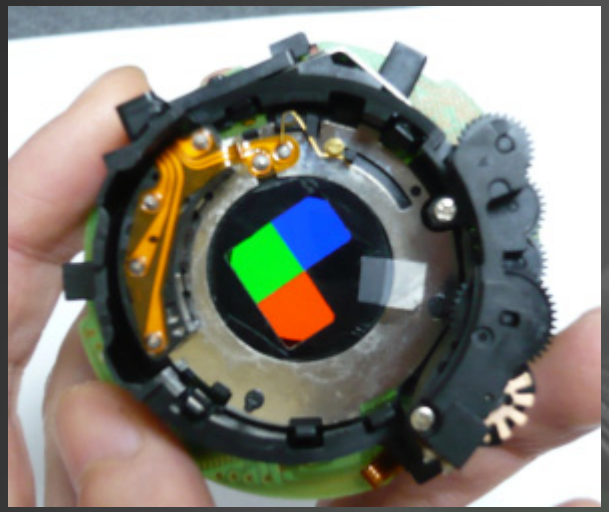


Aperture part of the
disassembled lens

Our Prototype Camera Lens

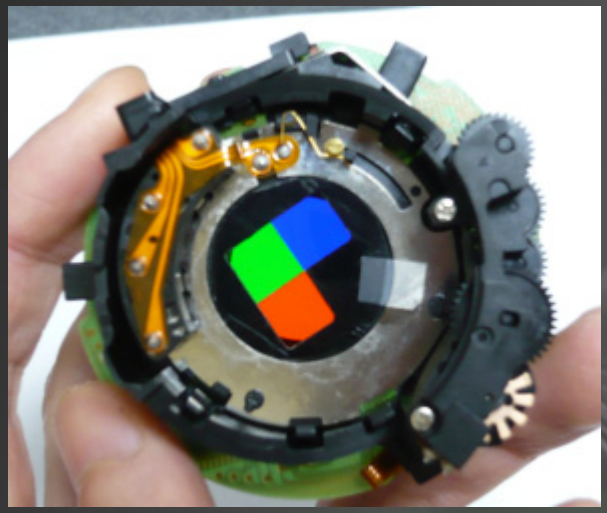
Canon EF 50mm
f/1.8 II lens



Fujifilter SC-58,
BPB-53, and BPB-45

Our Prototype Camera Lens

Canon EF 50mm
f/1.8 II lens



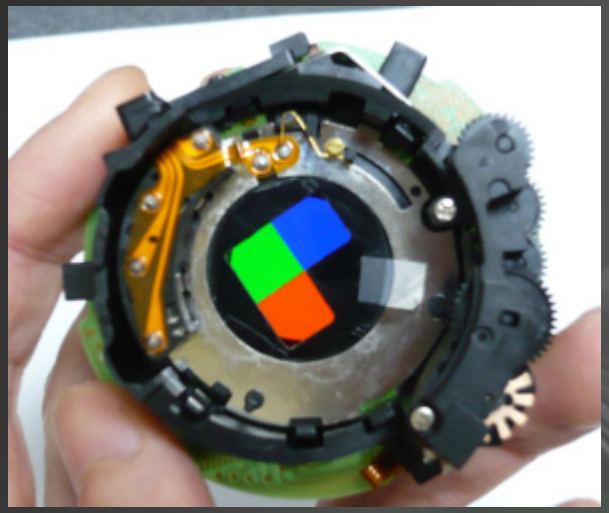
Fujifilter SC-58,
BPB-53, and BPB-45

Our prototype lens
with color-filters

Our Prototype Camera Lens

- Took me just a few hours to fabricate
  - Using a micro-screwdriver and a box cutter

Canon EF 50mm f/1.8 II lens



Fujifilter SC-58, BPB-53, and BPB-45

Our prototype lens with color-filters

Captured Image

Red Plane

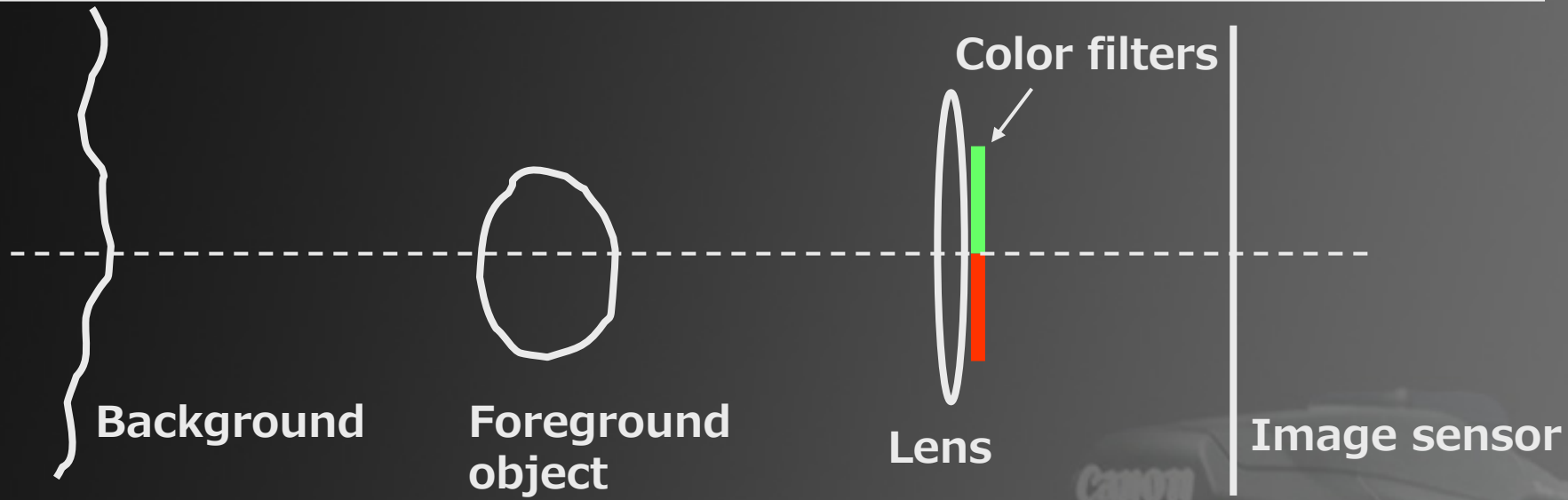
Green Plane

Blue Plane

Captured Image

- Has depth-dependent color-misalignment
  - NOT due to chromatic aberration

Why Do Colors Get Misaligned?



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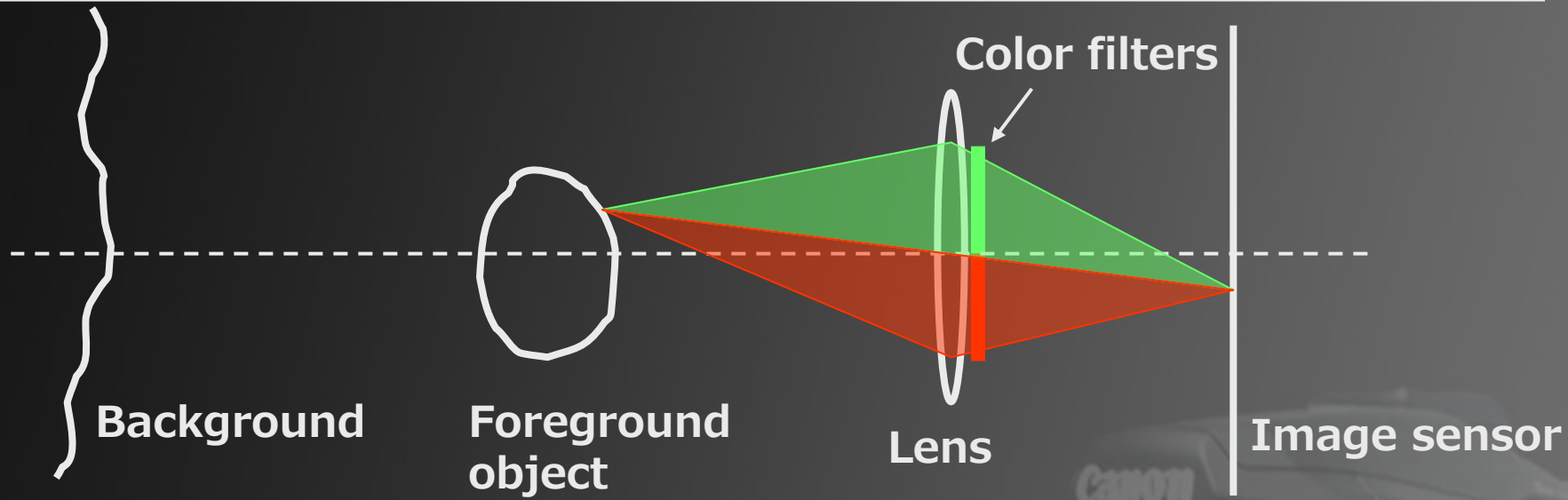

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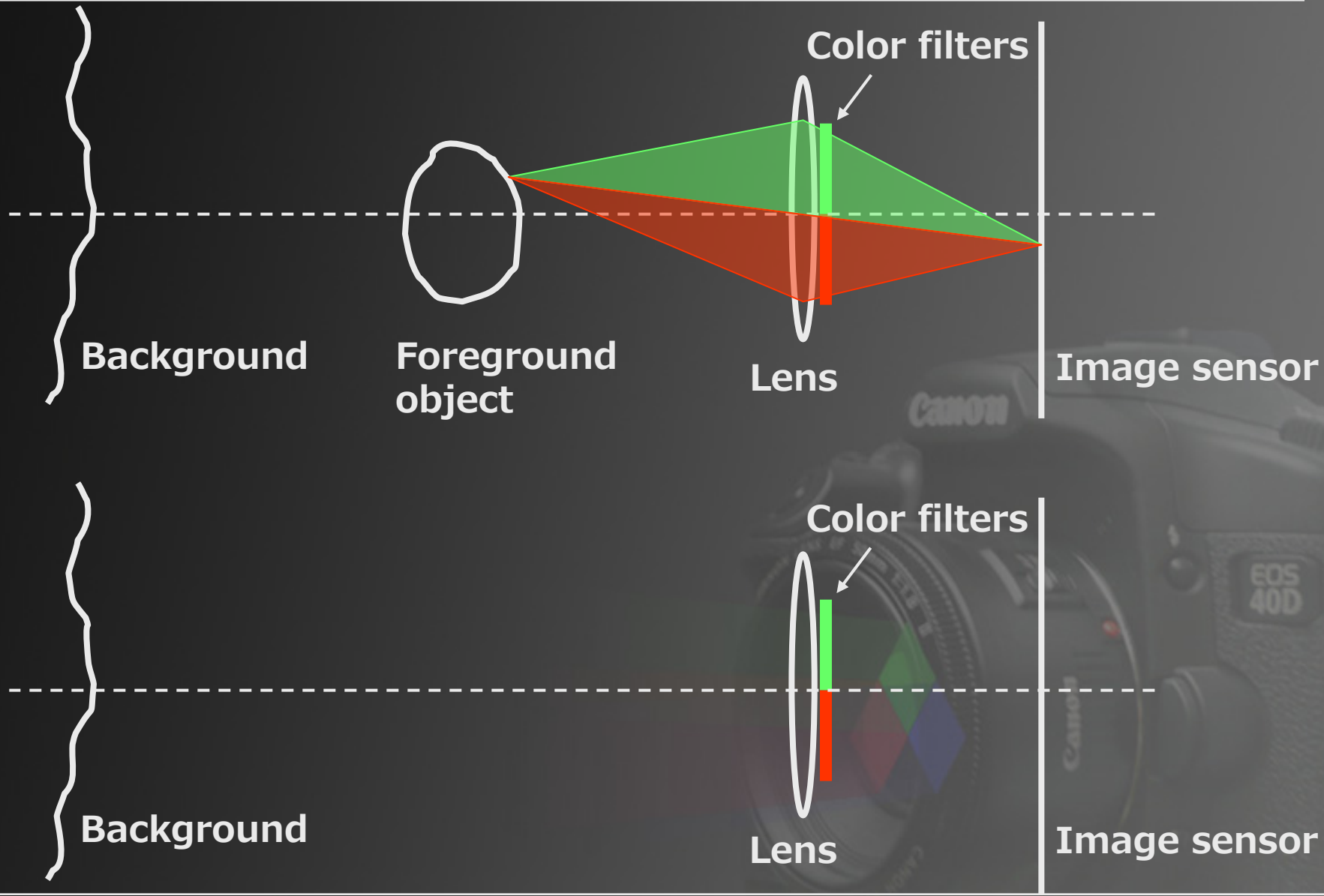

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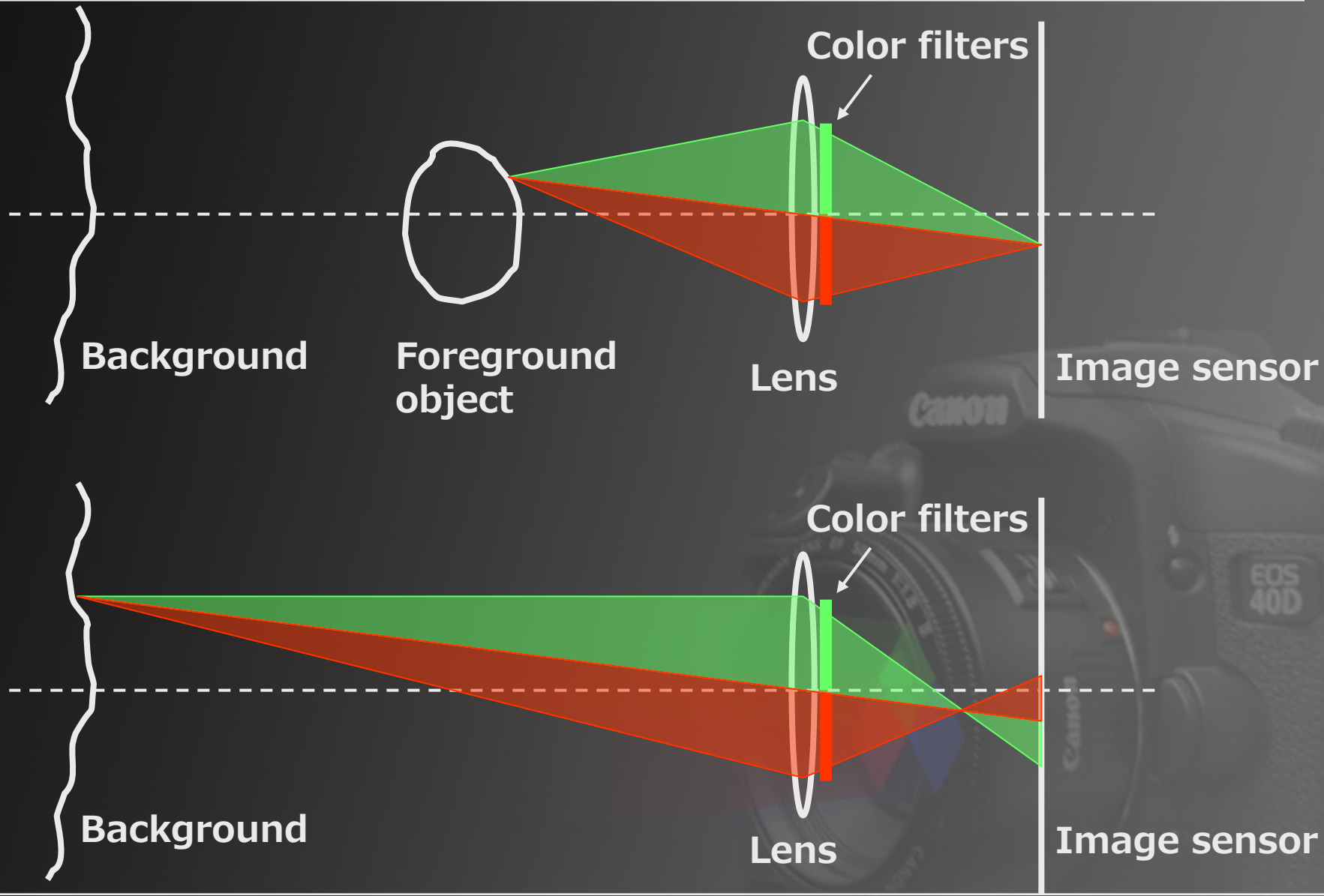

Our Method

- Color-filtered aperture
- **Depth estimation**
- Matting

Depth Estimation

- Our camera captures 3 views in the RGB planes
  - → Stereo reconstruction problem

Red plane

Green plane

Blue plane

Depth Estimation

- Our camera captures 3 views in the RGB planes
  - → Stereo reconstruction problem
- However, their intensities don't match
  - **Contribution 1:** improved correspondence measure between the RGB planes

Red plane

Green plane

Blue plane

Original Image

Disparity = 1

Disparity = 2

Disparity = 3

Disparity = 4

Disparity = 5

Disparity = 6

When Is The Color Aligned?

Color-Alignment Measure

- Local color distribution of natural images tends to form a line [Omer 2004, Levin 2006]

Color-Alignment Measure

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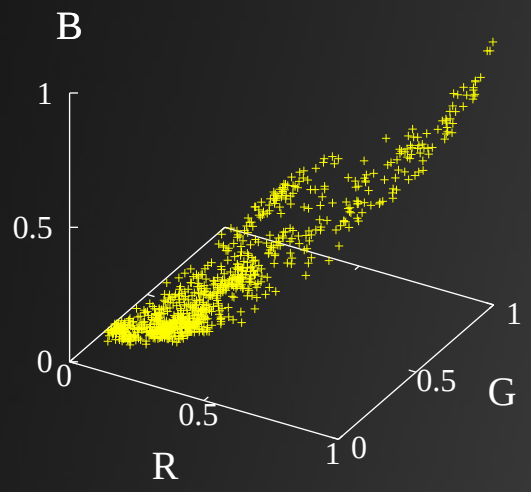
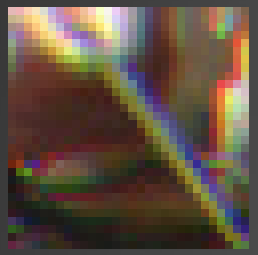


Color-Alignment Measure

- Local color distribution of natural images tends to form a line [Omer 2004, Levin 2006]

Misalign

by 1 pixel



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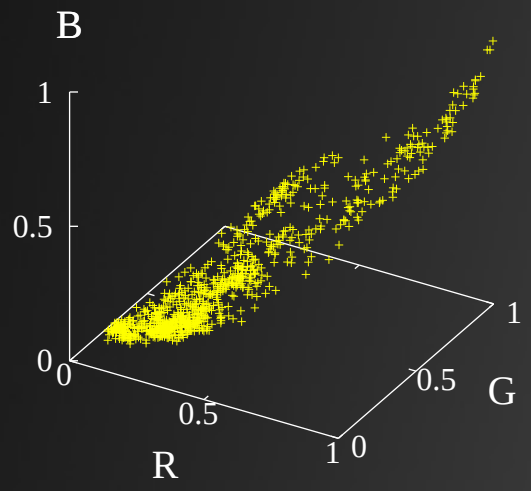
Disparity = 1



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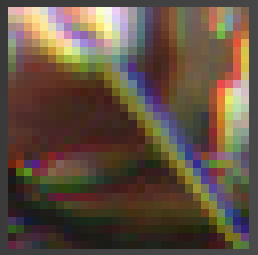

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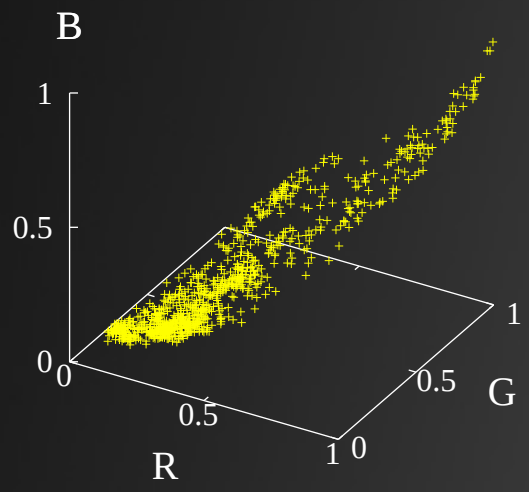
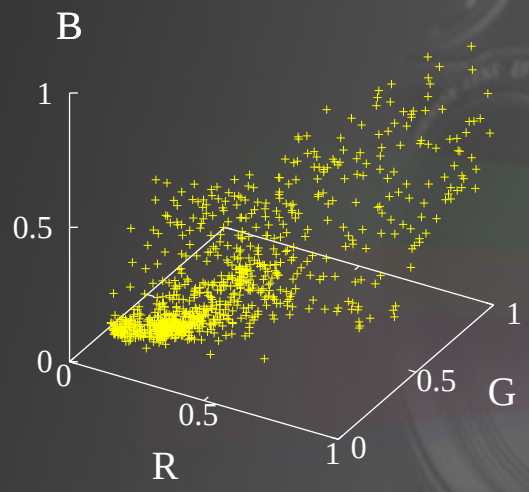
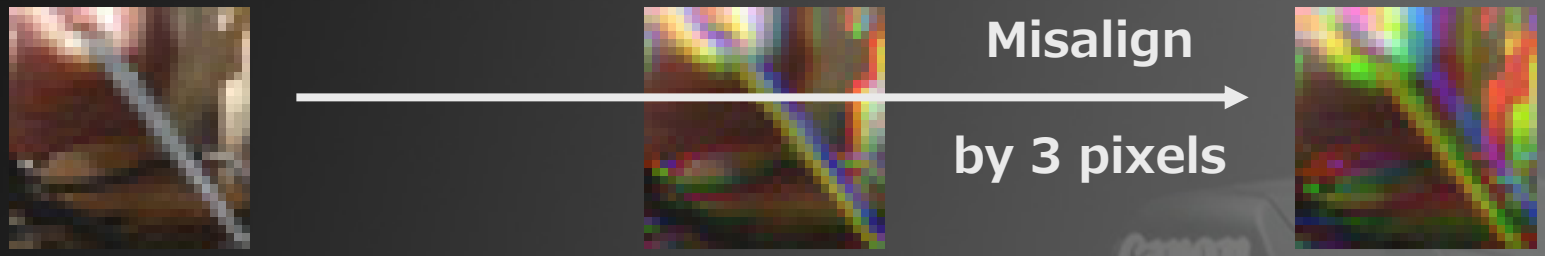


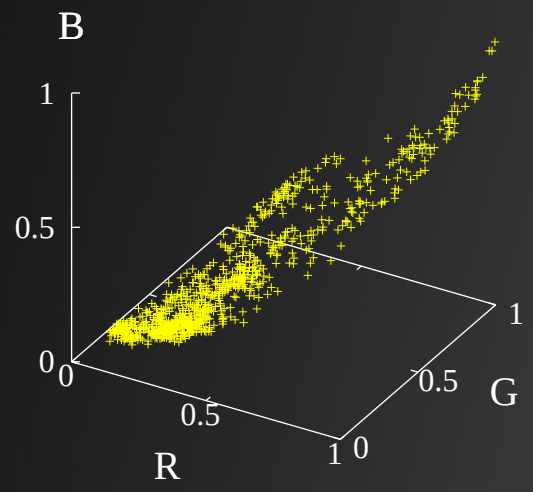


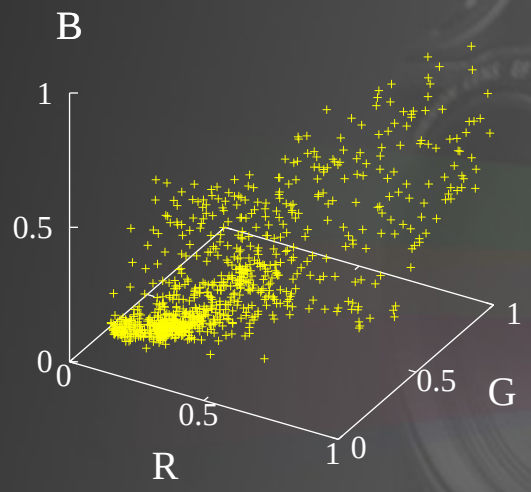
Color-Alignment Measure

- Local color distribution of natural images tends to form a line [Omer 2004, Levin 2006]



Disparity = 0 Disparity = 1 Disparity = 3





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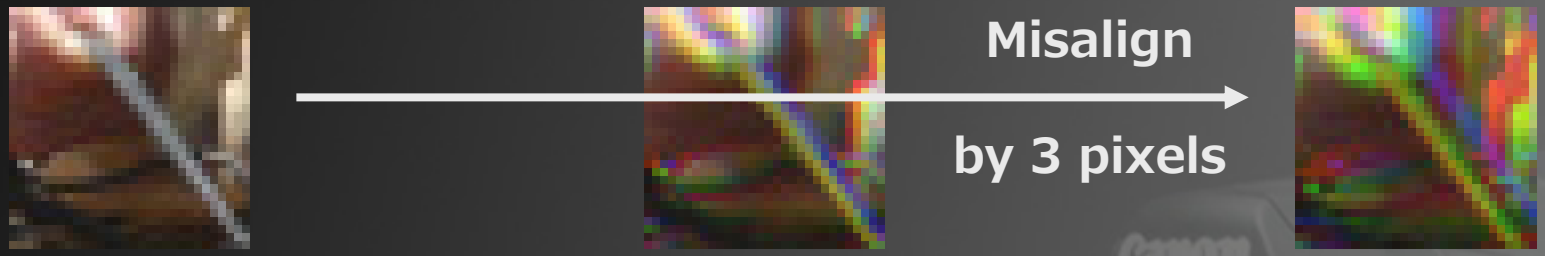

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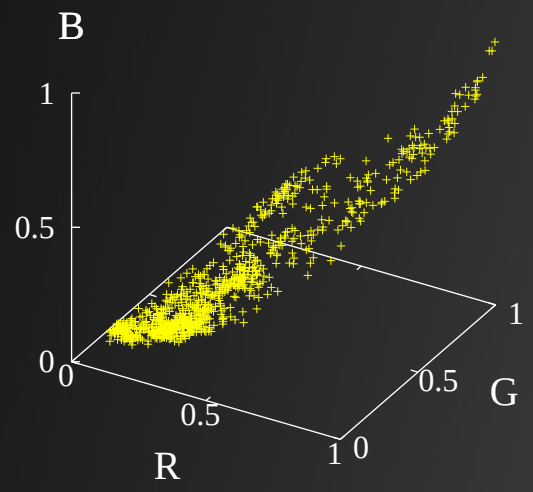
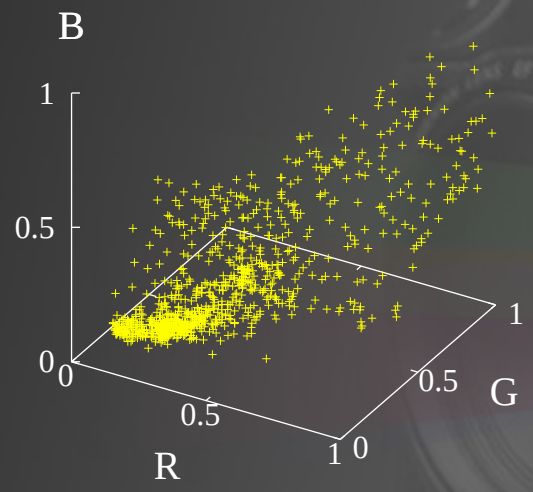
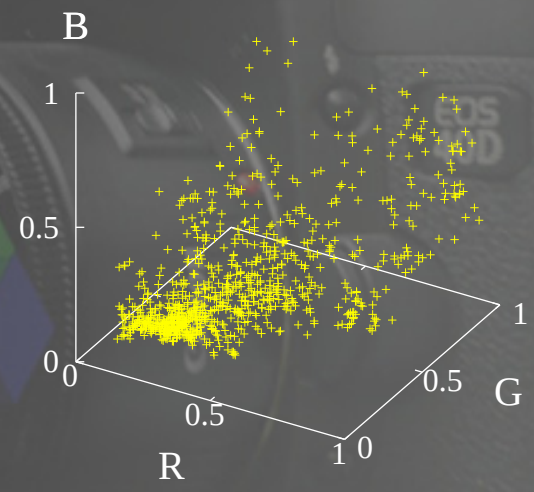






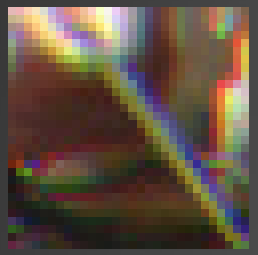
Color-Alignment Measure

$$L = \frac{\lambda_0 \lambda_1 \lambda_2}{\sigma_r^2 \sigma_g^2 \sigma_b^2}$$

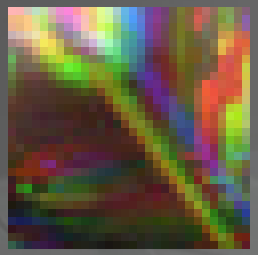
Variances along the principal axes (eigenvalues)

Variances along the RGB axes

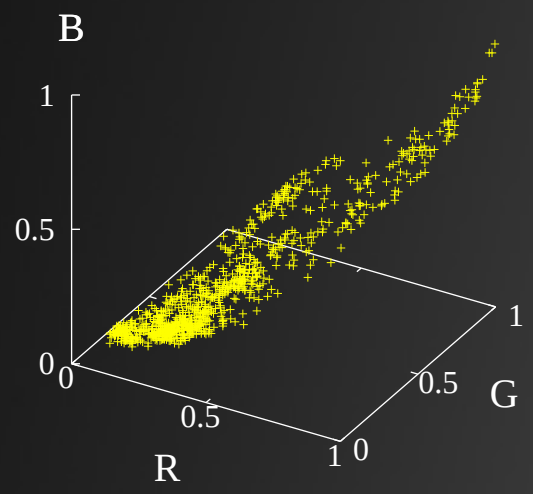
Disparity = 0

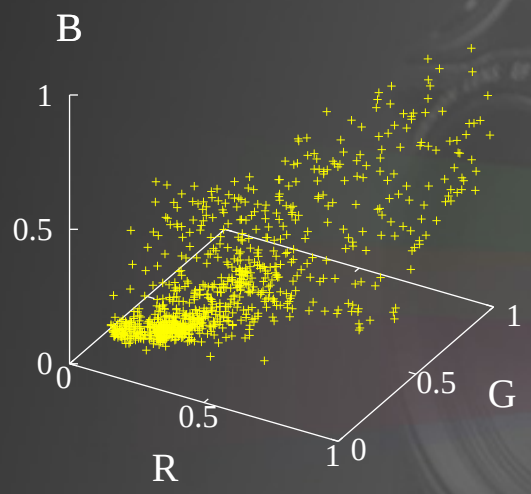


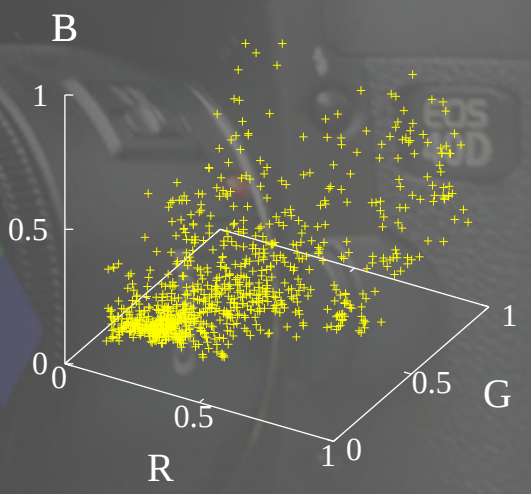
Disparity = 1



Disparity = 3







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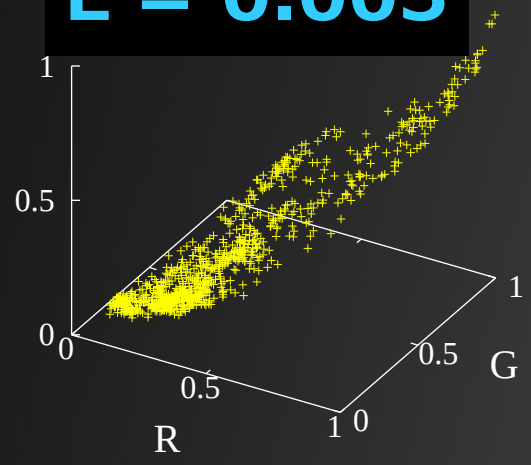
$$L = \frac{\lambda_0 \lambda_1 \lambda_2}{\sigma_r^2 \sigma_g^2 \sigma_b^2}$$

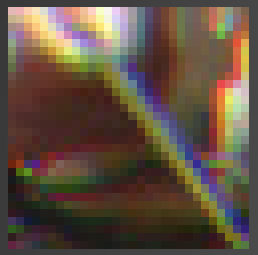
Variances along the principal axes (eigenvalues)

Variances along the RGB axes

Disparity = 0

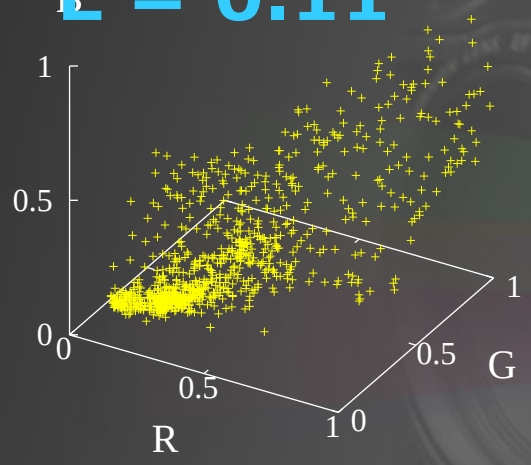
L = 0.003

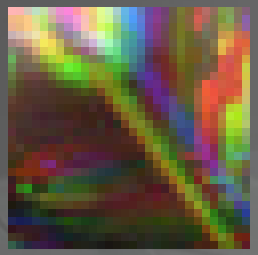




Disparity = 1

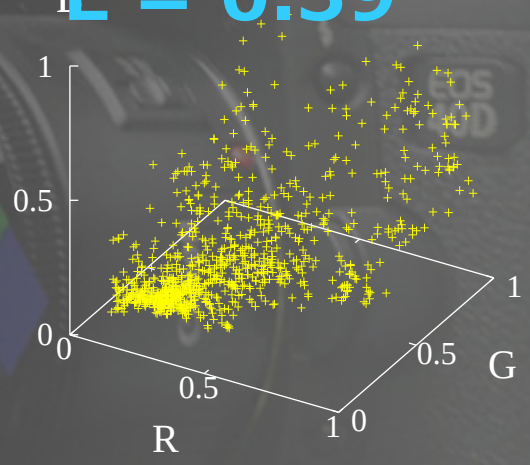
L = 0.11





Disparity = 3

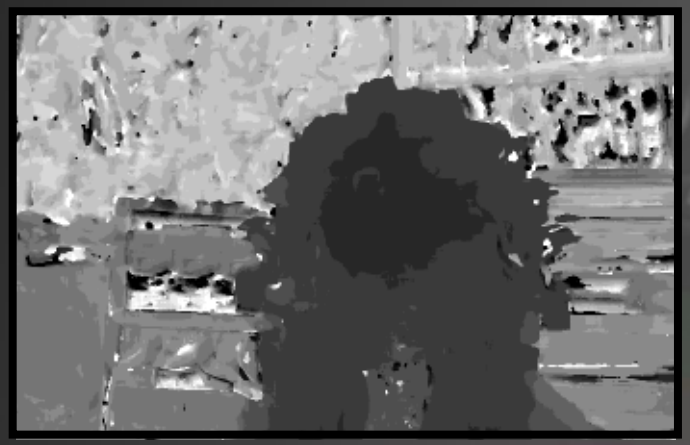
L = 0.39



Depth Estimation

- Solve for the disparity that makes the color-alignment measure minimum

Captured image

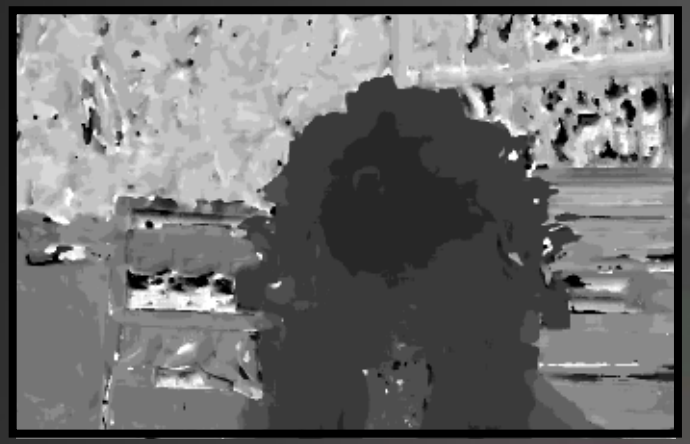


Pixel-wise estimates
(intensity ≈ depth)

Depth Estimation

- Solve for the disparity that makes the color-alignment measure minimum
- With smoothness constraints
  - Graph-cut optimization [Boykov 2001]

Captured image



Pixel-wise estimates
(intensity ≈ depth)

After graph-cuts

Our Method

- Color-filtered aperture
- Depth estimation
- **Matting**

Matting

- Problem of estimating foreground opacity

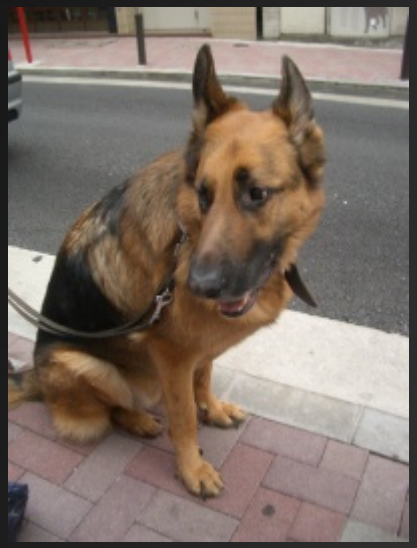
$$\mathbf{I}(x,y) = \alpha(x,y)\mathbf{F}(x,y) + (1-\alpha(x,y))\mathbf{B}(x,y)$$

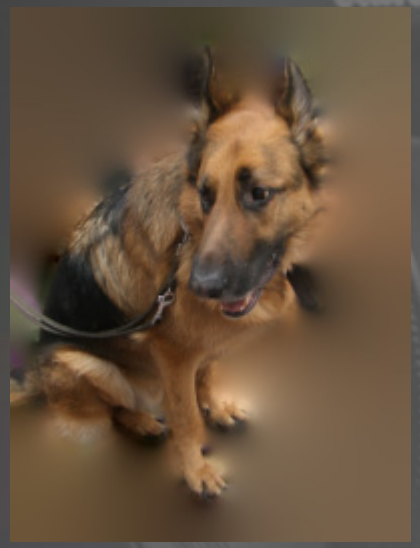
Input image

Matte

Foreground color

Background color





Trimap

- Assigns each pixel to one of 3 labels
  - Strictly foreground ($\alpha = 1$)
  - Strictly background ($\alpha = 0$)
  - Unknown (α to be computed)

Captured image

Trimap

Trimap

- Assigns each pixel to one of 3 labels
  - Strictly foreground ($\alpha = 1$)
  - Strictly background ($\alpha = 0$)
  - Unknown (α to be computed)
- Generated from the depth map

Captured image

Trimap

Trimap-Based Matting

Captured image

Trimap

Trimap-Based Matting

- Errors remain where the foreground and background colors are similar

Captured image

Trimap

[Levin 2006]

Trimap-Based Matting

- Errors remain where the foreground and background colors are similar
  - **Contribution 2:** matte error correction using color misalignment cues

Captured image

Trimap

[Levin 2006]

Basic Idea

- Estimate foreground and background colors based on the current matte

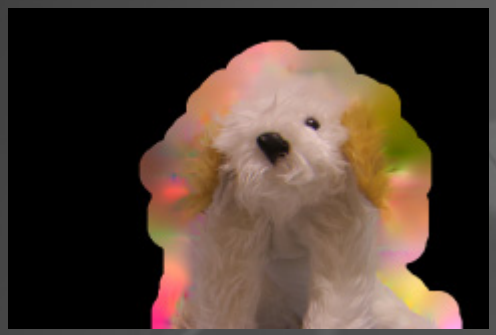
Captured image

Current matte

Basic Idea

- Estimate foreground and background colors based on the current matte

Captured image



Estimated foreground color

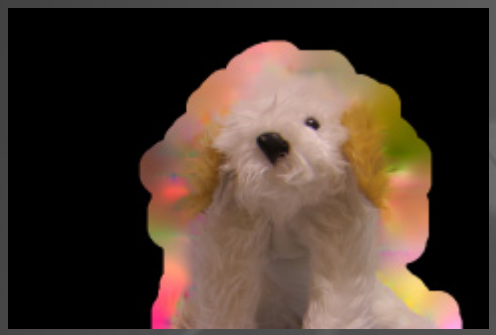
Current matte

Estimated background color

Basic Idea

- Estimate foreground and background colors based on the current matte
- Detect inconsistent color misalignments

Captured image

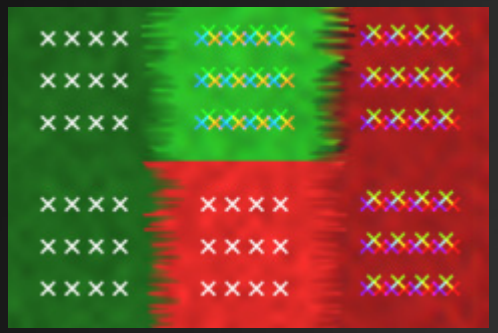


Estimated foreground color

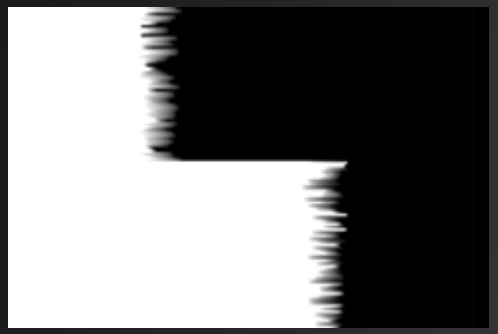
Current matte

Estimated background color

Synthetic Toy Example

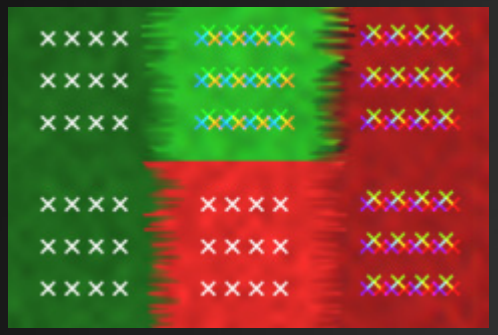


Synthesized input image

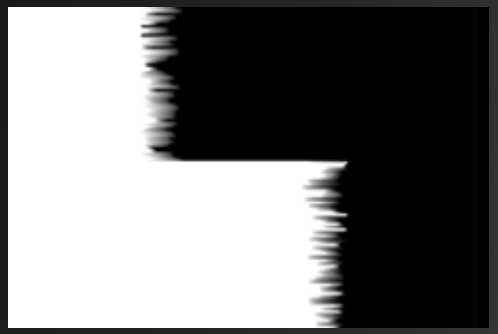


Ground truth matte

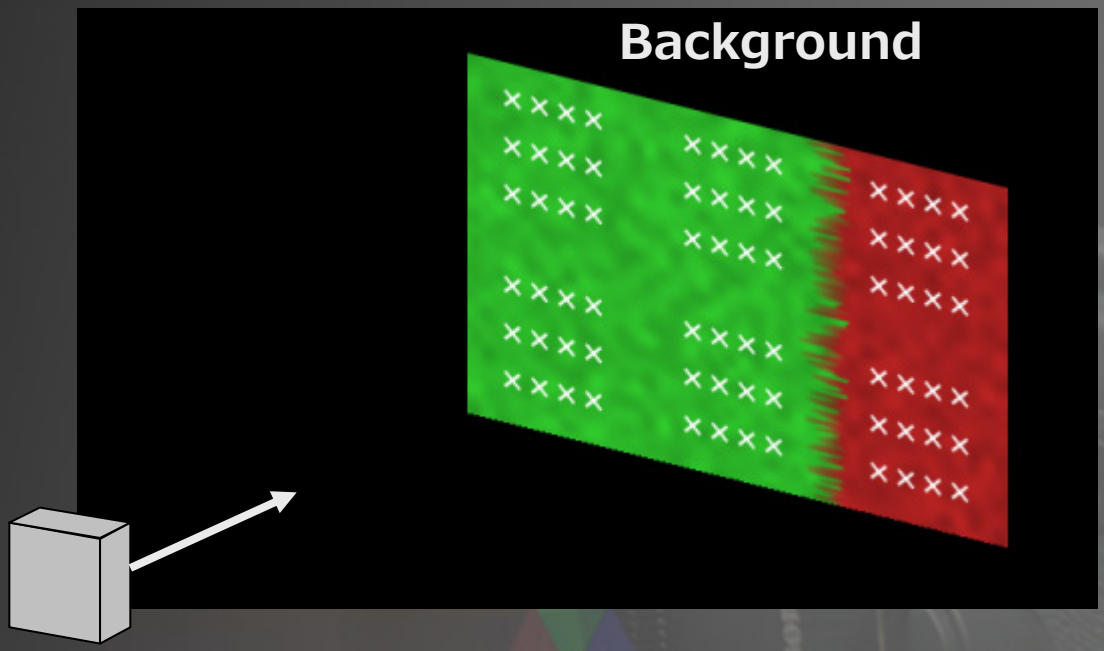
Synthetic Toy Example



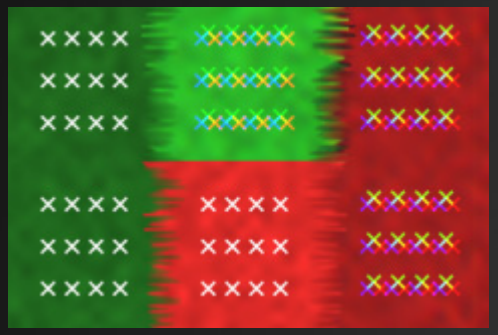
Synthesized input image



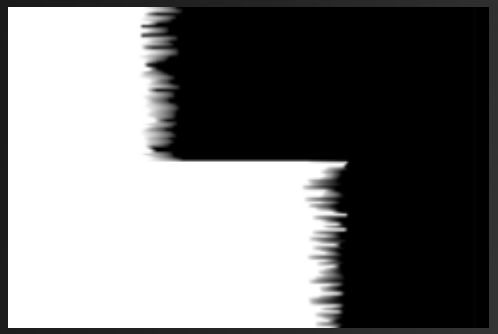
Ground truth matte



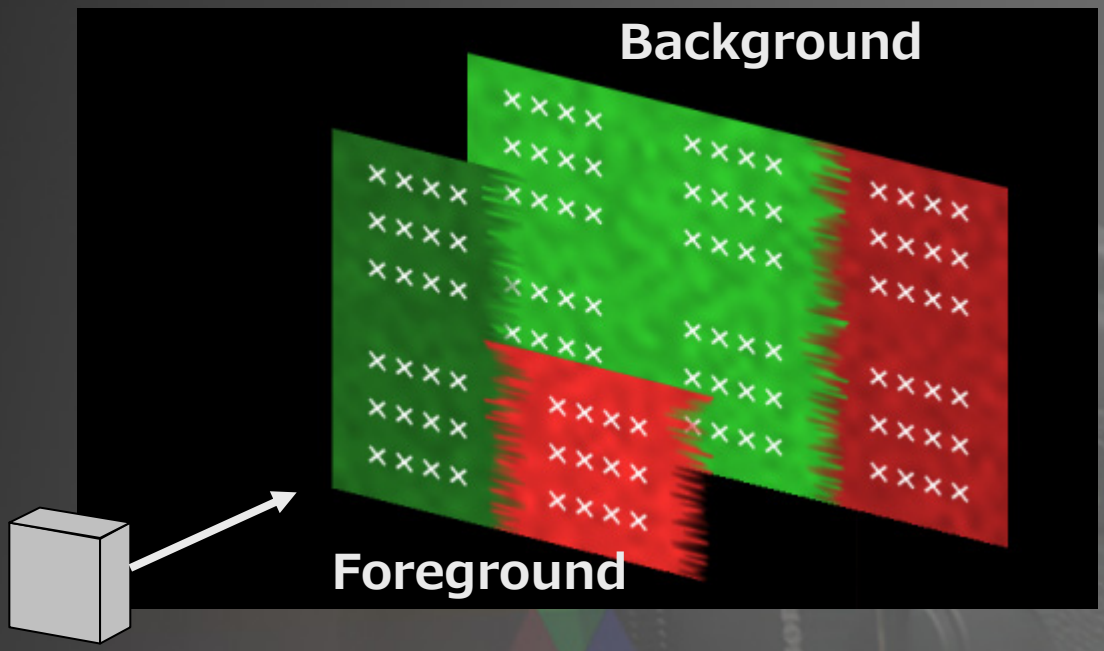
Synthetic Toy Example



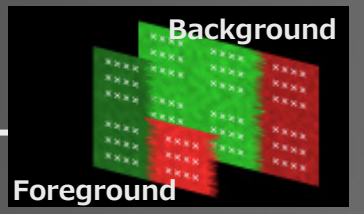
Synthesized input image



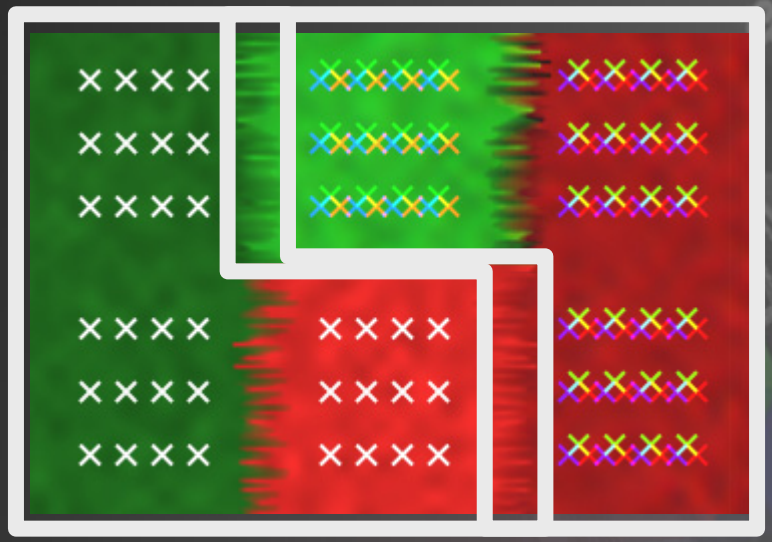
Ground truth matte



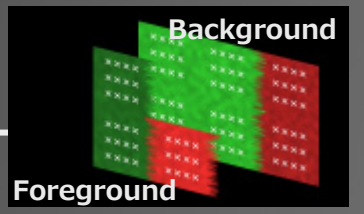
Synthetic Toy Example



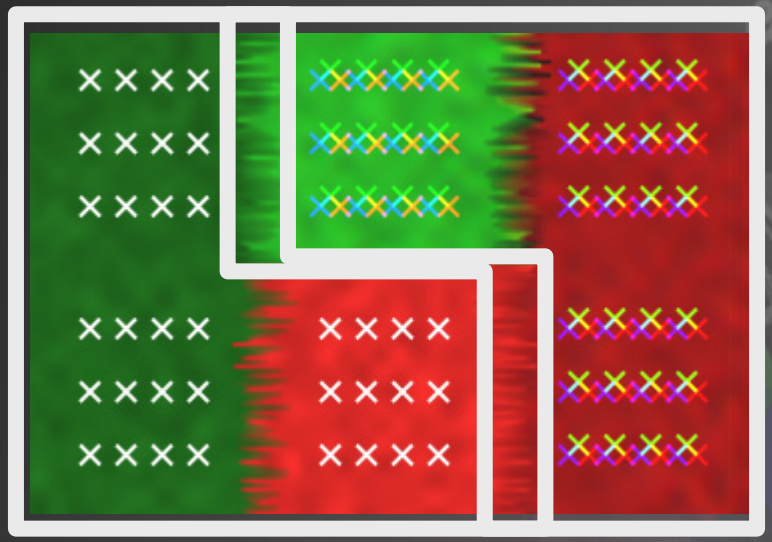
- **Hard example**
  - Similar foreground and background colors



Synthetic Toy Example

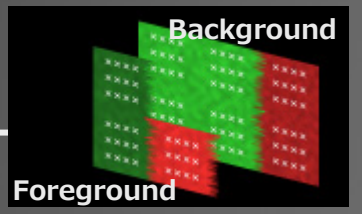


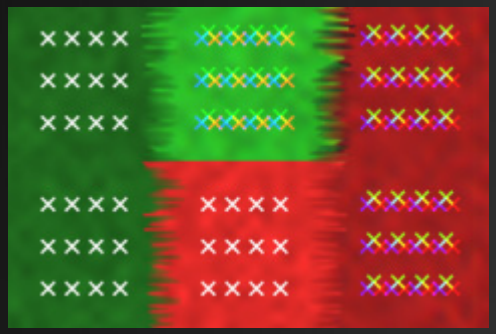
- **Hard example**
  - Similar foreground and background colors
- **But solvable**
  - Color misalignment cues from ‘x’ textures



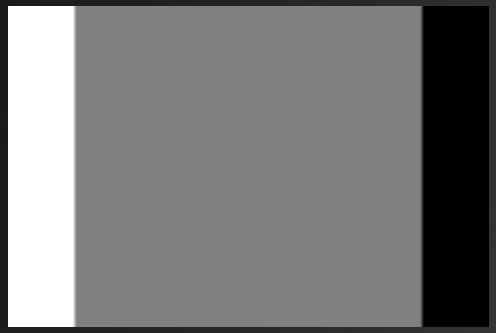
Foreground Background

Trimap-Based Matting



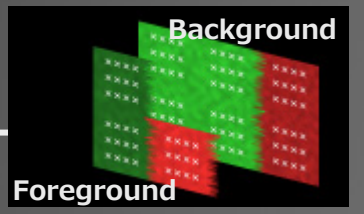


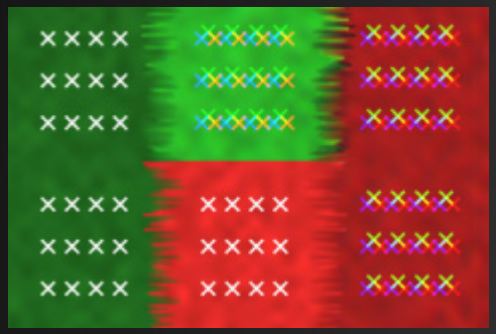
Input image



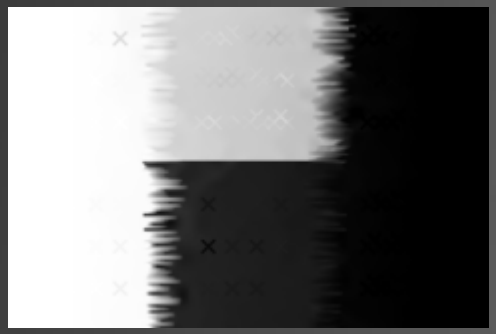
Trimap

Trimap-Based Matting

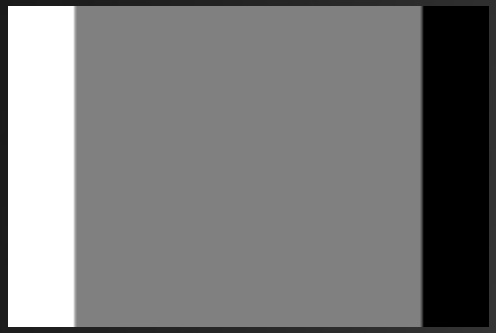




Input image

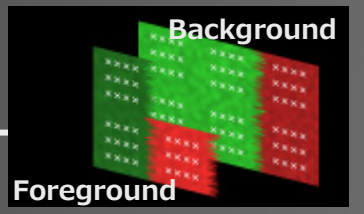


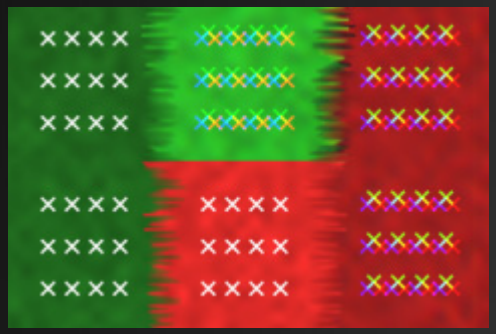
Estimated matte



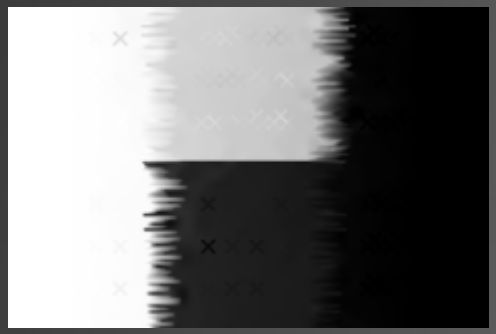
Trimap

Trimap-Based Matting

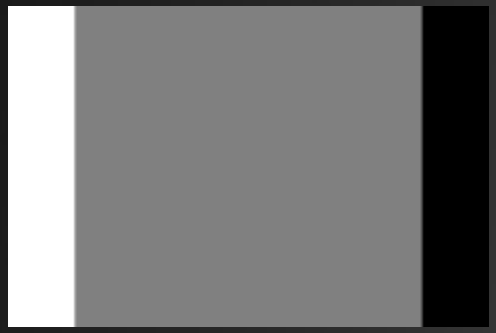




Input image



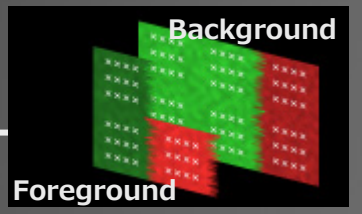
Estimated matte

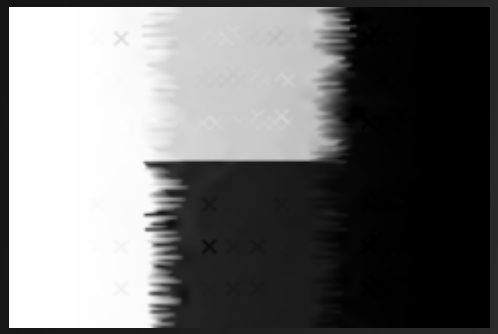


Trimap

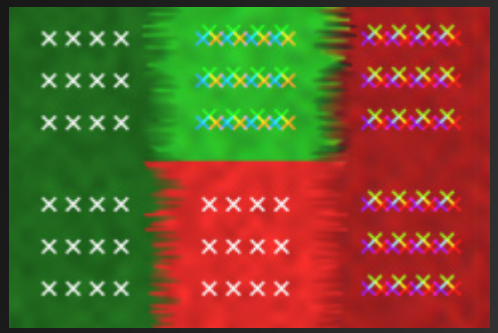
Ground truth

Matting Algorithm



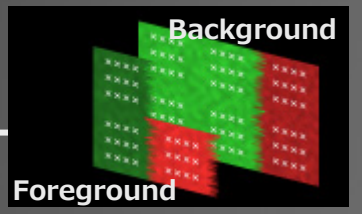


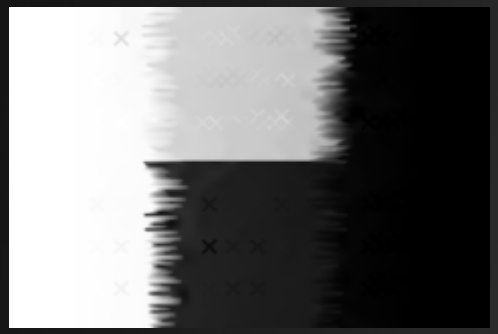
Current matte



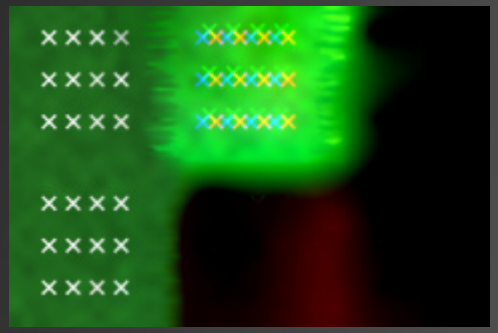
Input image

Matting Algorithm

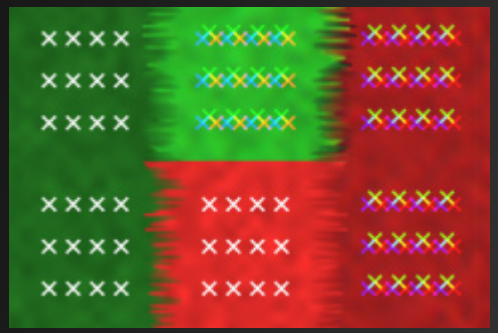




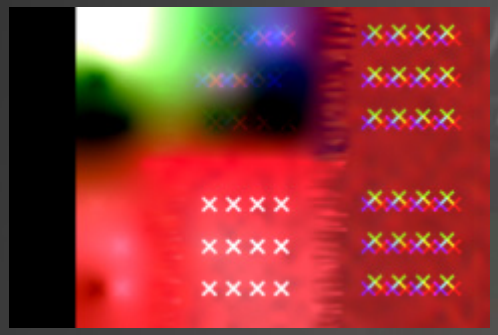
Current matte



Estimated foreground color

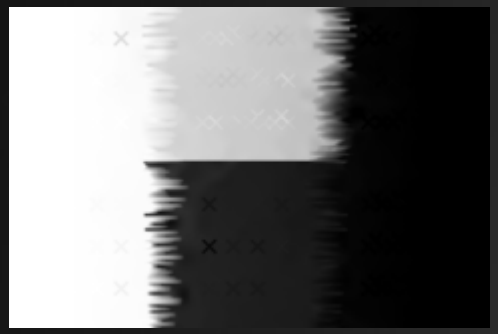


Input image

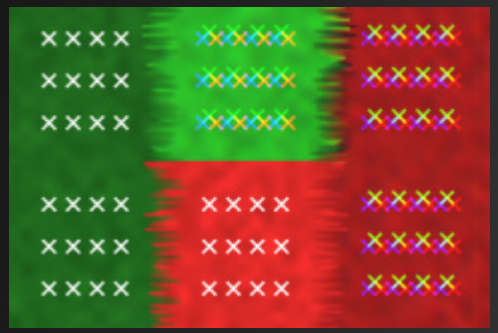


Estimated background color

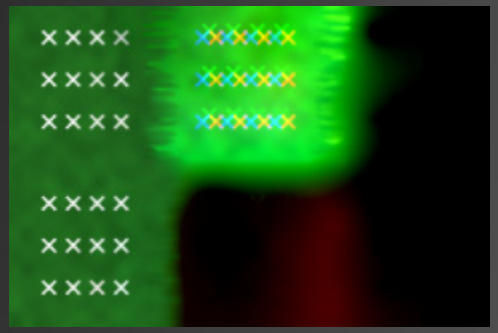
Matting Algorithm



Current matte

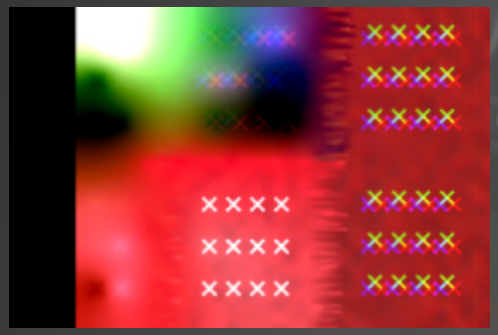


Input image



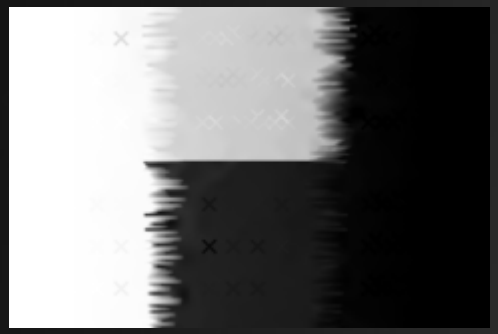
Estimated foreground color

Detected color-misalignment

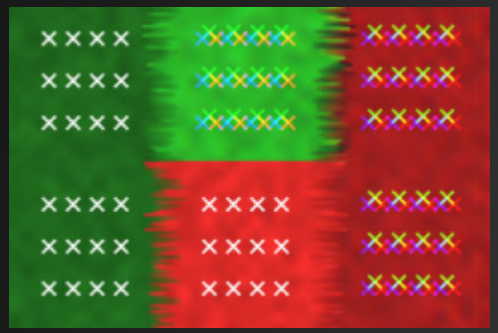


Estimated background color

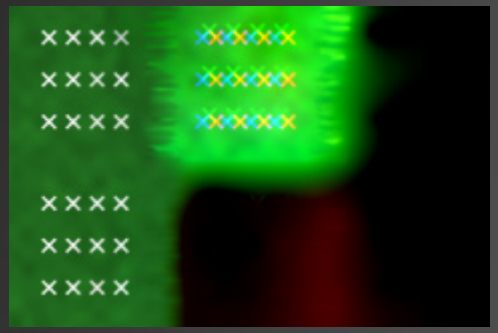
Matting Algorithm



Current matte

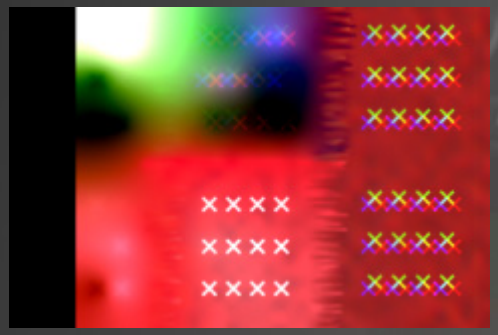


Input image



Estimated foreground color

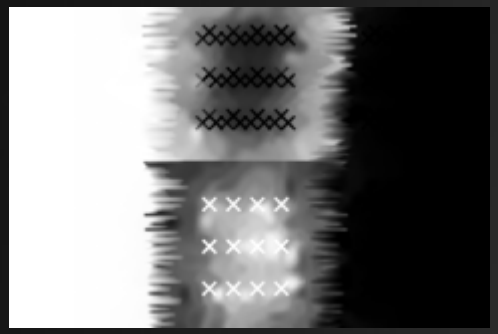
Detected color-misalignment



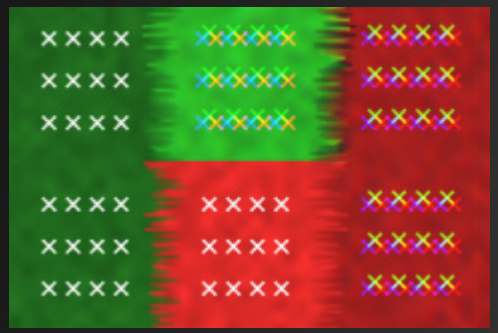
Estimated background color

Detected color-alignment

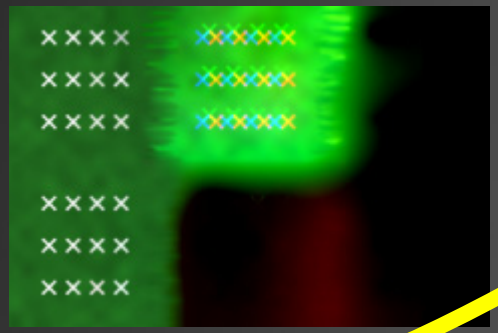
Matting Algorithm



Current matte

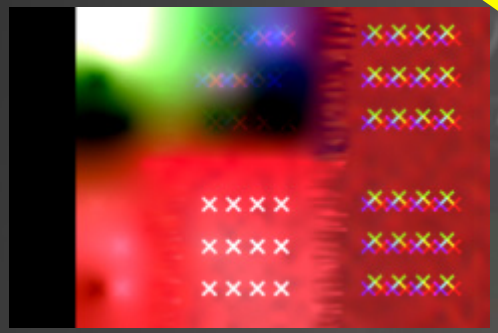


Input image



Estimated foreground color

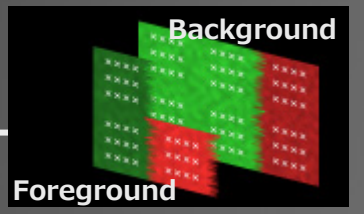
Detected color-misalignment



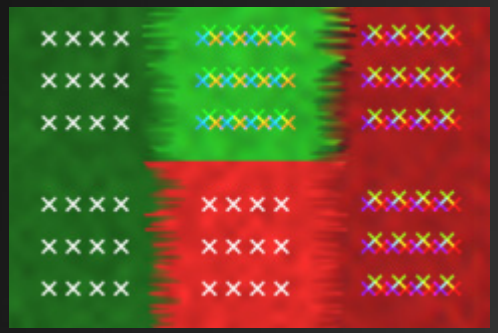
Estimated background color

Detected color-alignment

Matting Algorithm

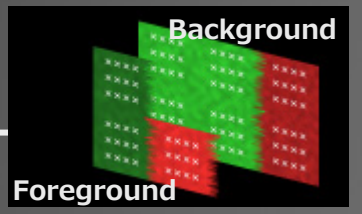


Final matte

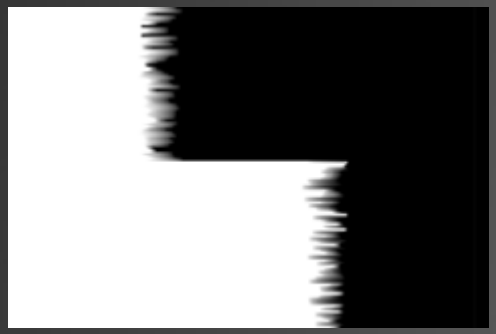


Input image

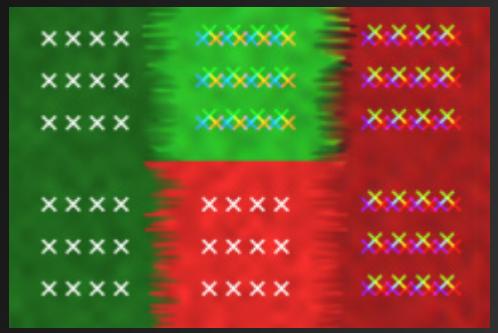
Matting Algorithm



Final matte



Ground truth



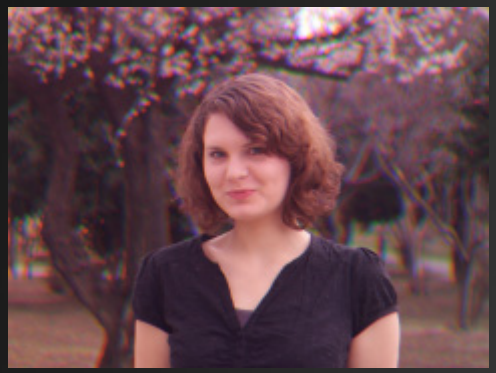
Input image

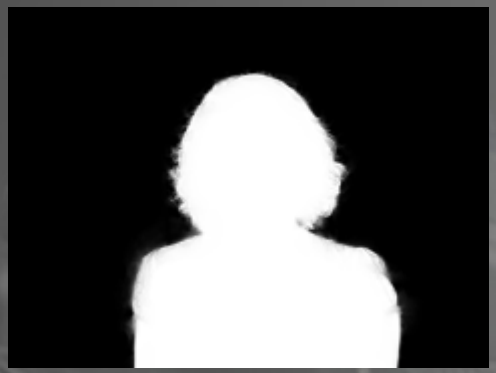
Outline

- Background
- Related Work
- Our Method
- **Results**
- Conclusion

Results of Depth & Matte Extraction



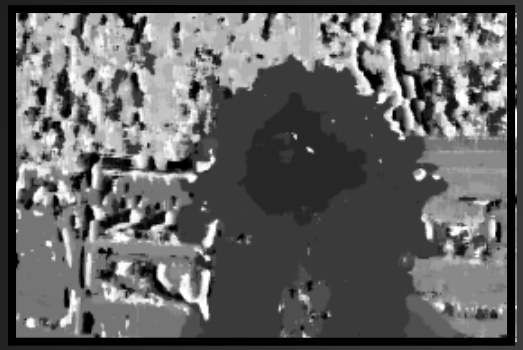


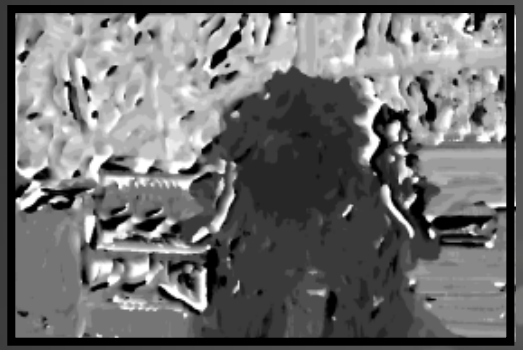

Captured image | Depth | Matte

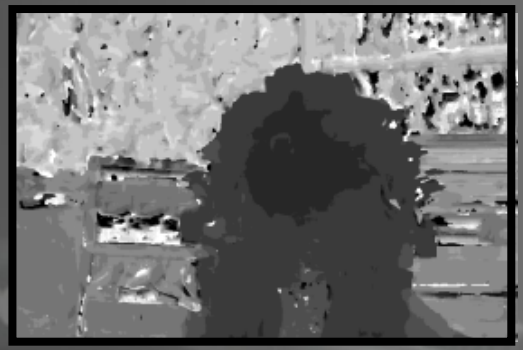
Comparison: Depth Estimation

- With the previous color-filter methods
  - Local estimation to show raw performance

Captured







Captured

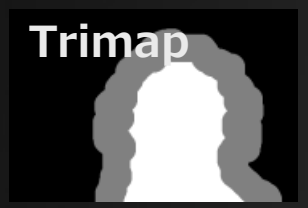
[Amari 1992]

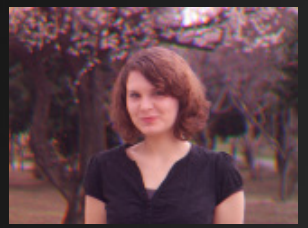
[Chang 2002]

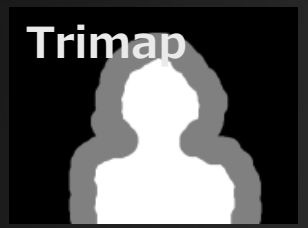
Our method

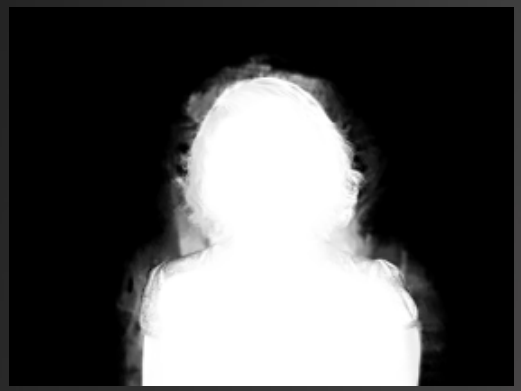
Comparison: Matting

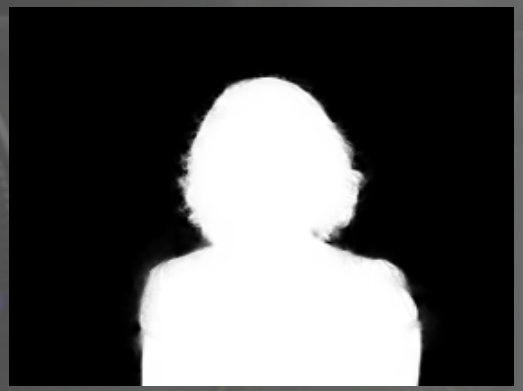
- With the trimap-based matting methods
  - The trimaps were generated by our method







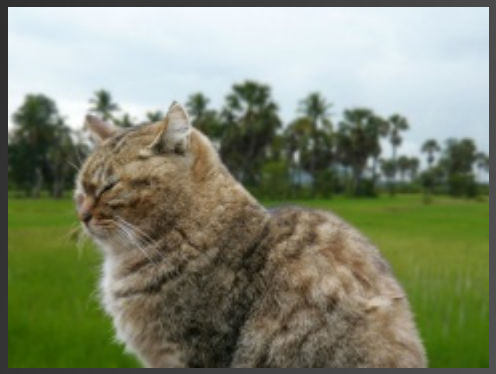




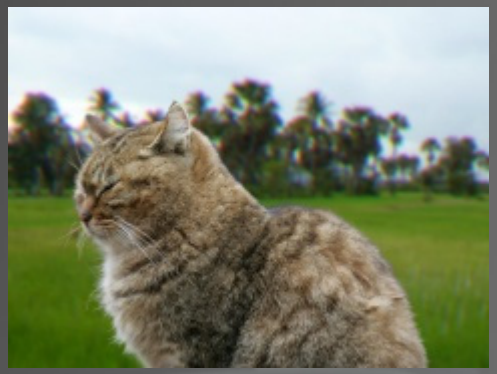
[Levin 2006] [Wang 2007] Our method

Comparison with Ground Truth Mattes

Ground truth



Composite image (color-aligned)



Composite image (color-misaligned)

[Levin 2006]

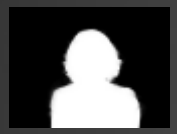
[Wang 2007]

Our method

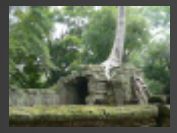
Image Editing

- Image composition
- Color-alignment reconstruction
- Novel view synthesis
- Refocusing
- Video matting

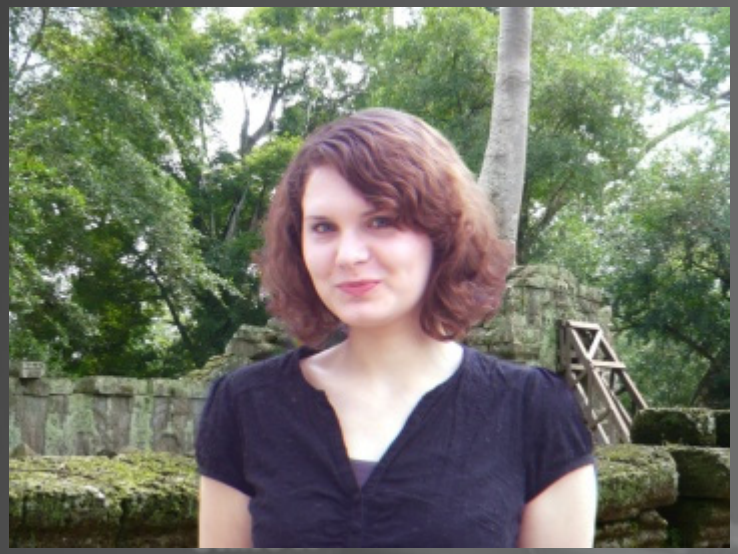
Example 1: Composition



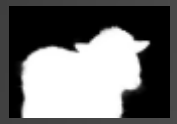
Matte



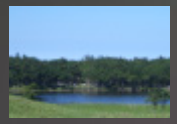
Different Background



Captured image



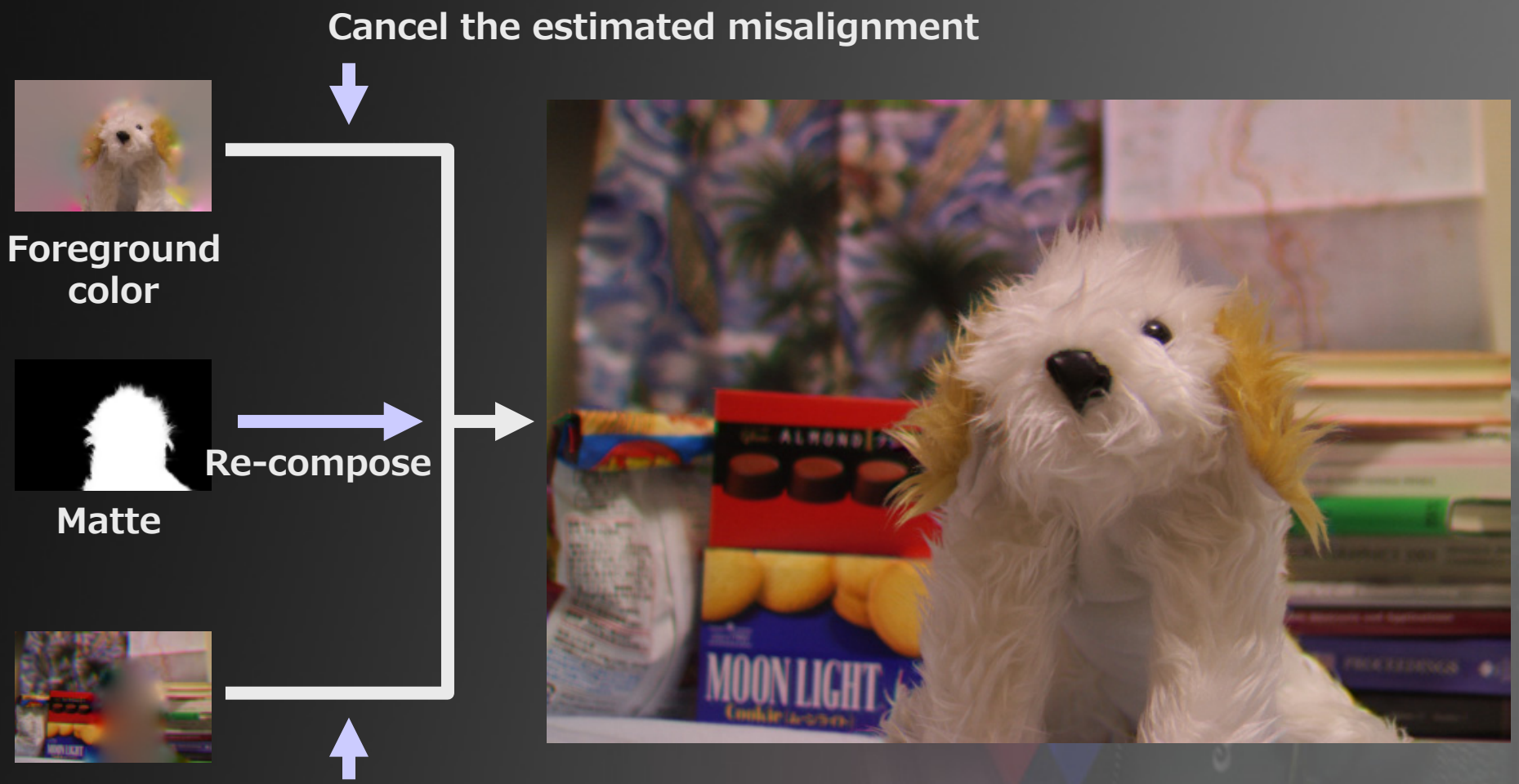
Matte



Different Background

Composite

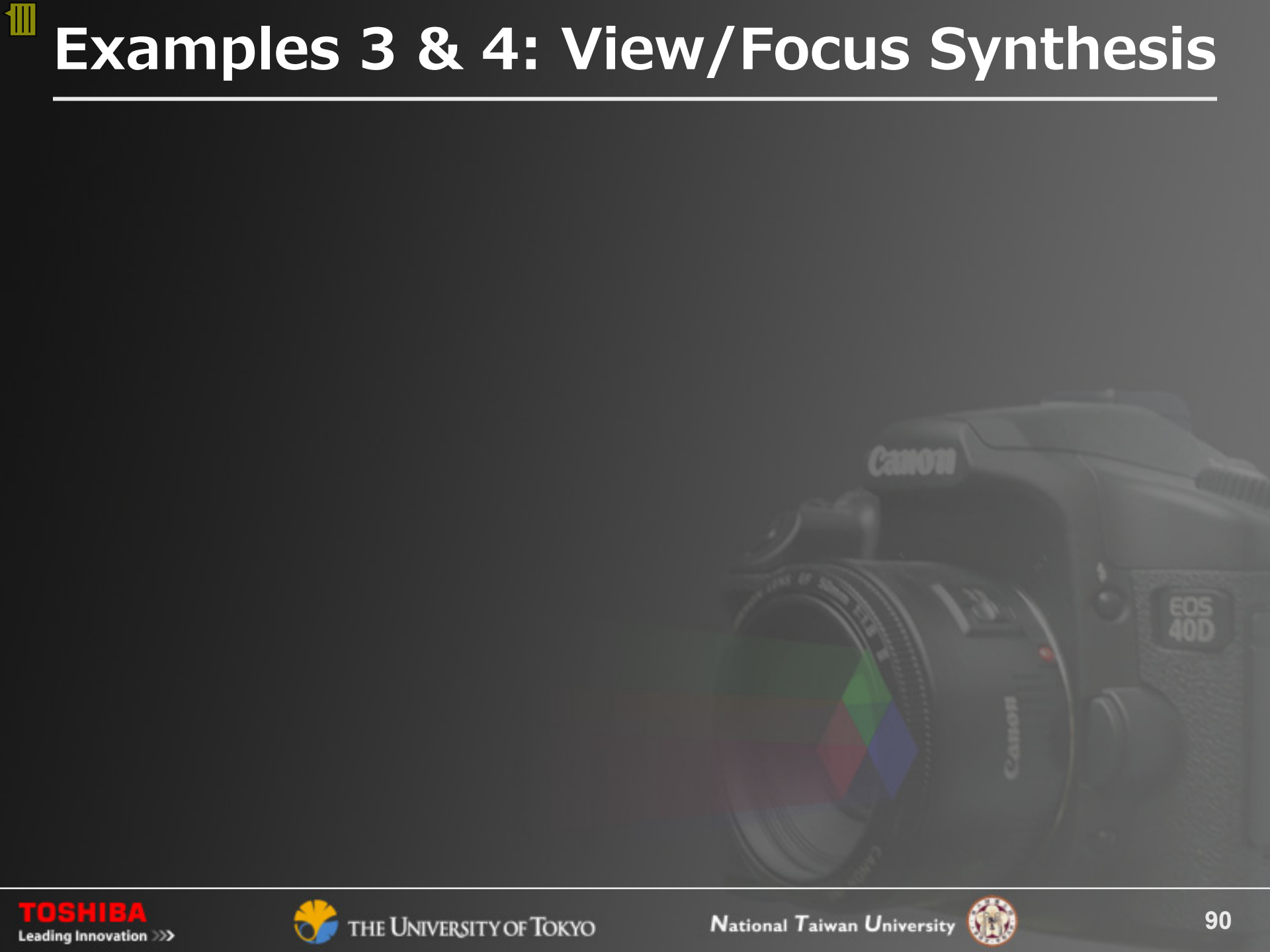
Example 2: Color-Alignment Reconst.



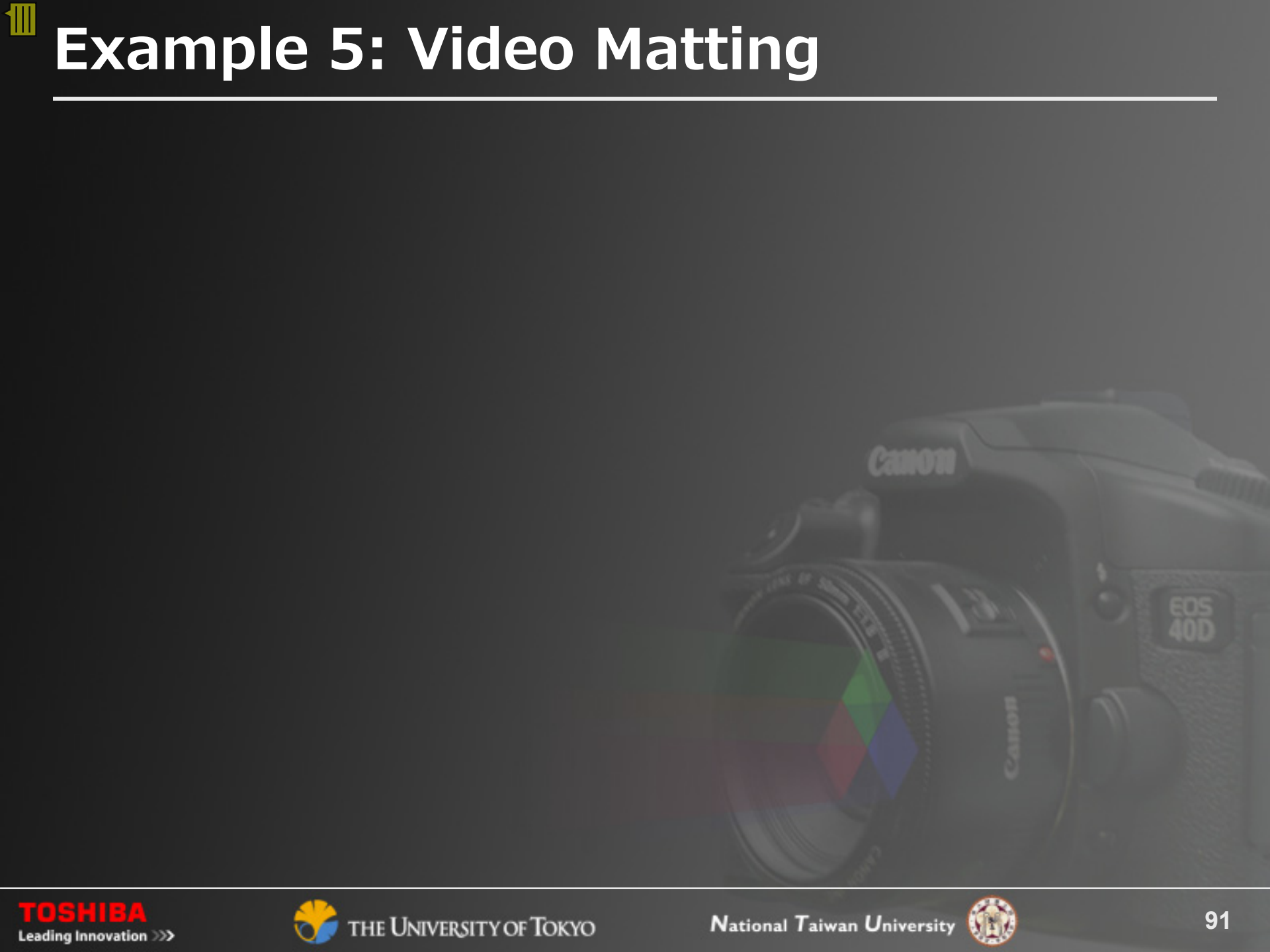
Reconstructed Image

Captured Image

Examples 3 & 4: View/Focus Synthesis



Example 5: Video Matting



Outline

- Background
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Conclusion

- **Automatic depth and matte extraction using a color-filtered aperture**
  - **Improved depth estimation**
  - **Novel matting algorithm**

Conclusion

- **Automatic depth and matte extraction using a color-filtered aperture**
  - Improved depth estimation
  - Novel matting algorithm

- **Easy-to-use computational photography**
  - Put color filters in a camera lens
  - Take a single photo with a hand-held camera

Conclusion

- **Automatic depth and matte extraction using a color-filtered aperture**
  - Improved depth estimation
  - Novel matting algorithm

- **Easy-to-use computational photography**
  - Put color filters in a camera lens
  - Take a single photo with a hand-held camera

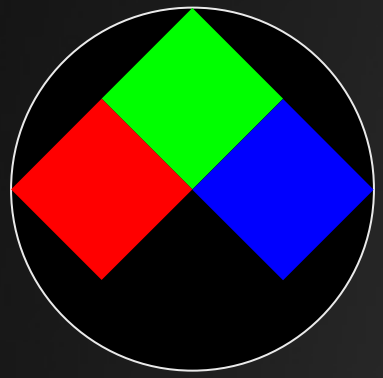
- **Limitation**
  - *Entirely* red objects cannot be handled

Thank You!!

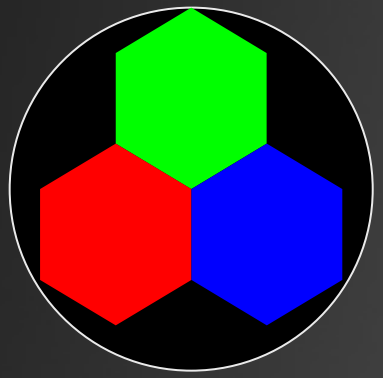
- Any questions?

- Acknowledgments
  - Takeshi Naemura
  - Yusuke Iguchi
  - Takuya Saito
  - Johanna Wolf
  - Zoltan Szego
  - Paulo Silva
  - Saori Horiuchi

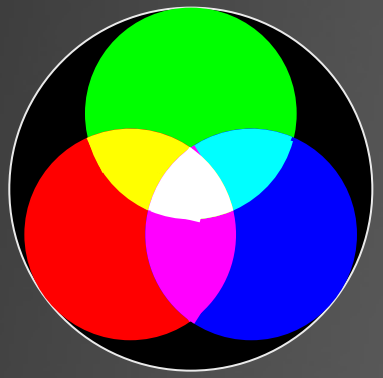
Other Possible Filter Arrangements



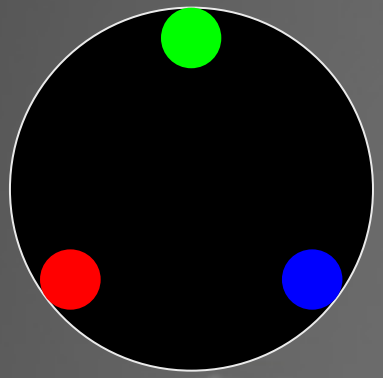
Our prototype



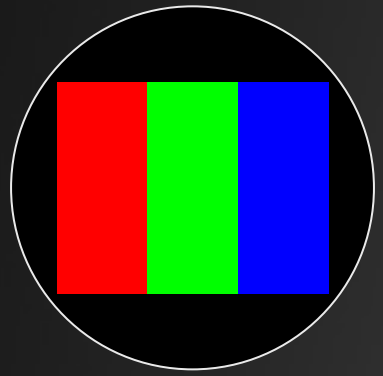
More light-efficient



Even more light-efficient but with lower depth resolution

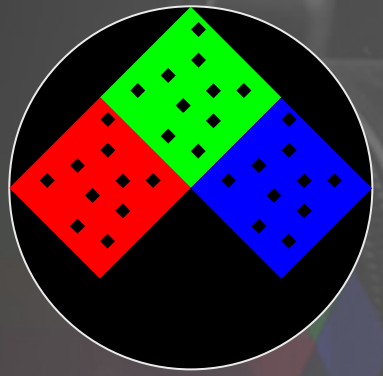


Higher depth resolution

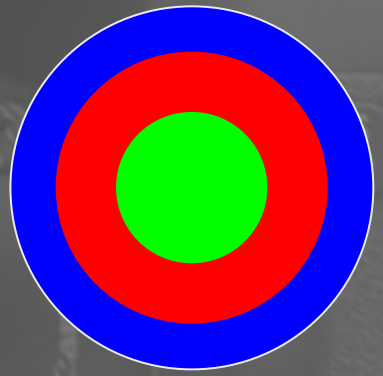


Simple horizontal arrangement

Arbitrary shapes



Combination with coded aperture



Multi-aperture