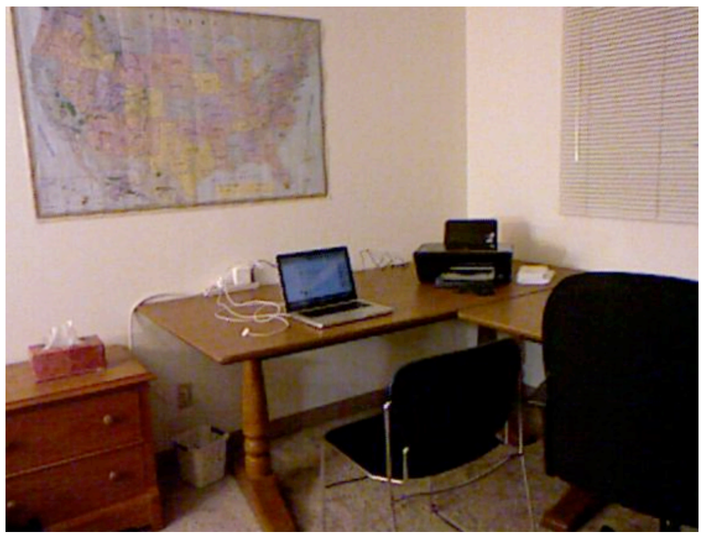
Perceptual Organization and Recognition of Indoor Scene from RGB-D Images

Saurabh Gupta, Pablo Arbeláez, Jitendra Malik

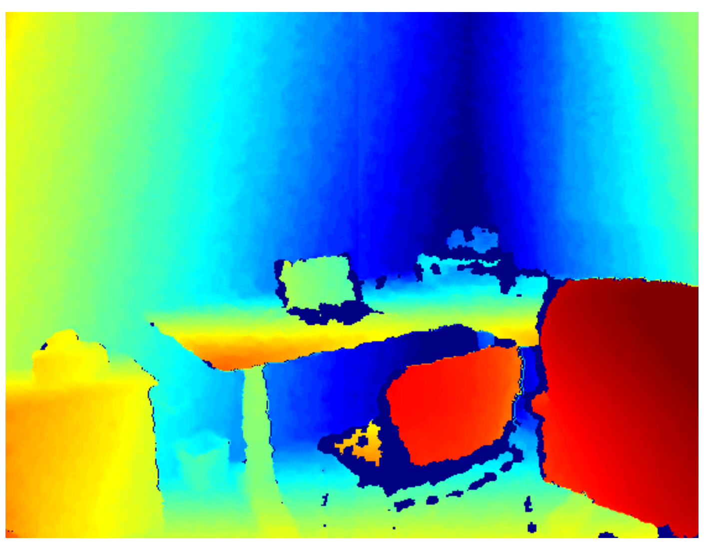
UC Berkeley

Semantic Segmentation with RGB-D

Input



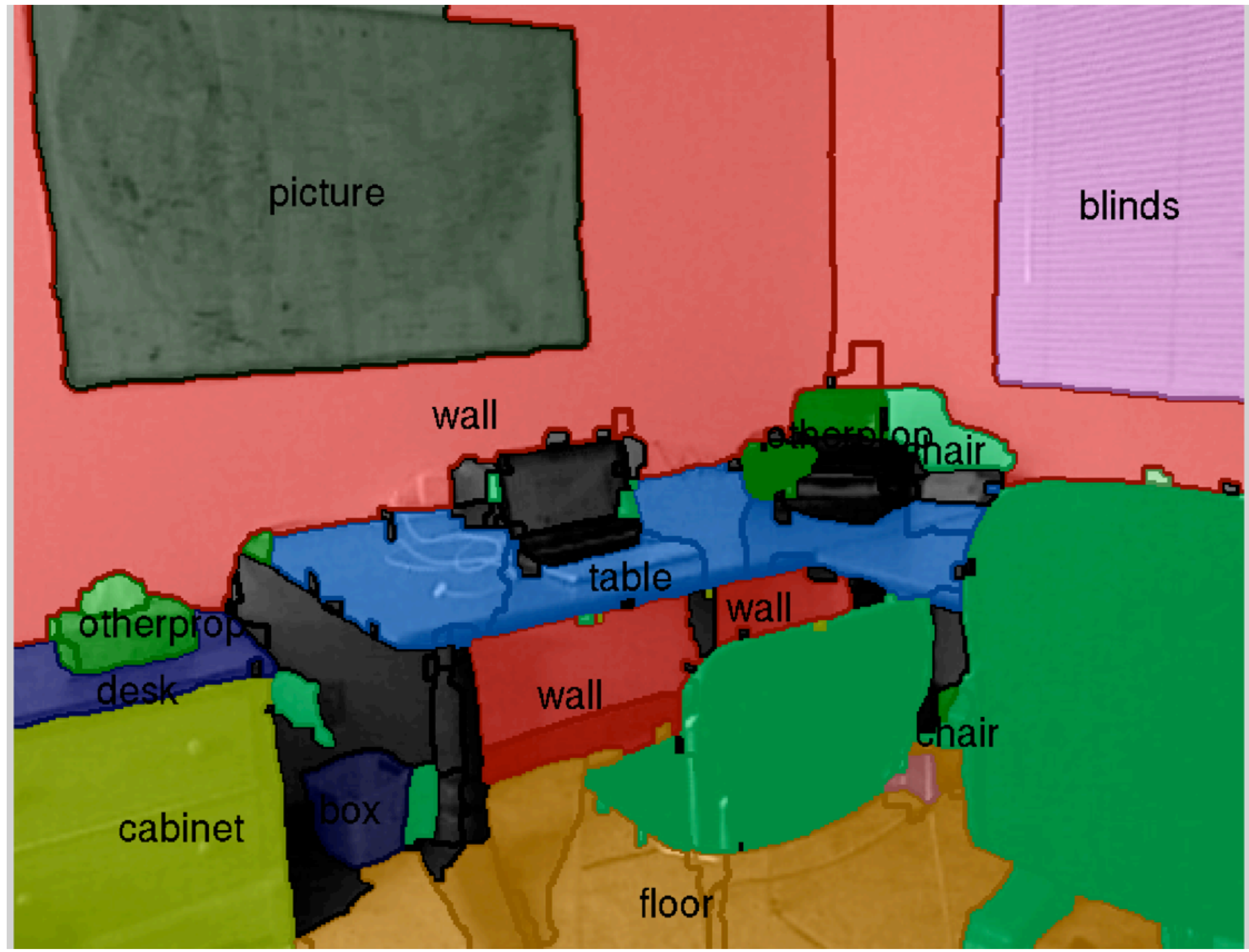
RGB



Depth

Near Far

Output



Semantic Segmentation with RGB-D

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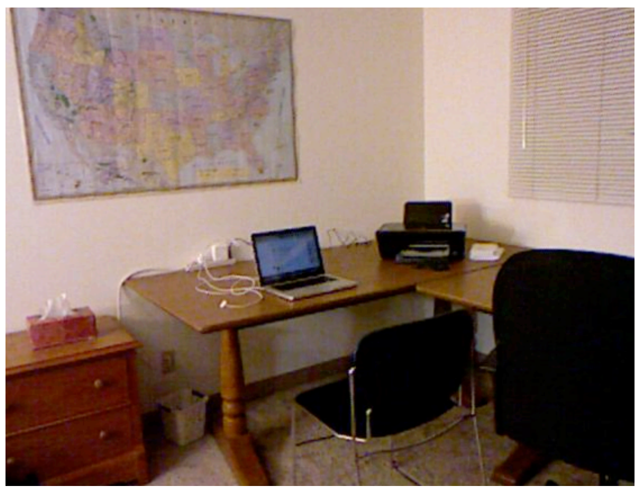
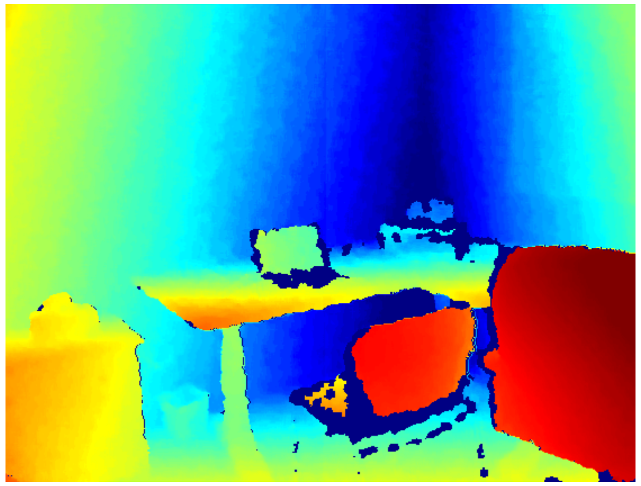


RGB

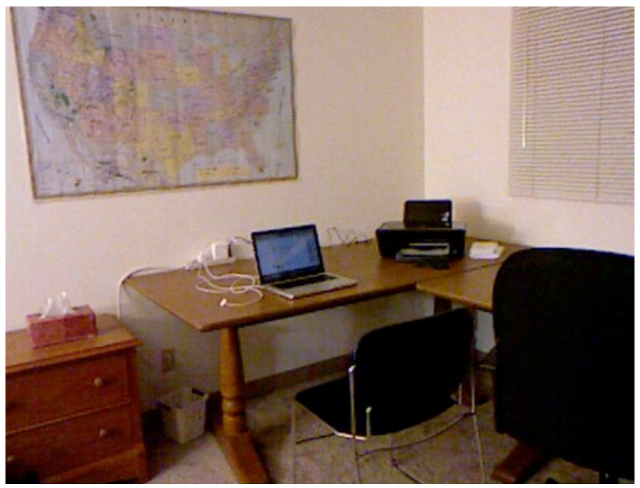


Depth

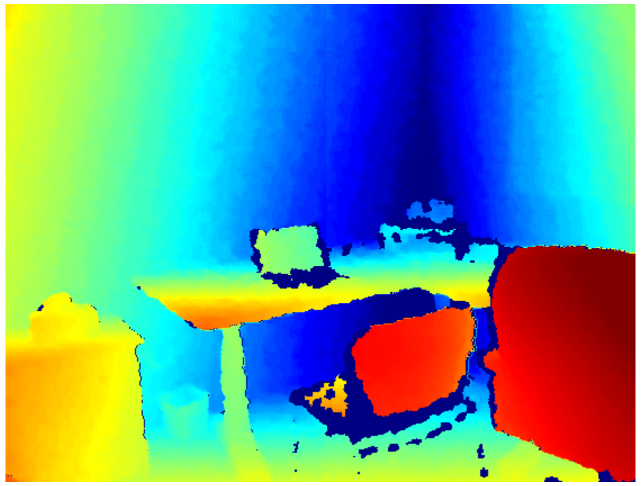
Semantic Segmentation with RGB-D

Input

Reorganization



RGB



Depth

Semantic Segmentation with RGB-D

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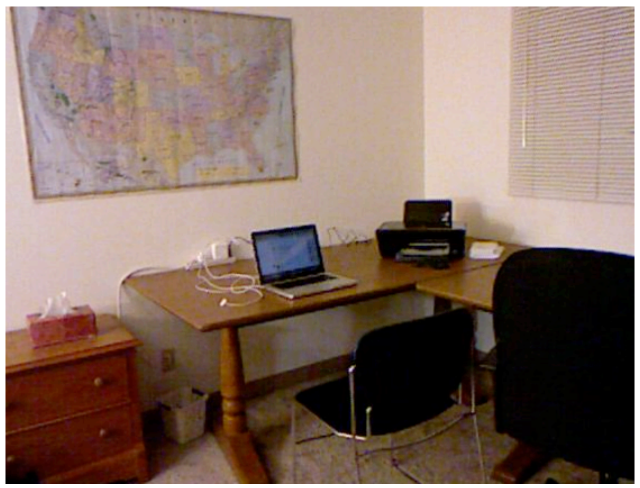
Reorganization



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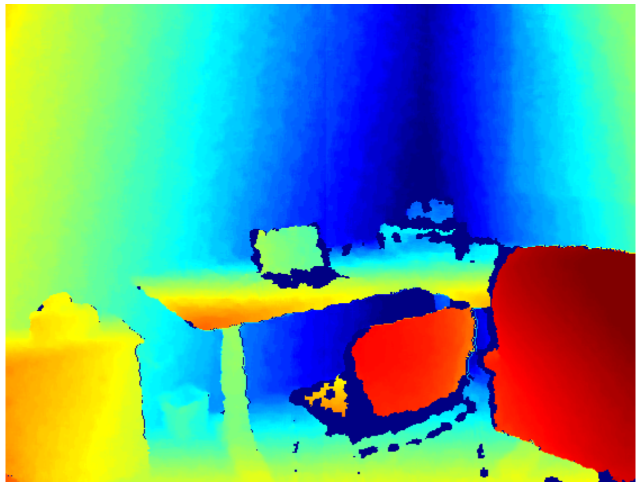

Depth

Semantic Segmentation with RGB-D

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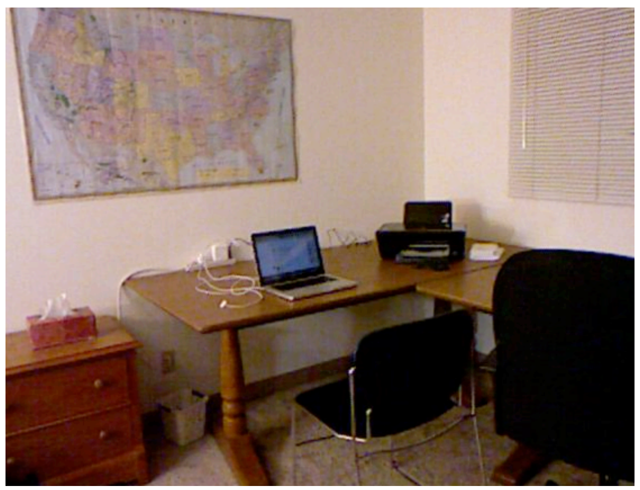
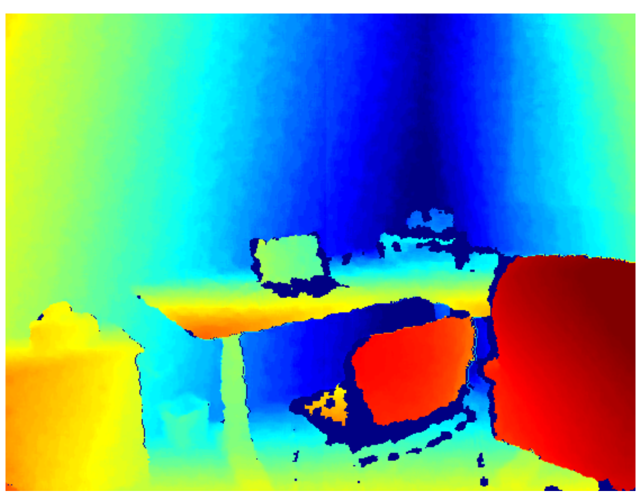
Reorganization



RGB



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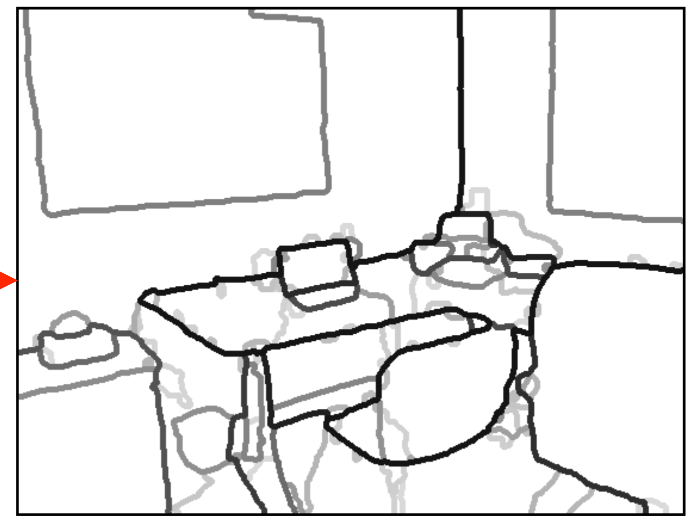
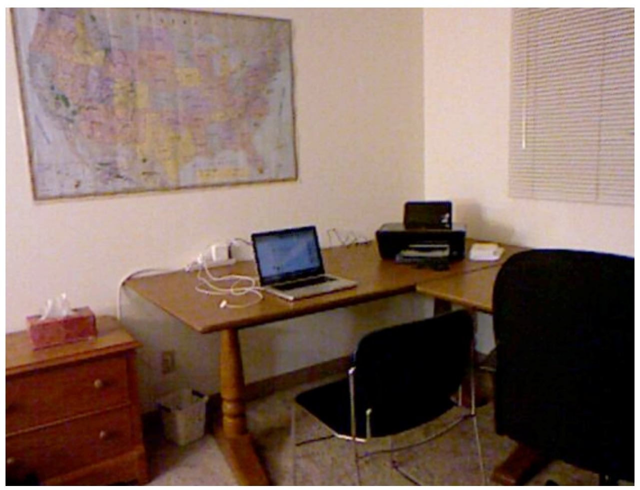


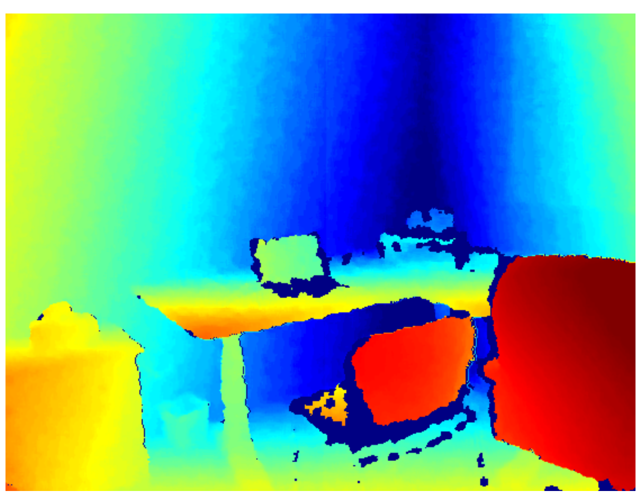
Bottom-Up Segmentation

Semantic Segmentation with RGB-D

Input

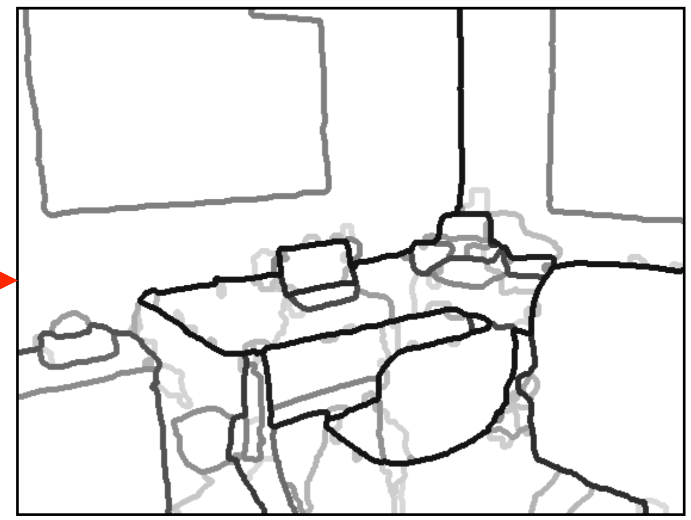


RGB



Depth

Reorganization



Bottom-Up
Segmentation

Amodal
Completion

Semantic Segmentation with RGB-D

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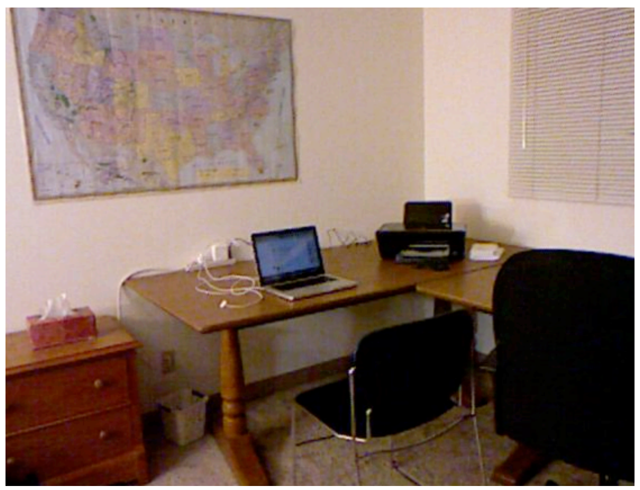

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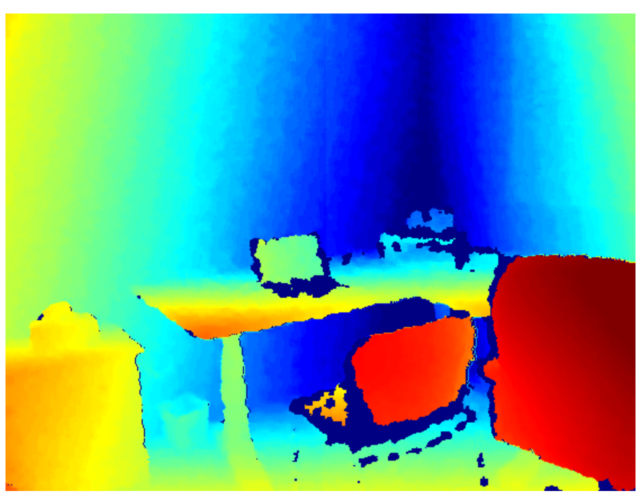

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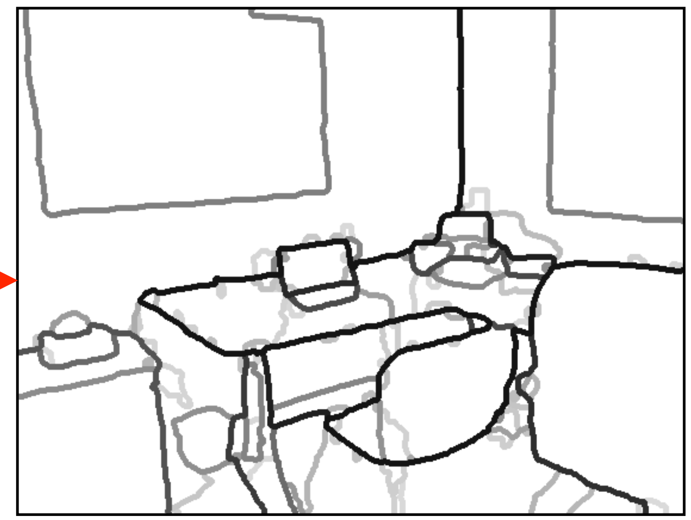


Bottom-Up Segmentation

Amodal Completion

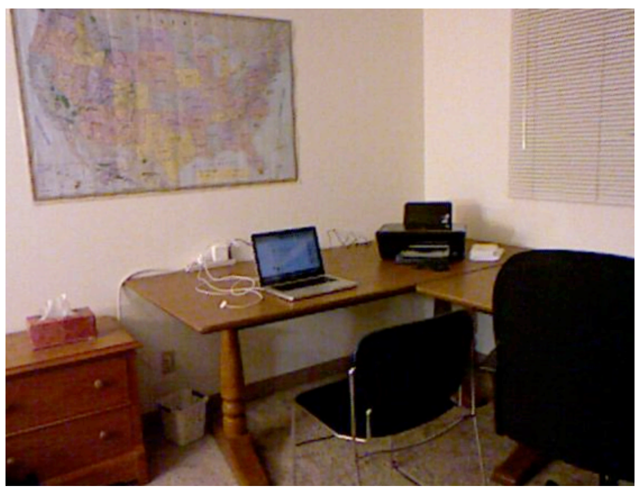
Semantic Segmentation

Semantic Segmentation with RGB-D

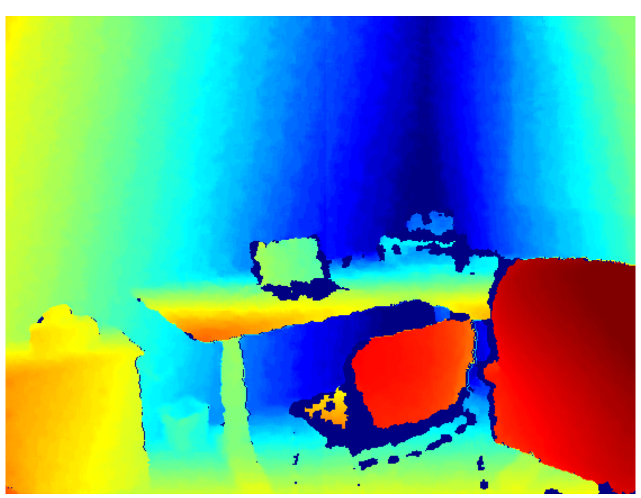
Input

Reorganization

Semantic Segmentation



RGB



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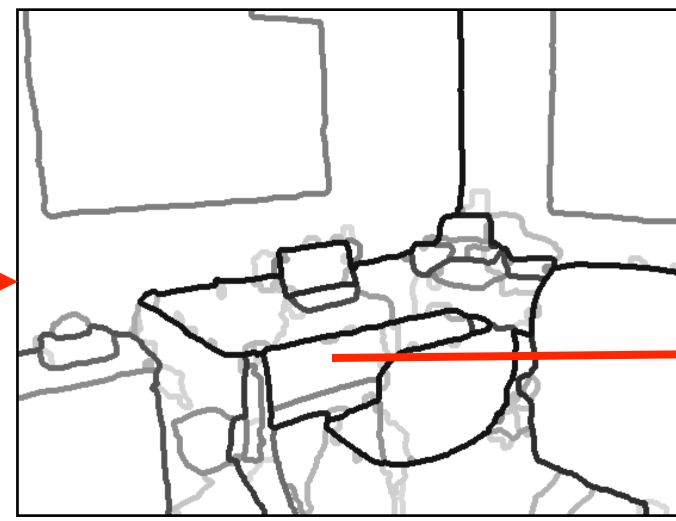

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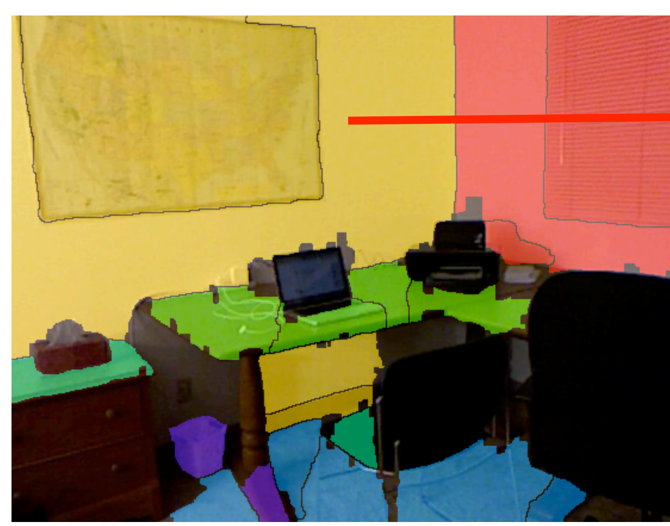

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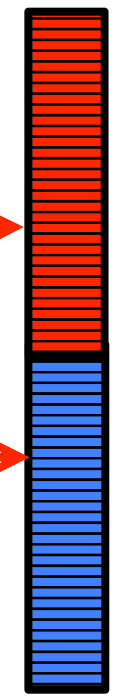
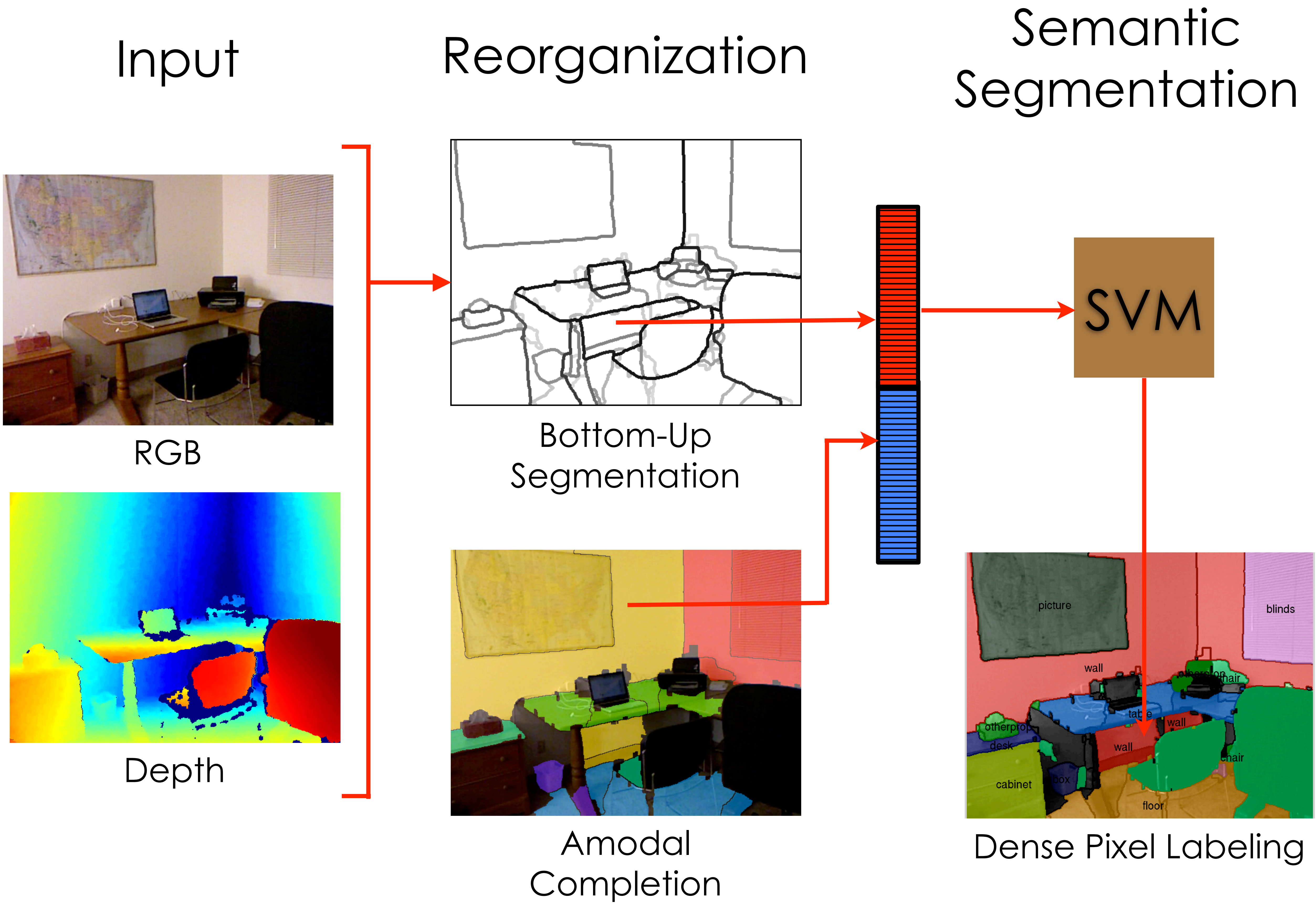


Semantic Segmentation with RGB-D



Related Work

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Anand et al., IJRR12, Contextually Guided Semantic Labeling and Search for 3D Point Clouds **[Cornell]**

Modeled context using structural SVMs for semantic segmentation in full 3D Scenes

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Using Kernel descriptor features and Tree path context for semantic segmentation

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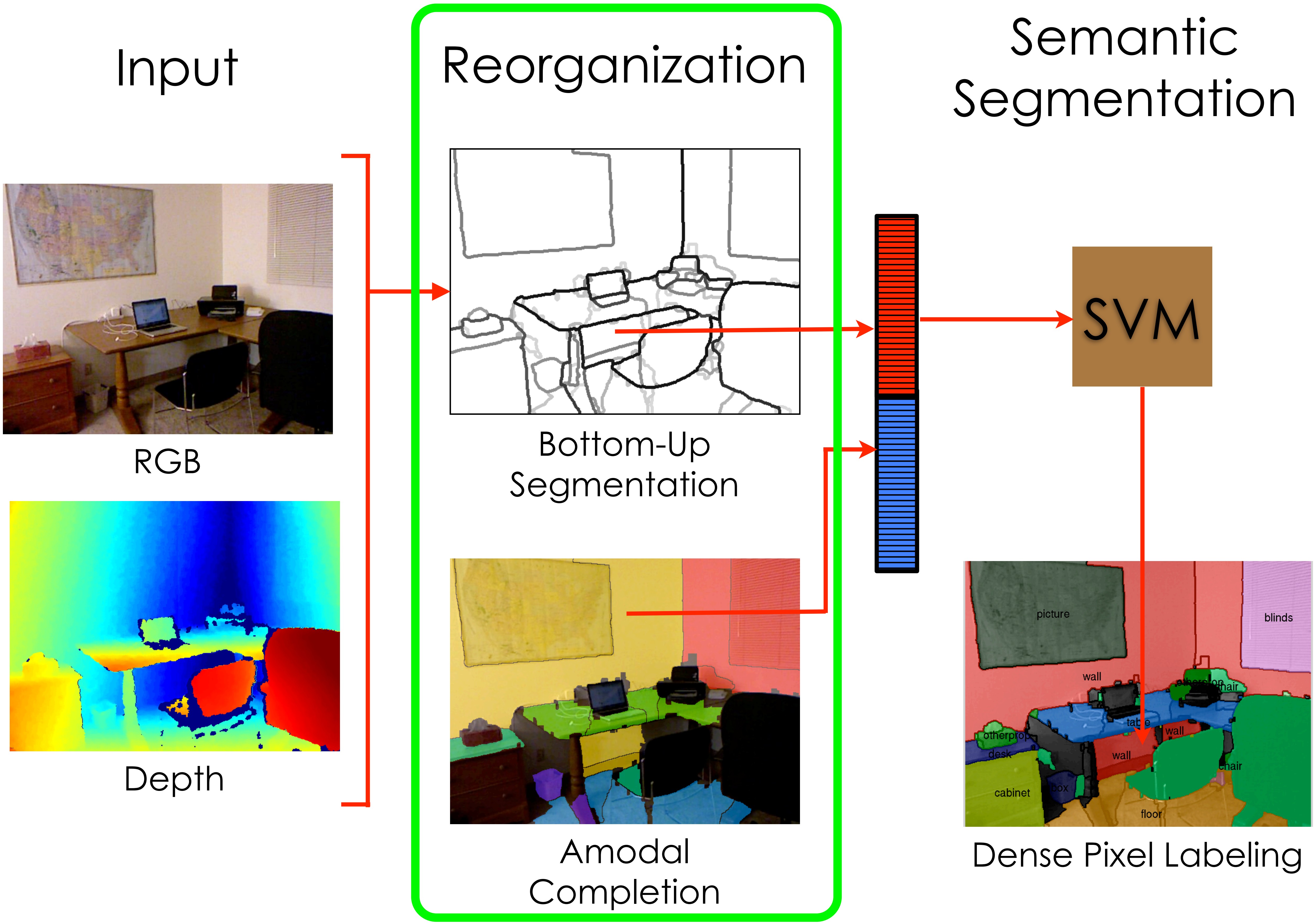
Silberman et al., ECCV12, Indoor segmentation and support inference from RGBD images **[NYU]**

Bottom-up and semantic segmentation, and inference of support relations in RGBD Scenes

- Also introduced a RGBD dataset (NYUD2) with semantic segmentation labels (~1500 images, ~900 classes)

- Looked at a 4 class semantic segmentation (floor, structure, furniture, props)

Semantic Segmentation with RGB-D



Bottom-Up Segmentation

Arbeláez et al., PAMI 2011, Contour Detection and Hierarchical Image Segmentation.
Martin et al., PAMI 2004, Learning to Detect Natural Image Boundaries Using Local Brightness, Color, and Texture Cues

Bottom-Up Segmentation

Adapt the gPb-ucm machinery from Arbeláez et al. from RGB to RGB-D images

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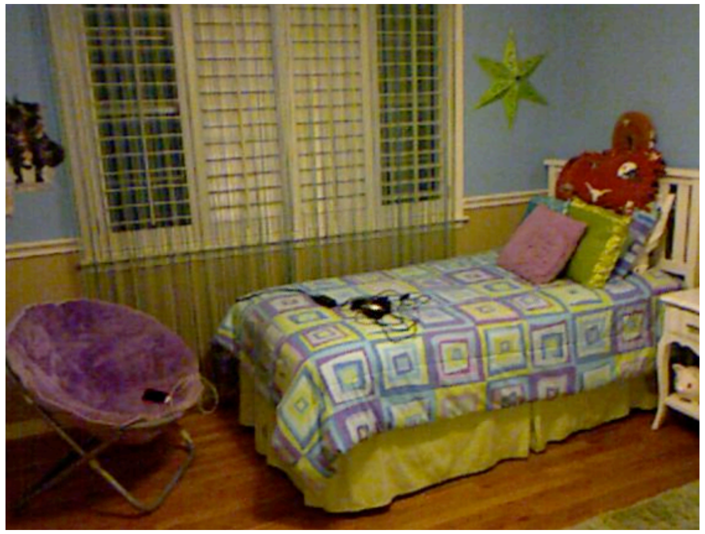

Input RGB Image

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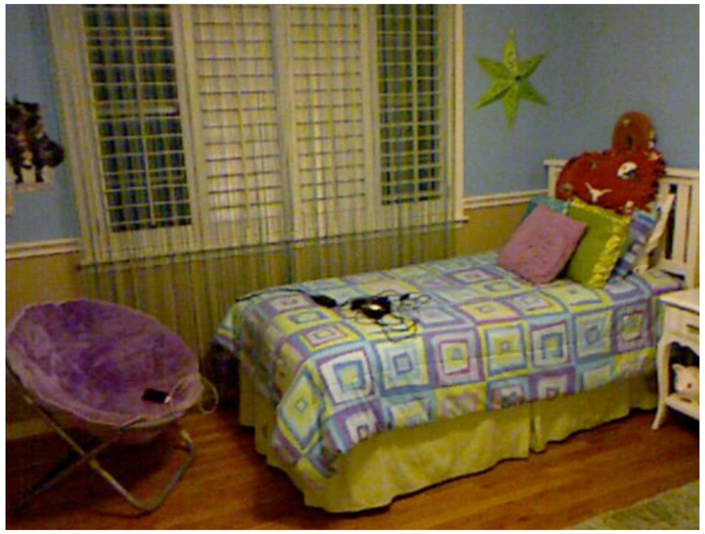

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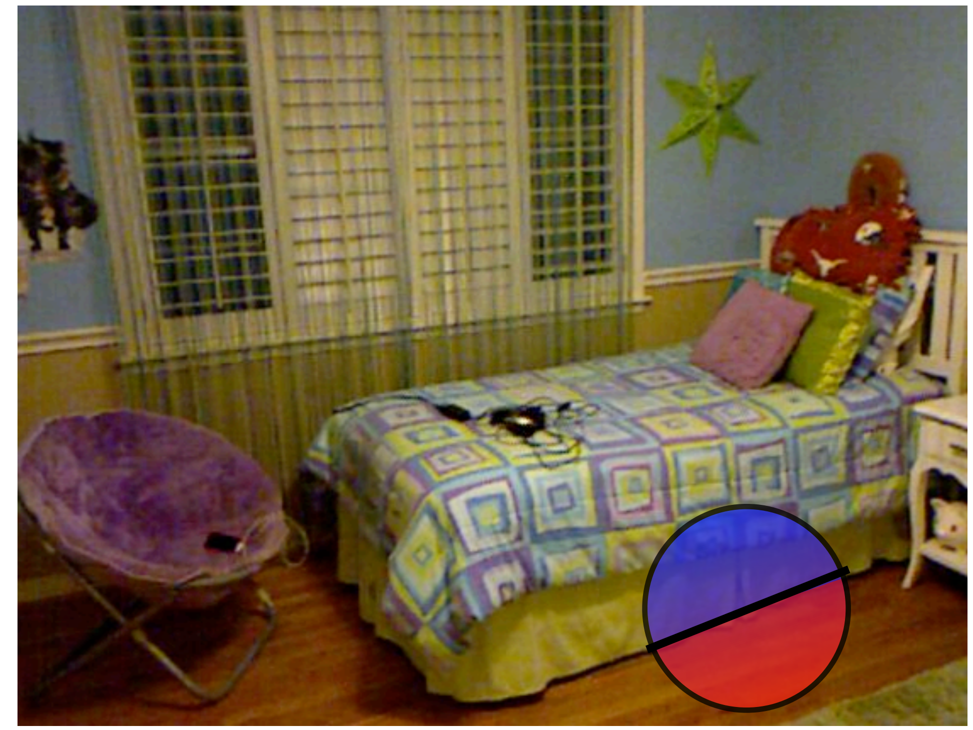

Oriented Local Gradients

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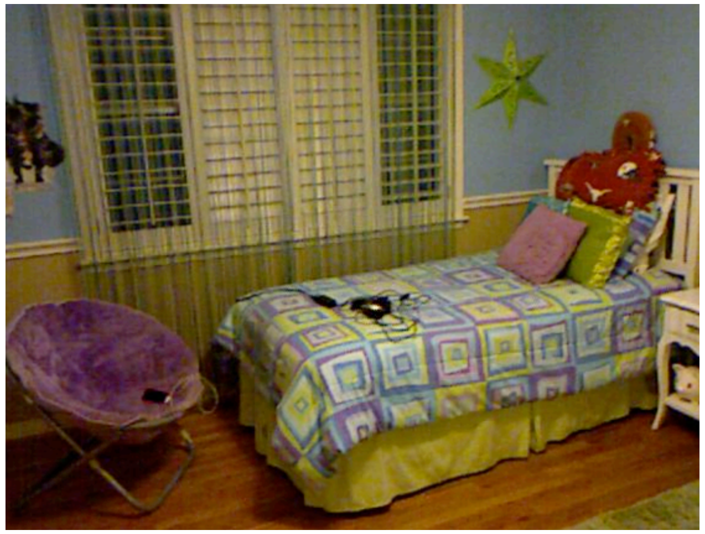
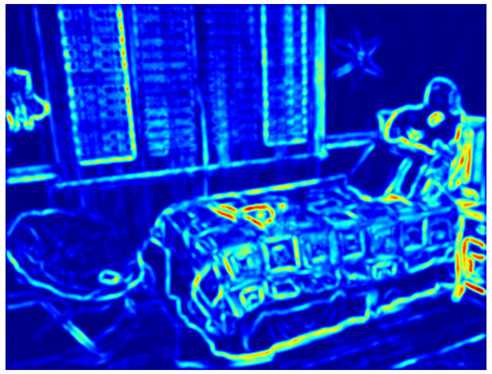


Input RGB Image

Brightness Gradient



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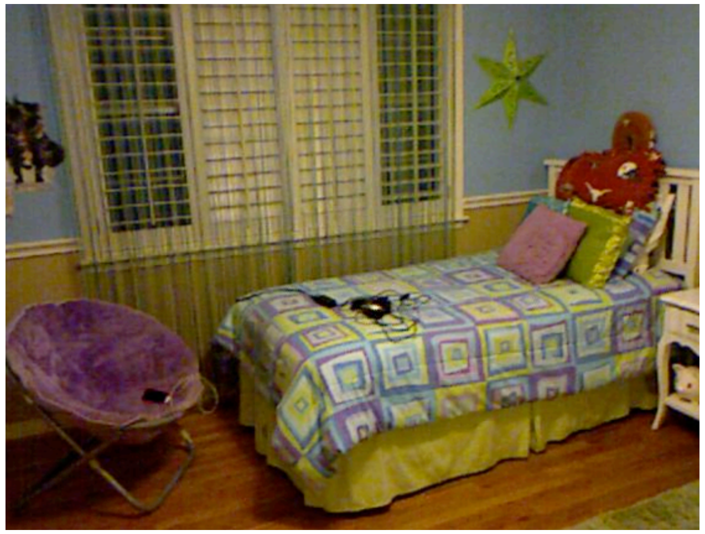

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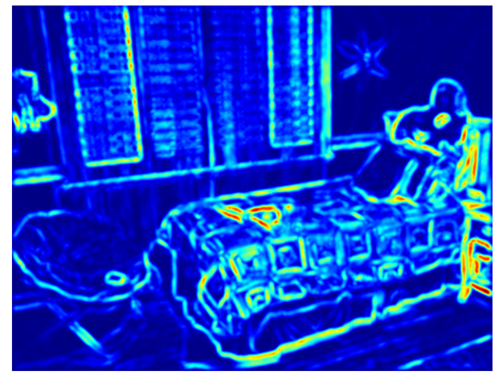
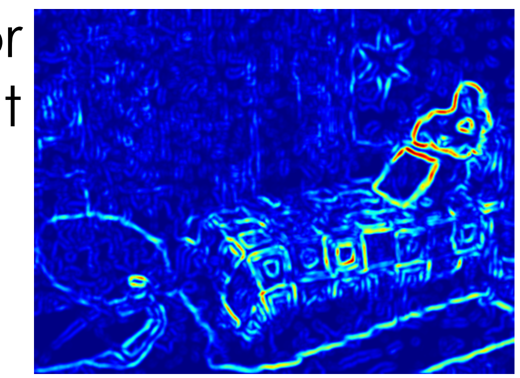
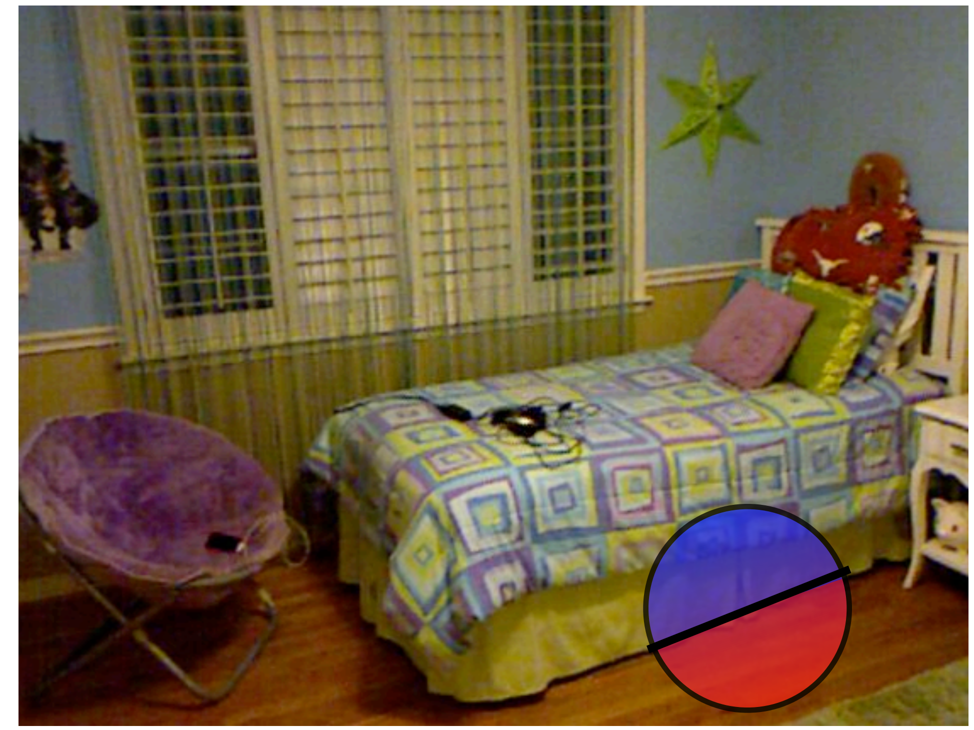
Brightness Gradient



Color Gradient





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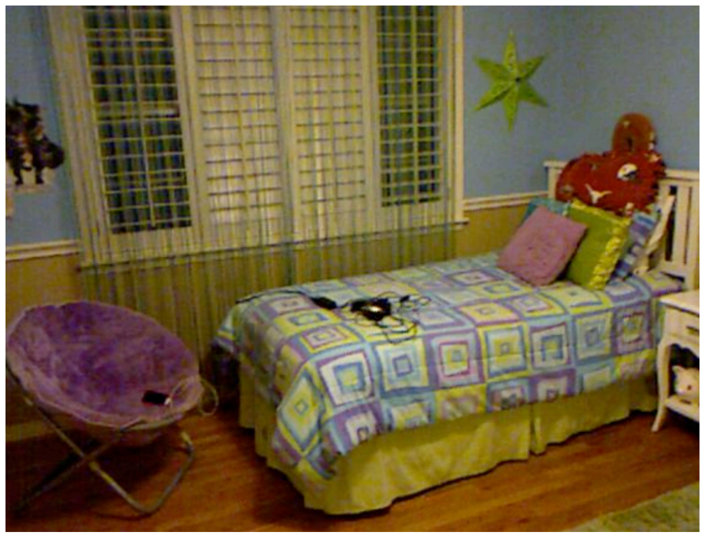
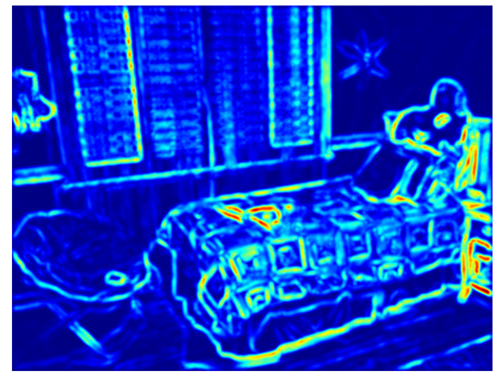
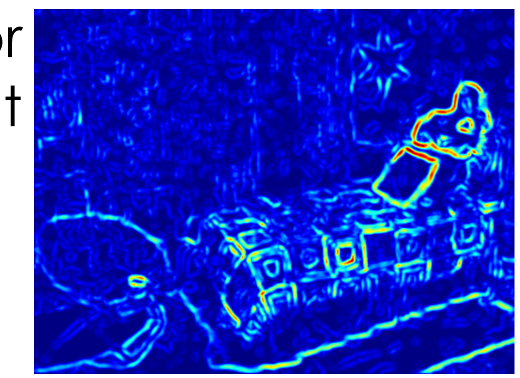


Input RGB Image

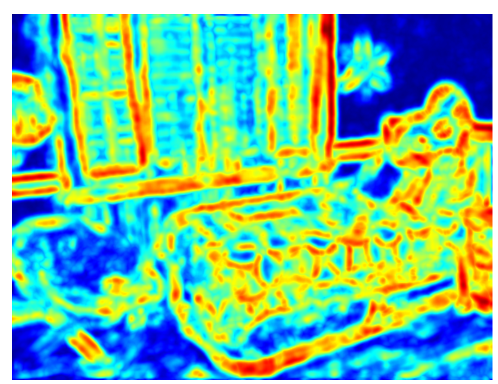
Brightness Gradient



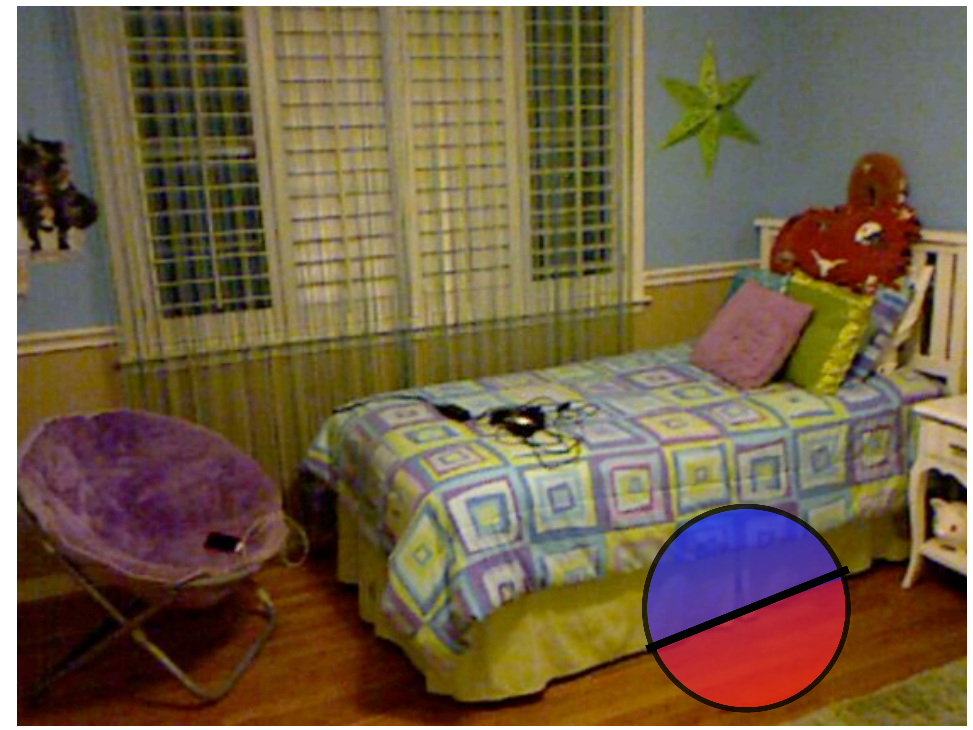
Color Gradient



Texture Gradient



Multi-scale Local Gradients



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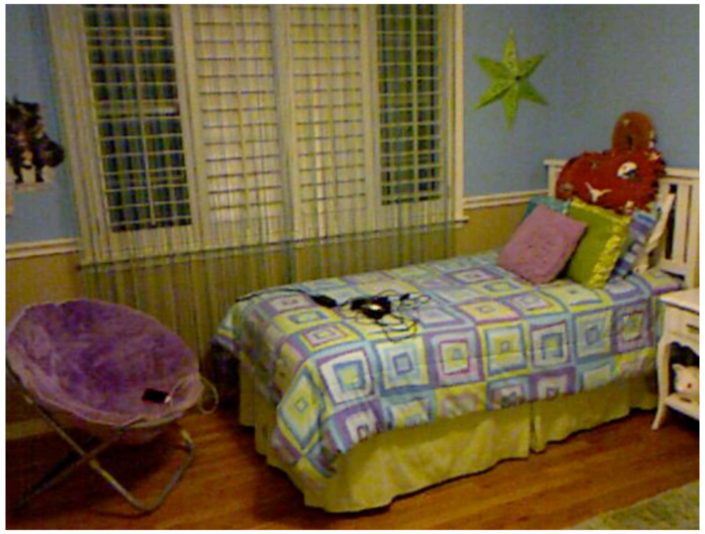
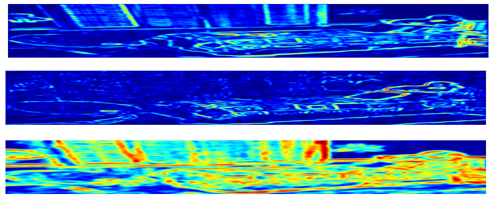
Bottom-Up Segmentation

Adapt the gPb-ucm machinery from Arbeláez et al. from RGB to RGB-D images



Input RGB Image

Gradient from Color Image



Multi-scale Local Gradients

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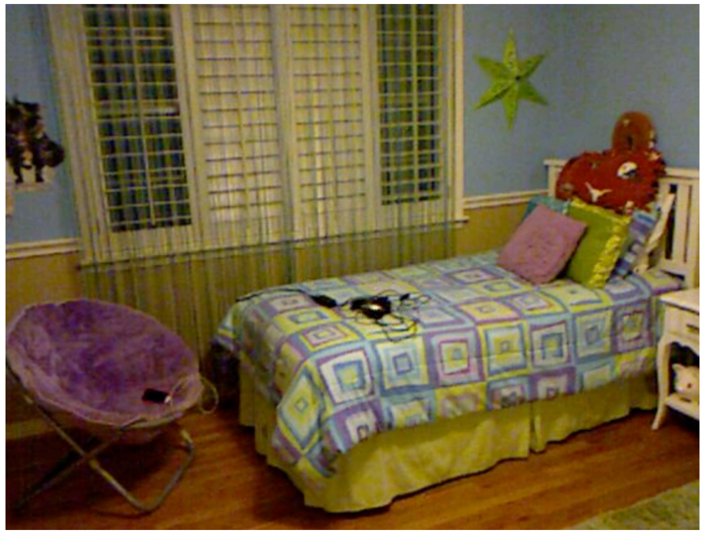

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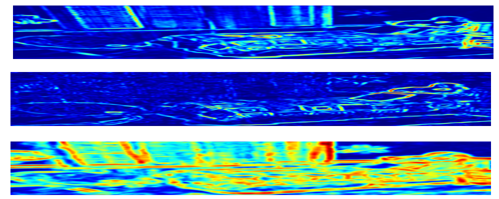
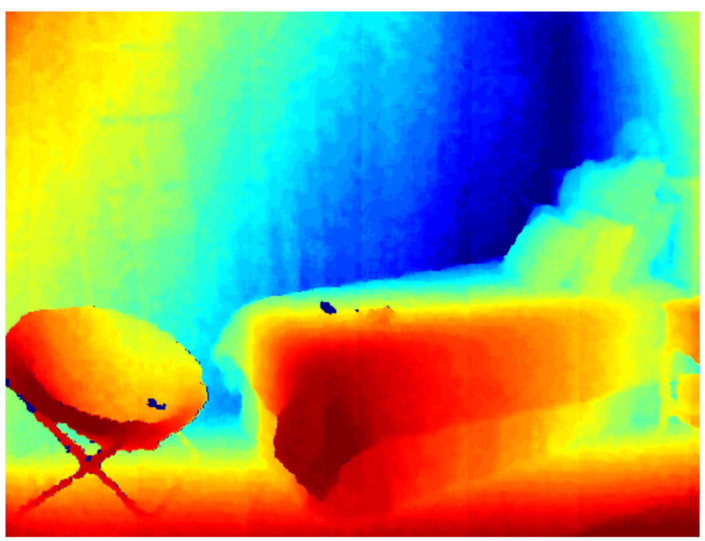


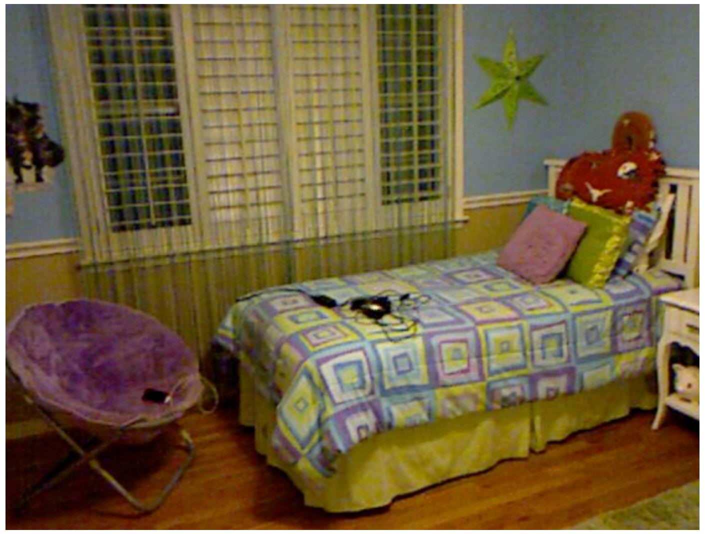


Input Depth Image

Multi-scale Local Gradients

Bottom-Up Segmentation

Adapt the gPb-ucm machinery from Arbeláez et al. from RGB to RGB-D images



Input RGB Image

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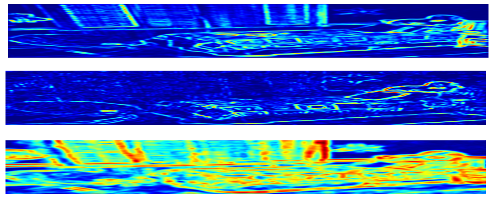
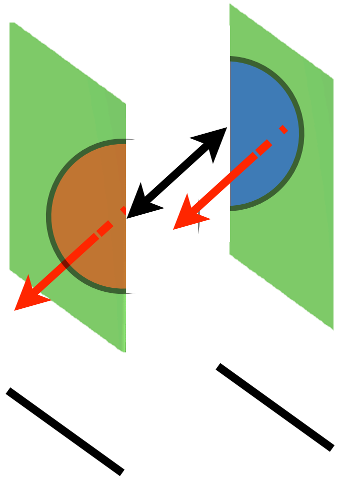
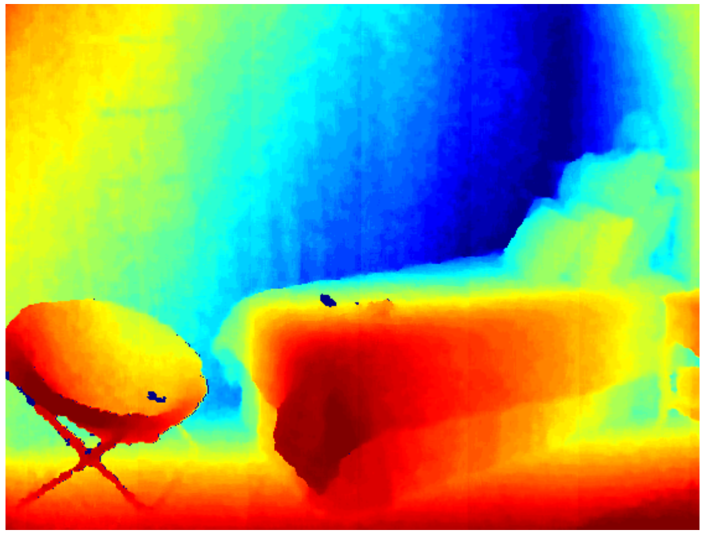




Depth Gradient



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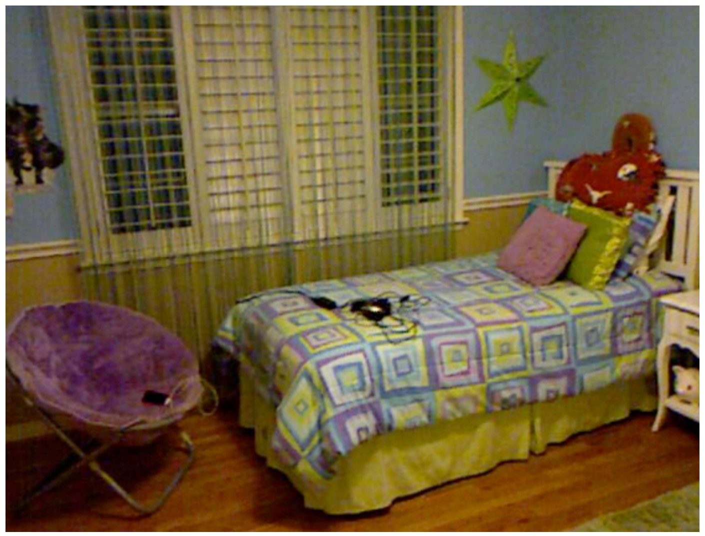
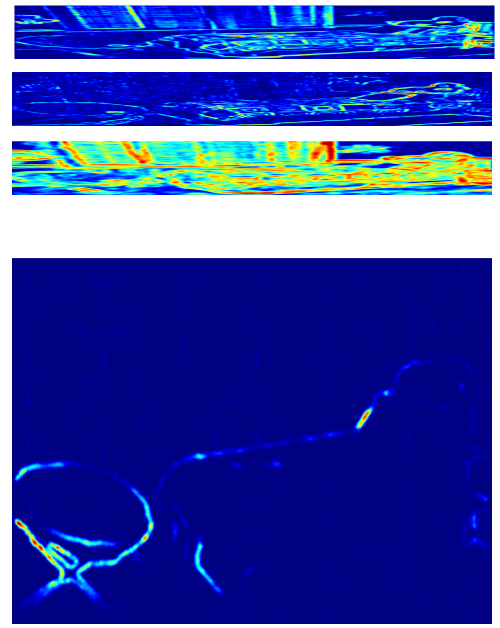
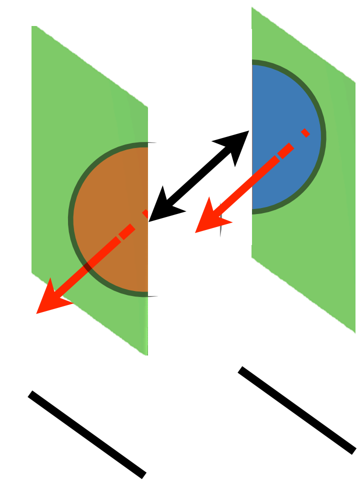


Input RGB Image

Gradient from Color Image

Depth Gradient





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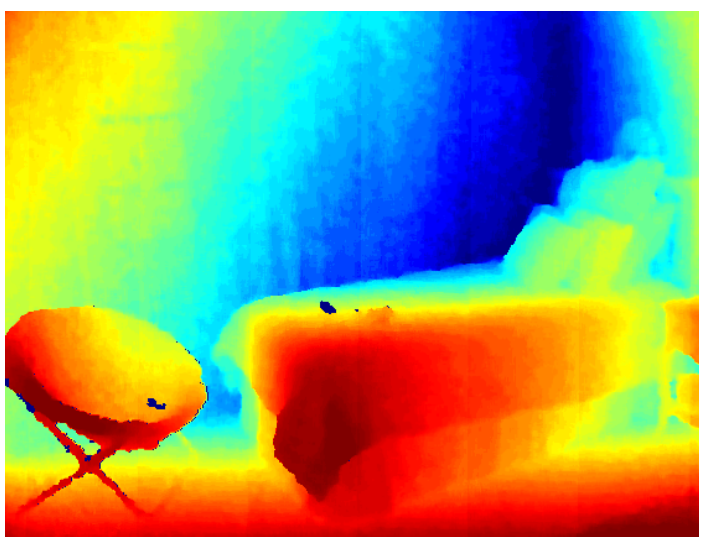

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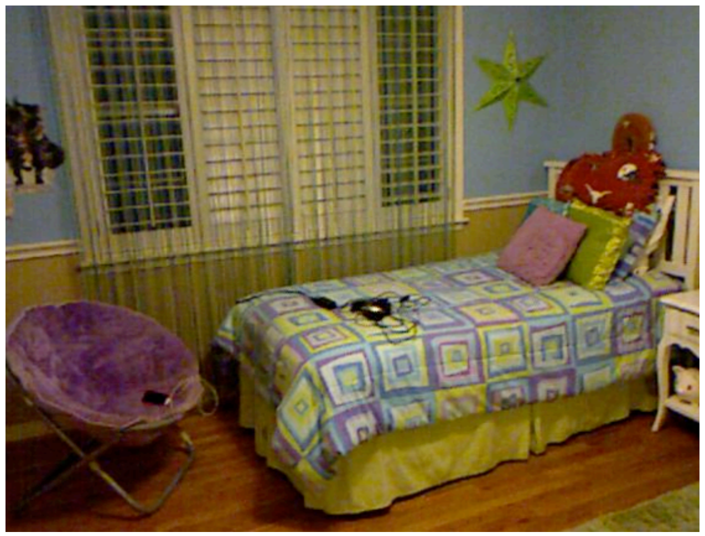

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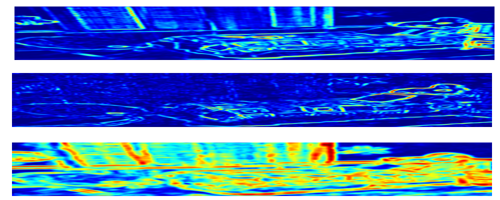
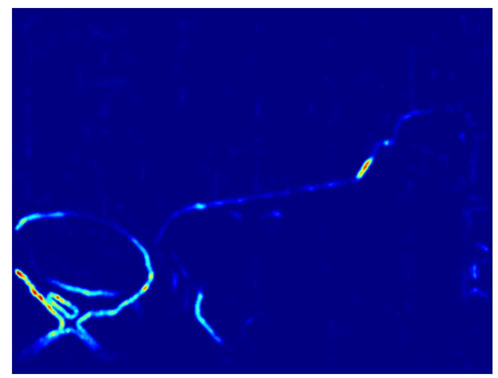
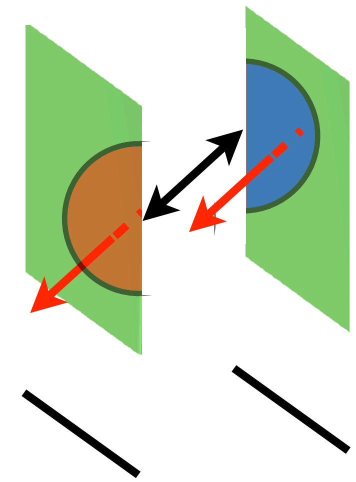


Depth Gradient





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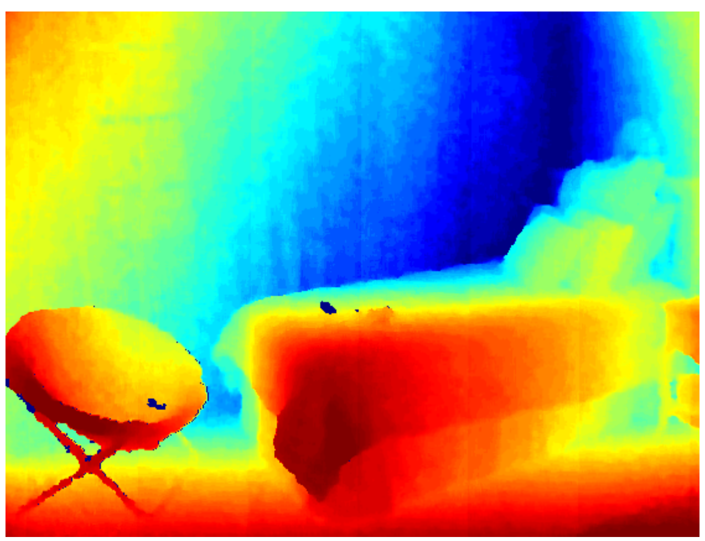
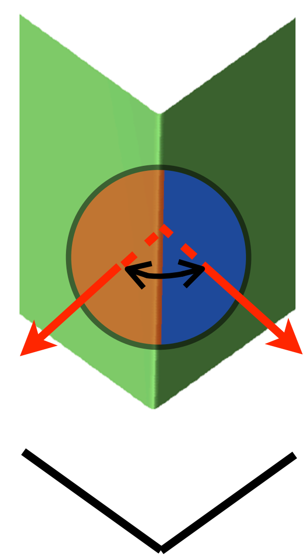
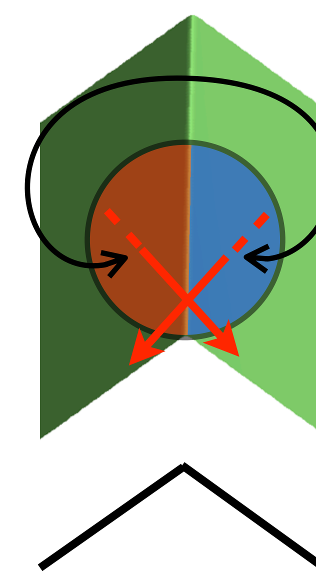


Input Depth Image

Multi-scale Local Gradients



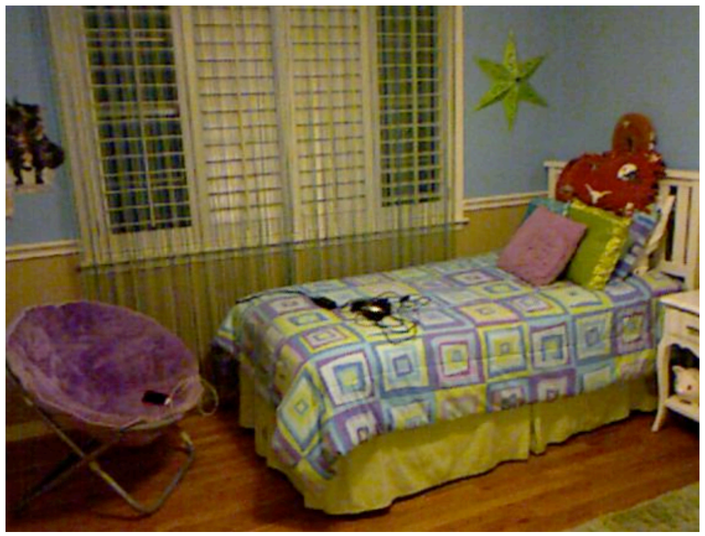
Normal Gradient



Normal Gradient

Bottom-Up Segmentation

Adapt the gPb-ucm machinery from Arbeláez et al. from RGB to RGB-D images



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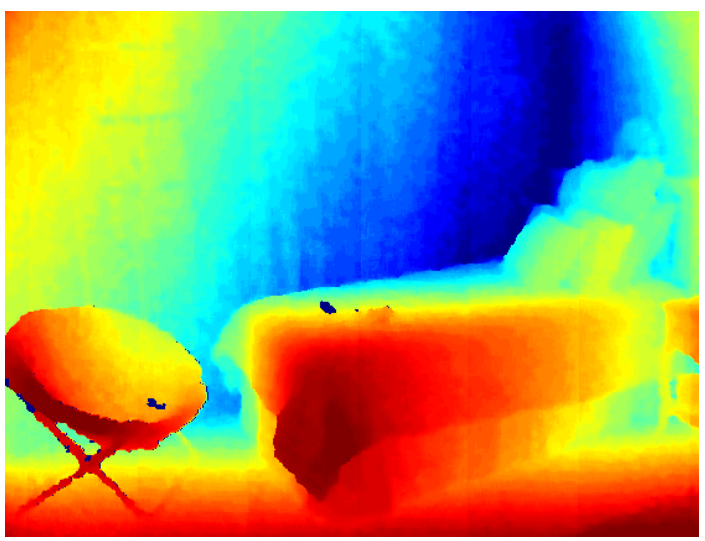
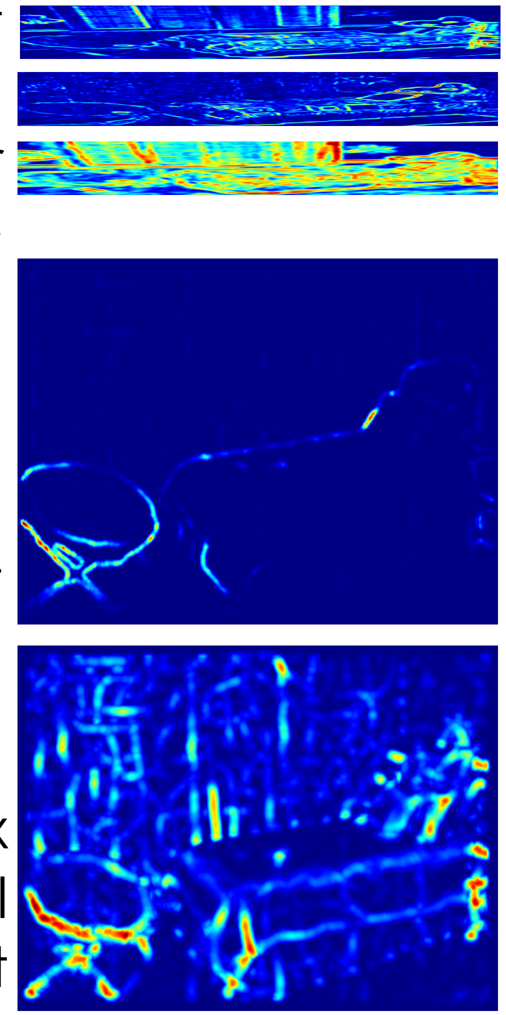


Input Depth Image

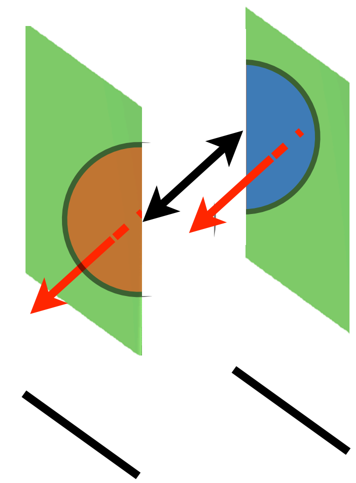
Gradient from Color Image

Depth Gradient

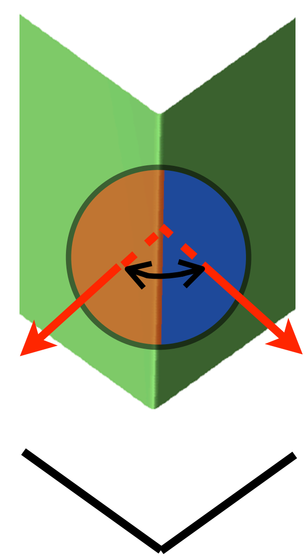
Convex Normal Gradient



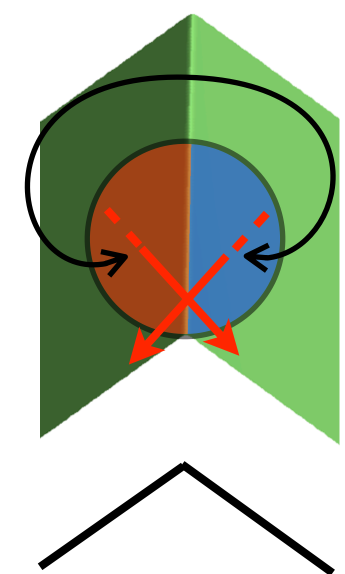
Multi-scale Local Gradients



Depth Gradient



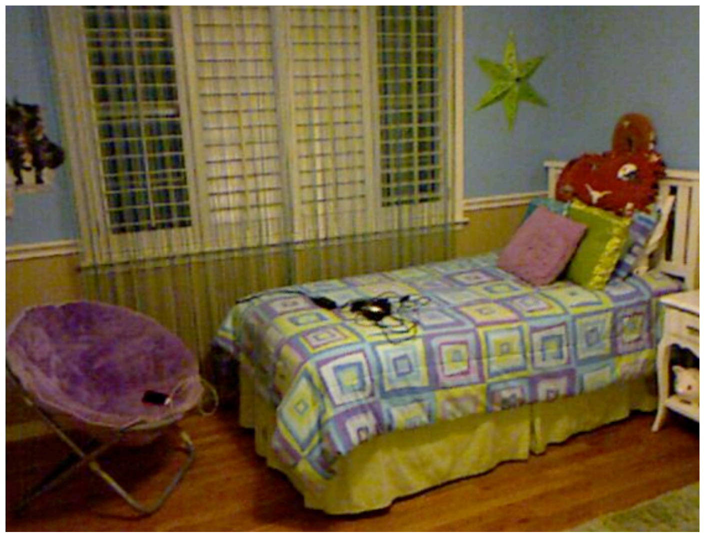
Convex Normal Gradient



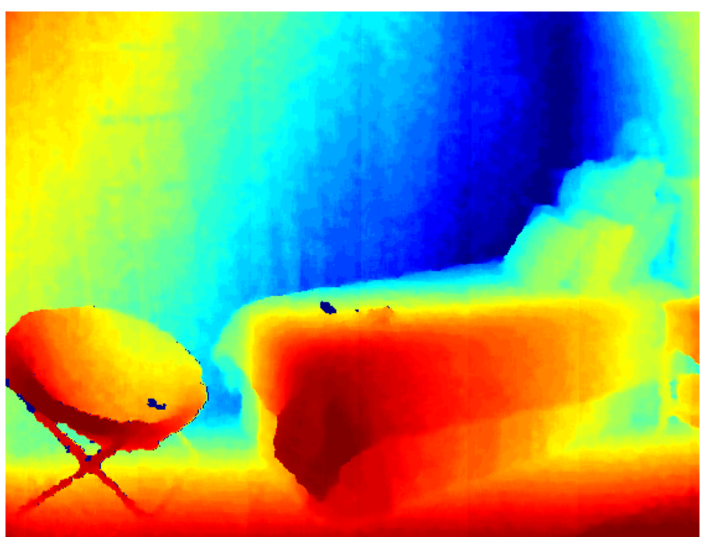
Normal Gradient

Bottom-Up Segmentation

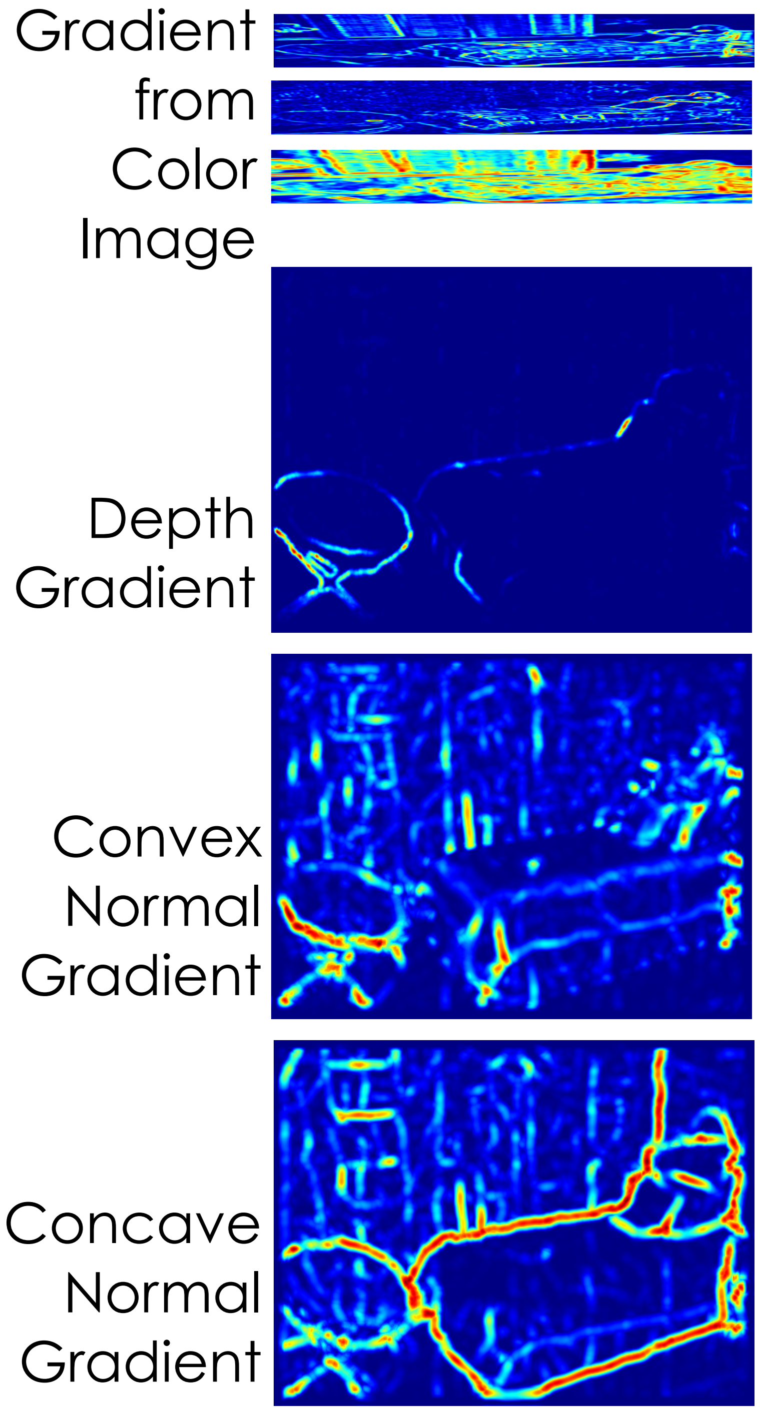
Adapt the gPb-ucm machinery from Arbeláez et al. from RGB to RGB-D images



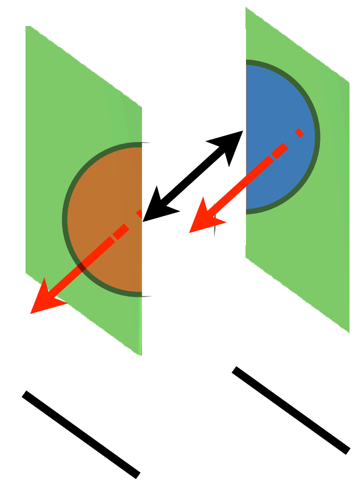
Input RGB Image



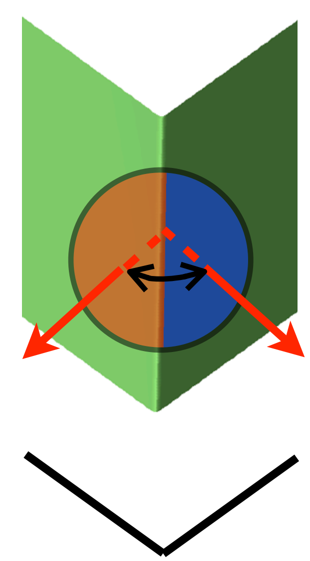
Input Depth Image



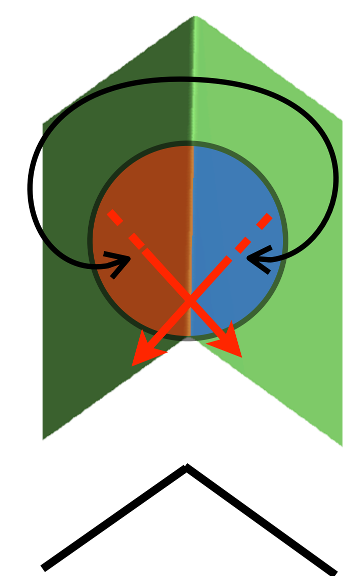
Multi-scale Local Gradients



Depth Gradient



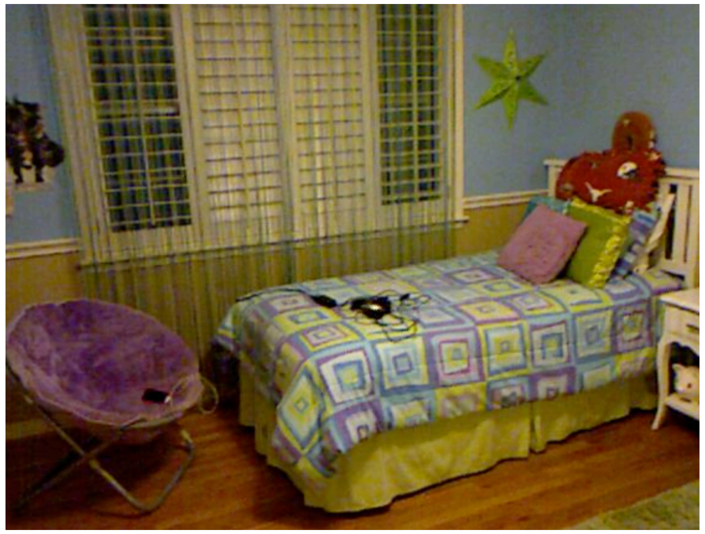
Convex Normal Gradient



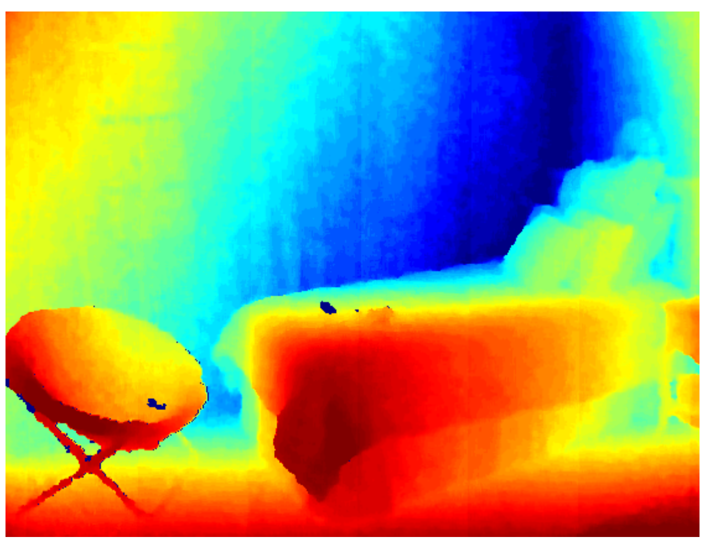
Concave Normal Gradient

Bottom-Up Segmentation

Adapt the gPb-ucm machinery from Arbeláez et al. from RGB to RGB-D images

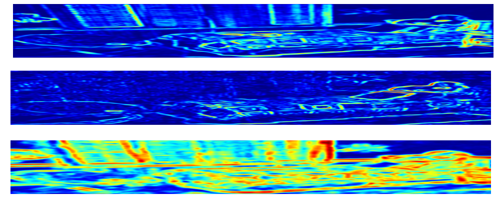


Input RGB Image

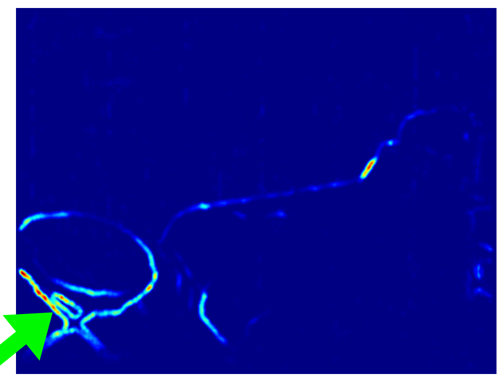


Input Depth Image

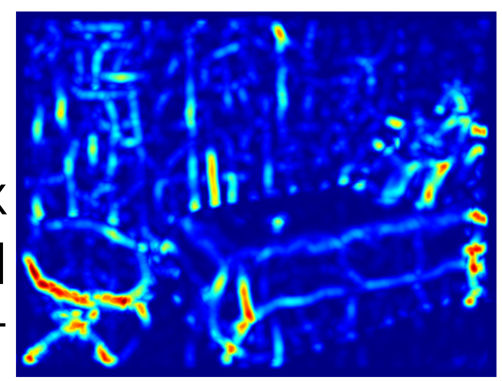
Gradient from Color Image



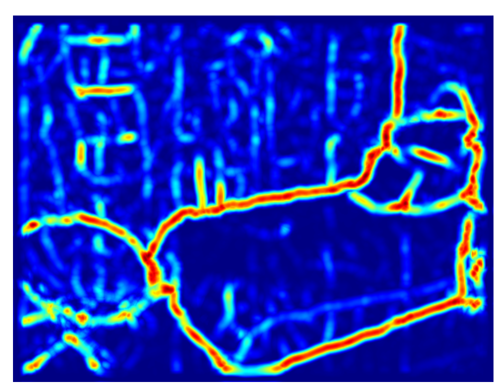
Depth Gradient



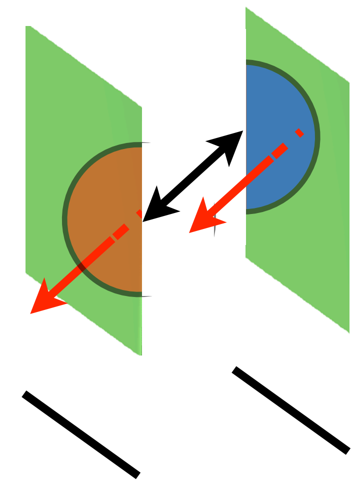
Convex Normal Gradient



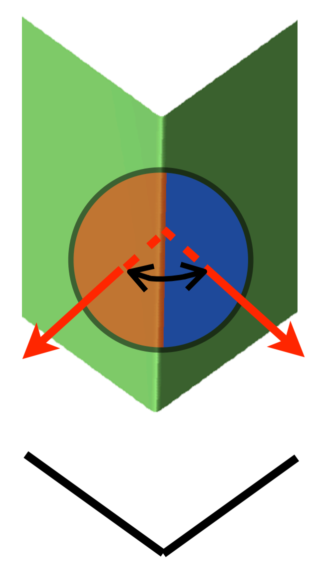
Concave Normal Gradient



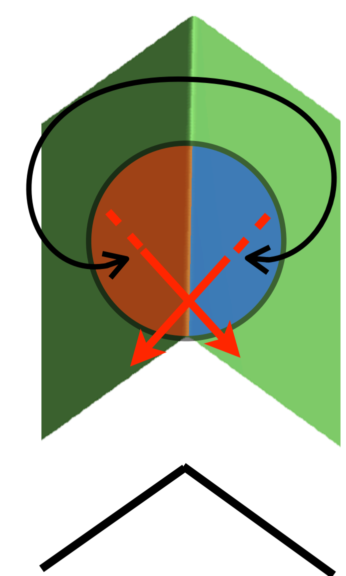
Multi-scale Local Gradients



Depth Gradient



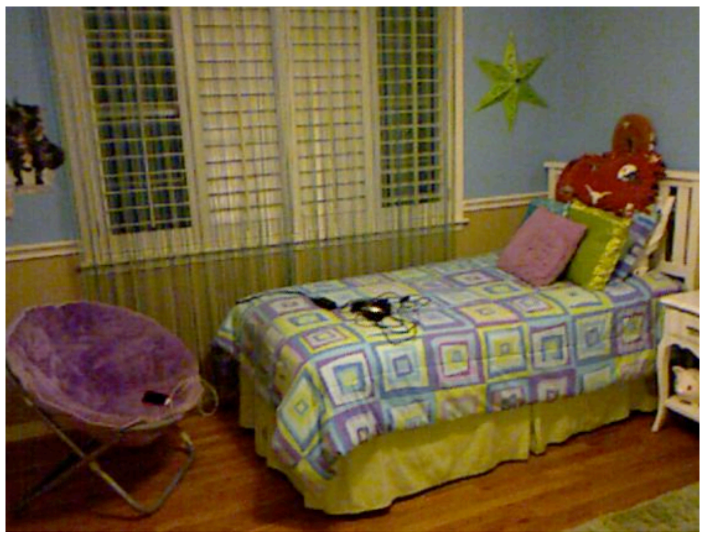
Convex Normal Gradient



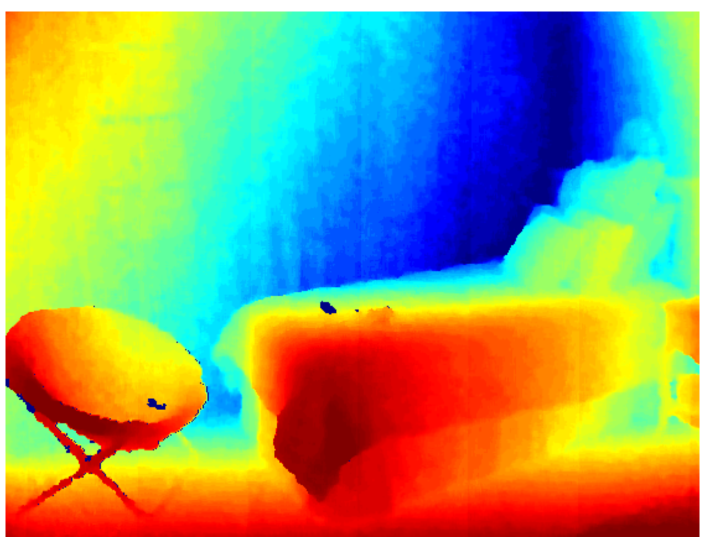
Concave Normal Gradient

Bottom-Up Segmentation

Adapt the gPb-ucm machinery from Arbeláez et al. from RGB to RGB-D images



Input RGB Image



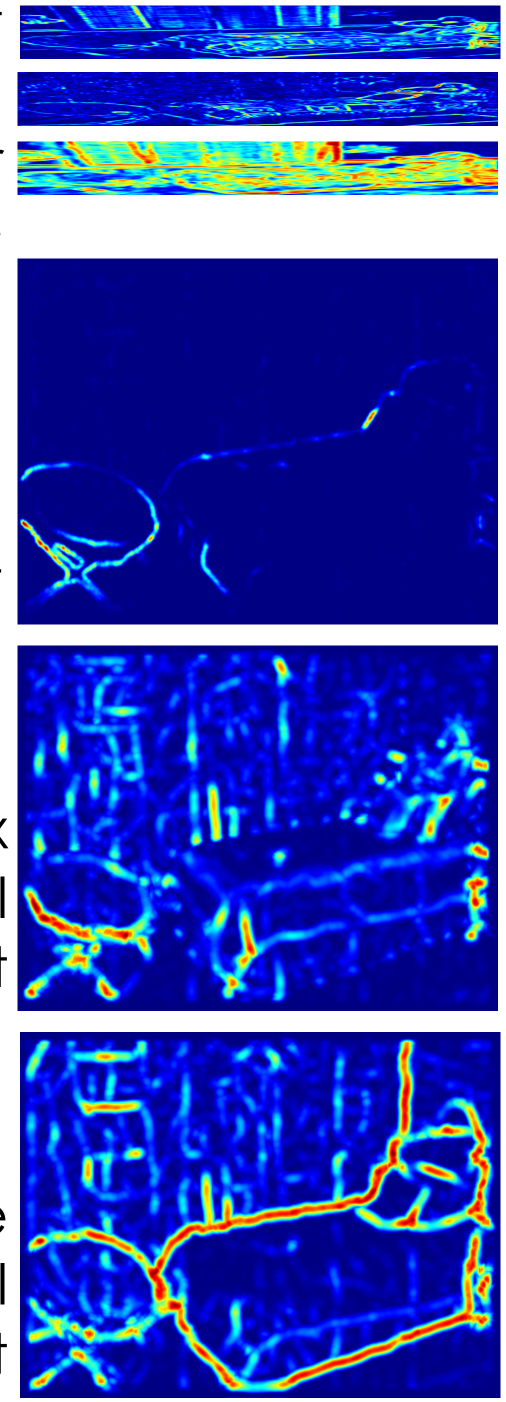
Input Depth Image

Gradient from Color Image

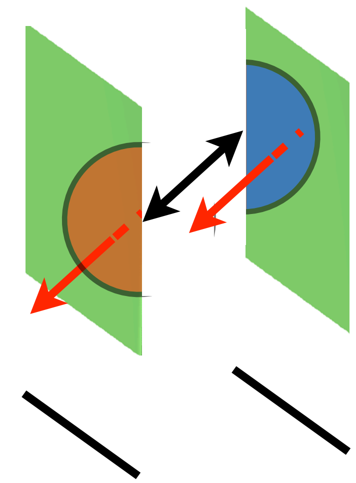
Depth Gradient

Convex Normal Gradient

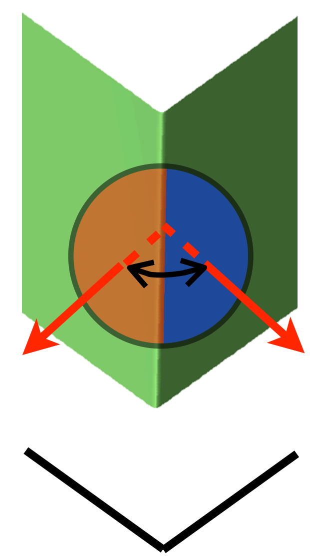
Concave Normal Gradient



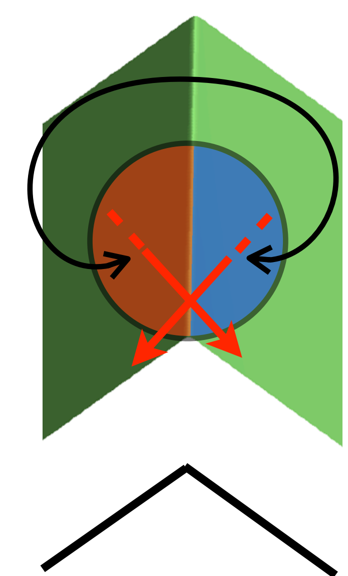
Multi-scale Local Gradients



Depth Gradient



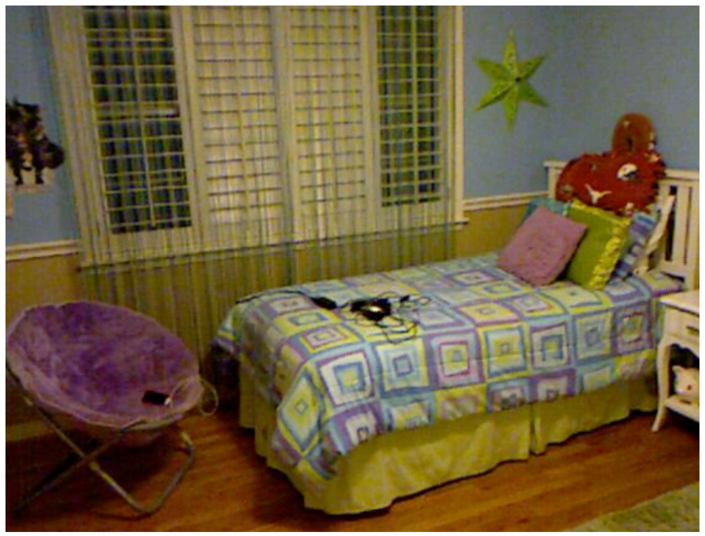
Convex Normal Gradient



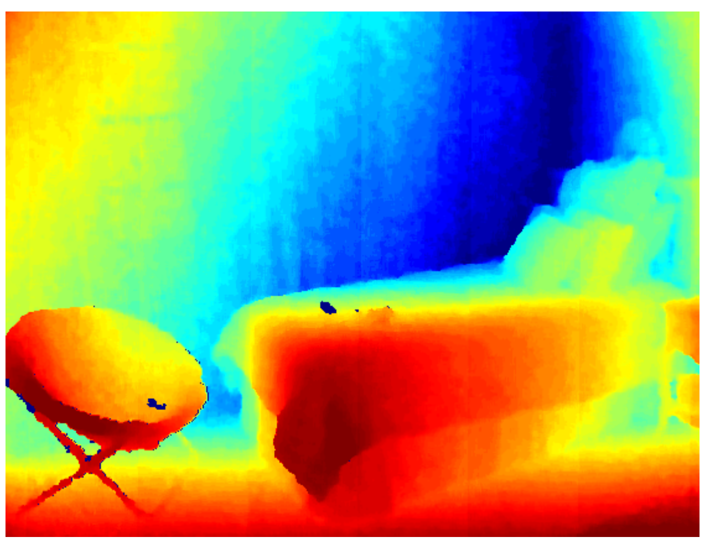
Concave Normal Gradient

Bottom-Up Segmentation

Adapt the gPb-ucm machinery from Arbeláez et al. from RGB to RGB-D images

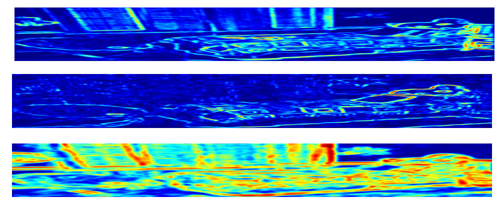


Input RGB Image

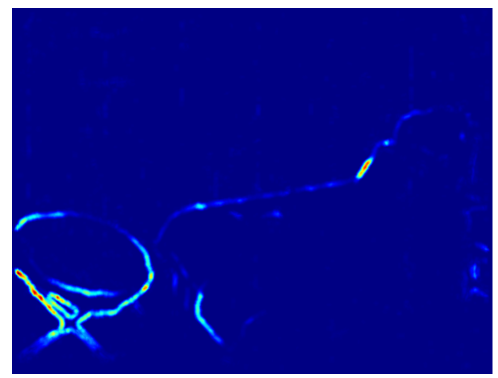


Input Depth Image

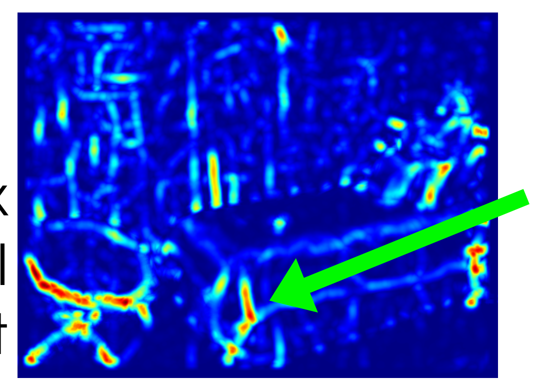
Gradient from Color Image



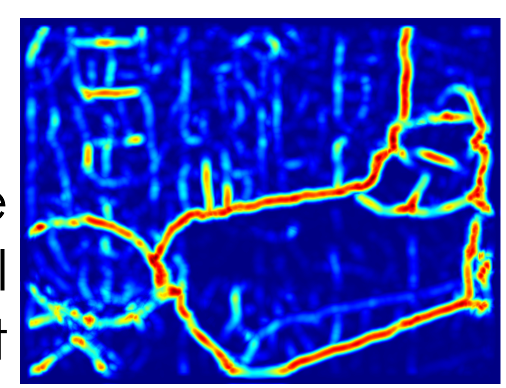
Depth Gradient



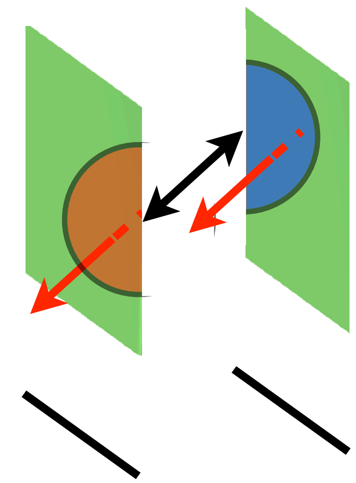
Convex Normal Gradient



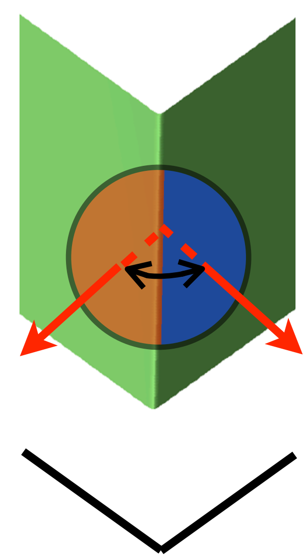
Concave Normal Gradient



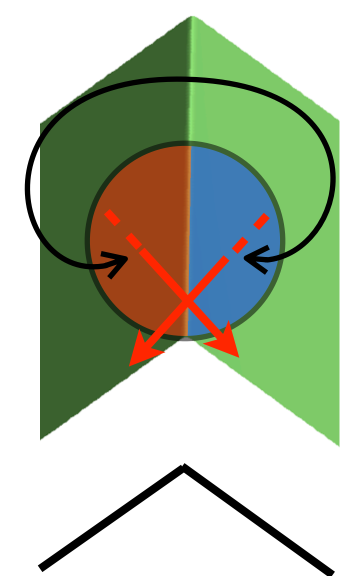
Multi-scale Local Gradients



Depth Gradient



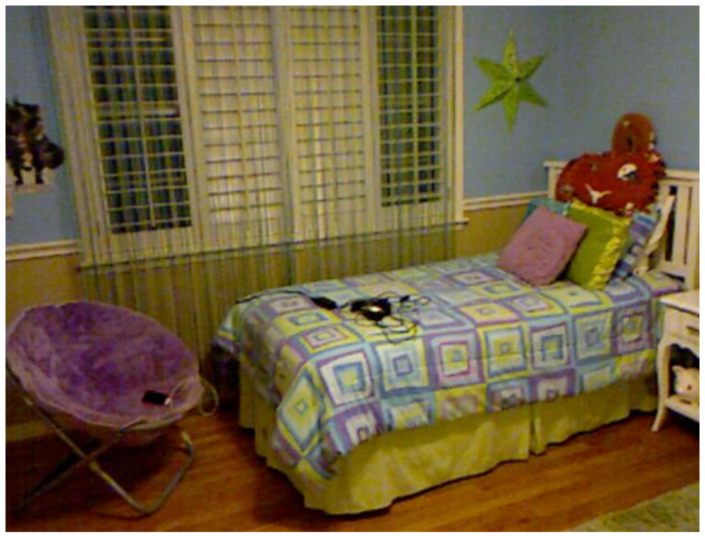
Convex Normal Gradient



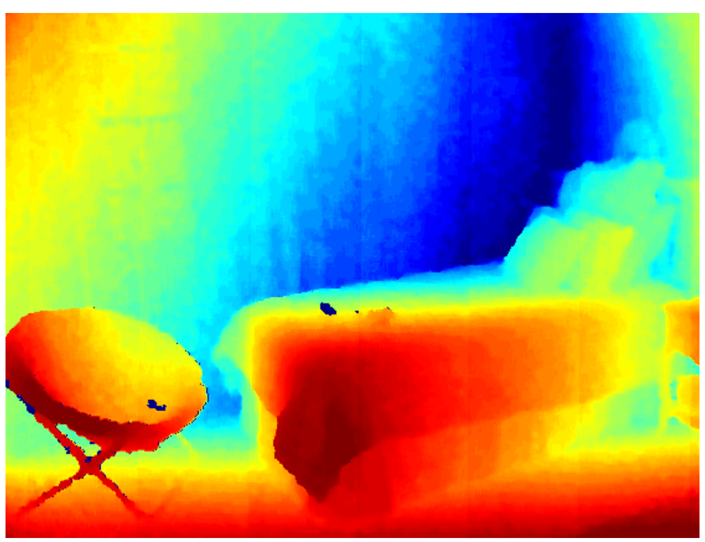
Concave Normal Gradient

Bottom-Up Segmentation

Adapt the gPb-ucm machinery from Arbeláez et al. from RGB to RGB-D images



Input RGB Image



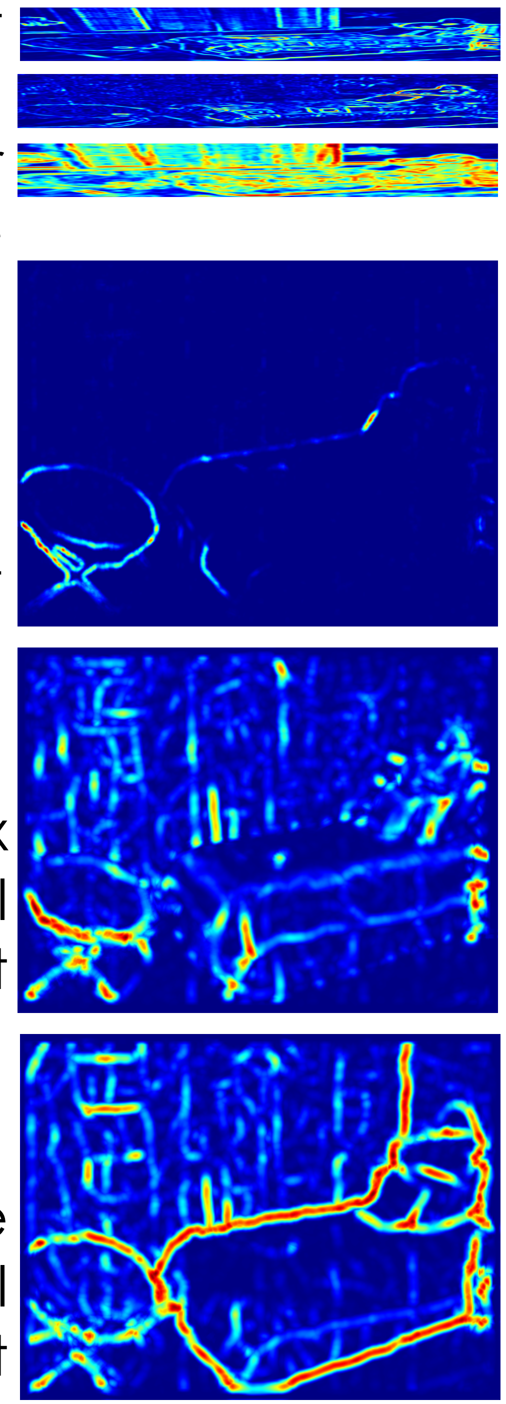
Input Depth Image

Gradient from Color Image

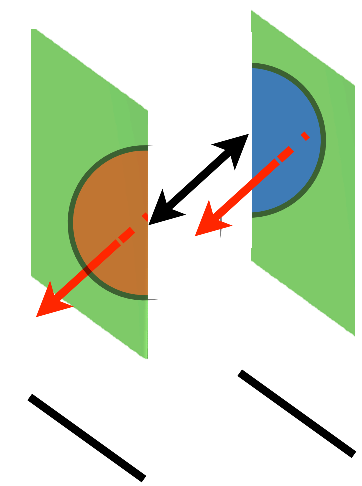
Depth Gradient

Convex Normal Gradient

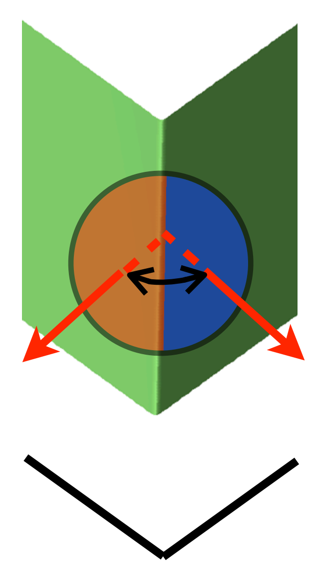
Concave Normal Gradient



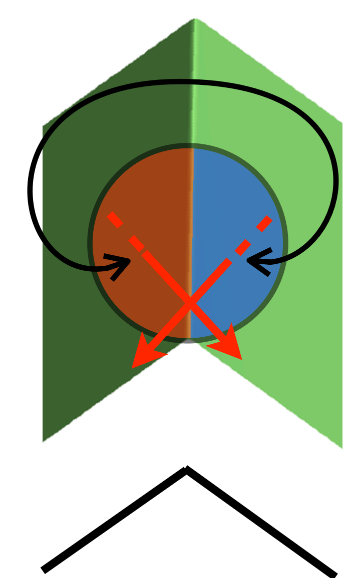
Multi-scale Local Gradients



Depth Gradient



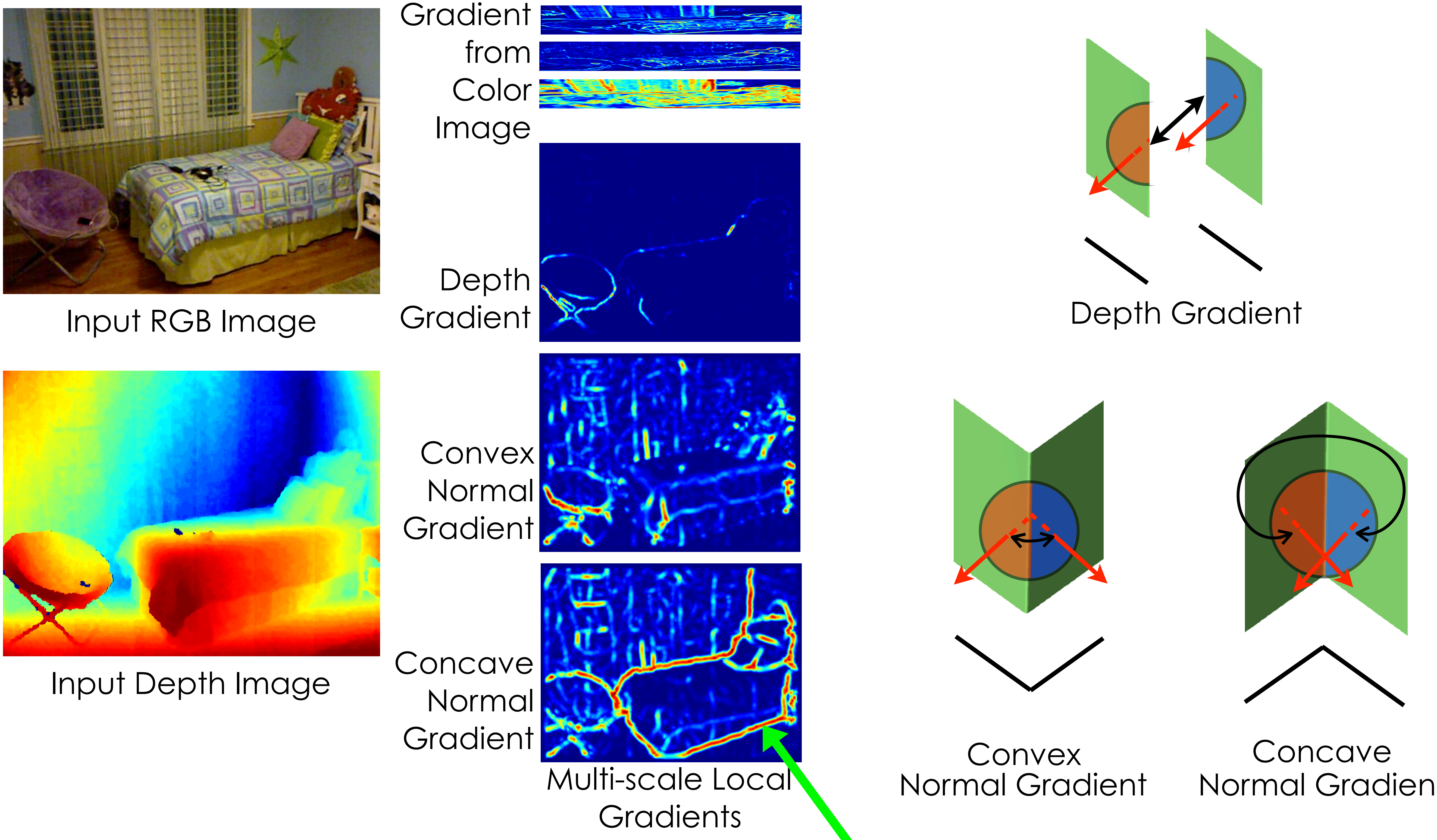
Convex Normal Gradient



Concave Normal Gradient

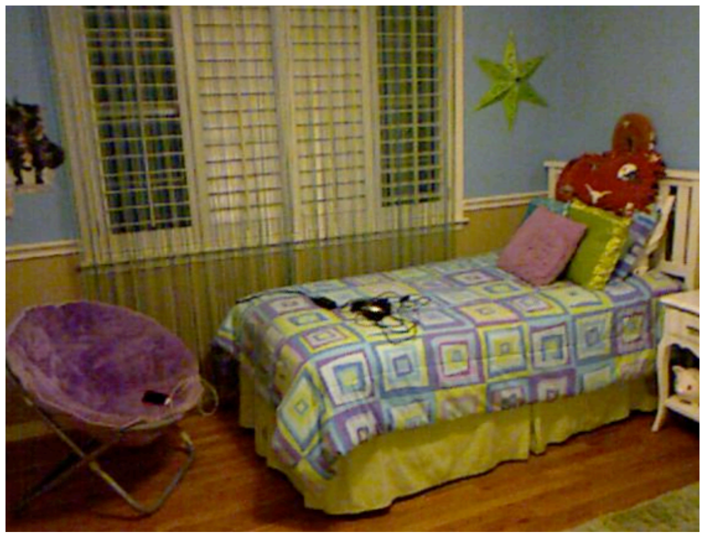
Bottom-Up Segmentation

Adapt the gPb-ucm machinery from Arbeláez et al. from RGB to RGB-D images

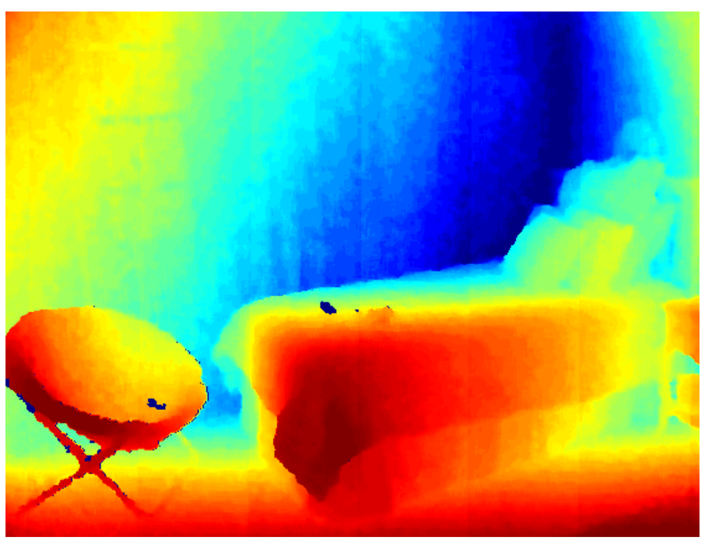


Bottom-Up Segmentation

Adapt the gPb-ucm machinery from Arbeláez et al. from RGB to RGB-D images

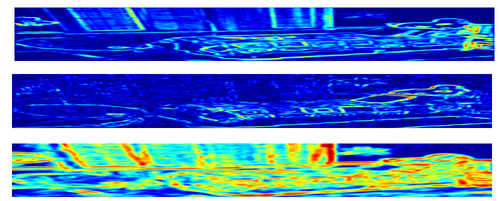


Input RGB Image

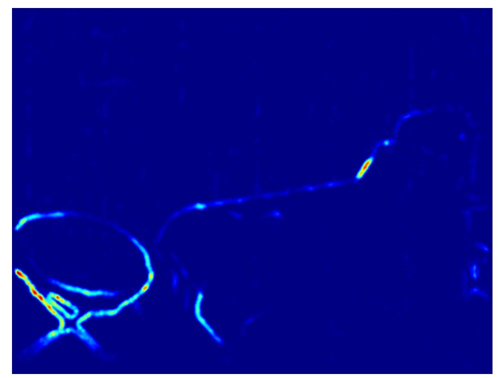


Input Depth Image

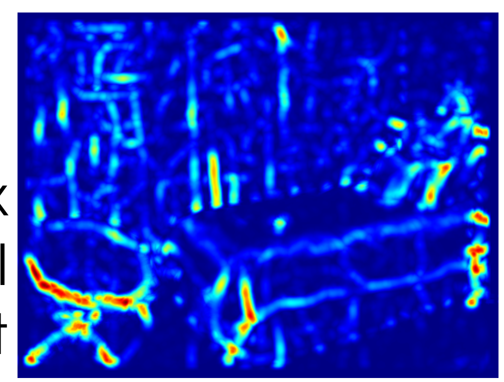
Gradient from Color Image



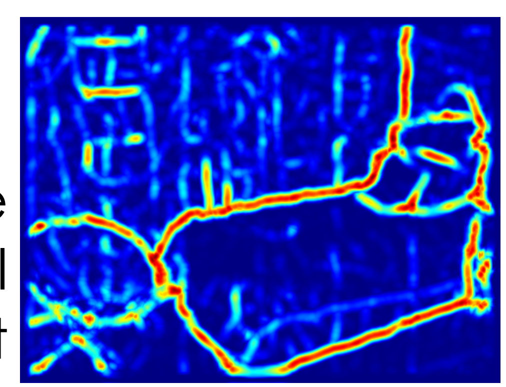
Depth Gradient



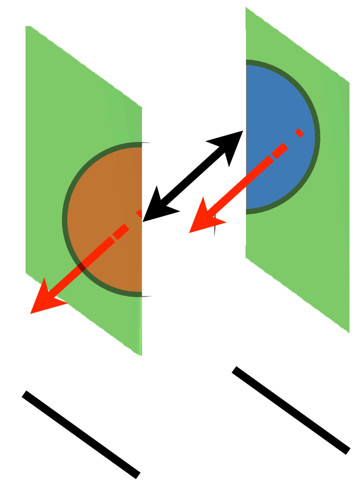
Convex Normal Gradient



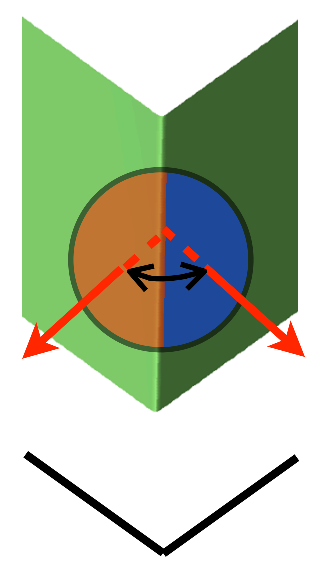
Concave Normal Gradient



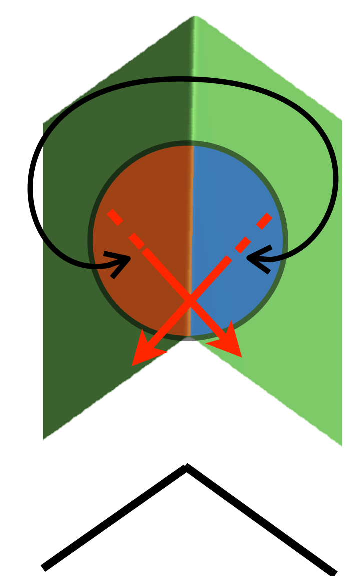
Multi-scale Local Gradients



Depth Gradient



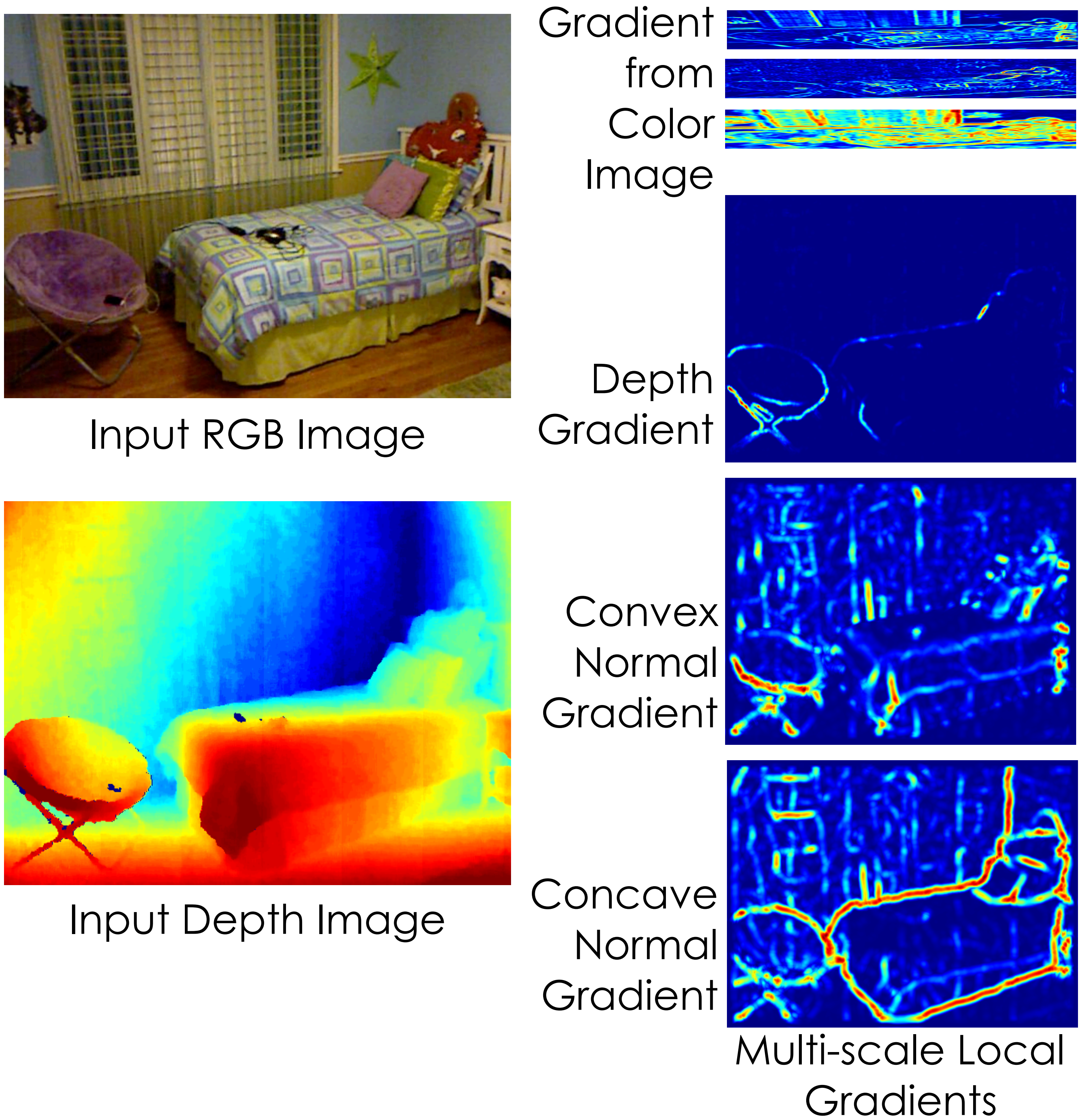
Convex Normal Gradient



Concave Normal Gradient

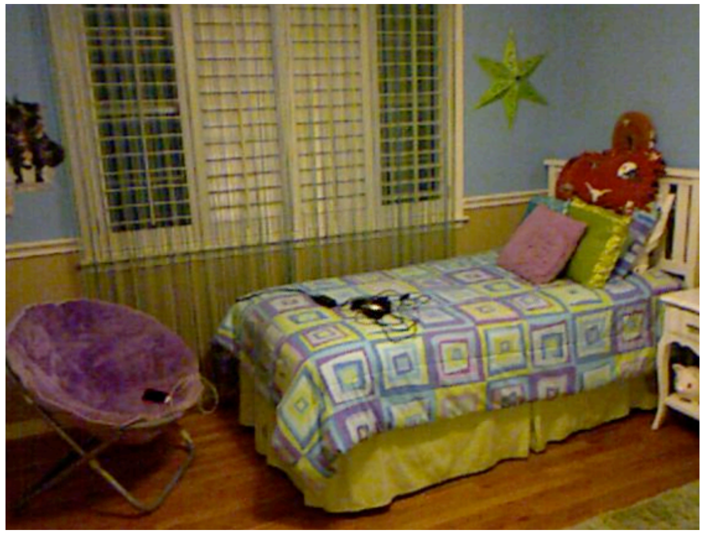
Bottom-Up Segmentation

Adapt the gPb-ucm machinery from Arbeláez et al. from RGB to RGB-D images

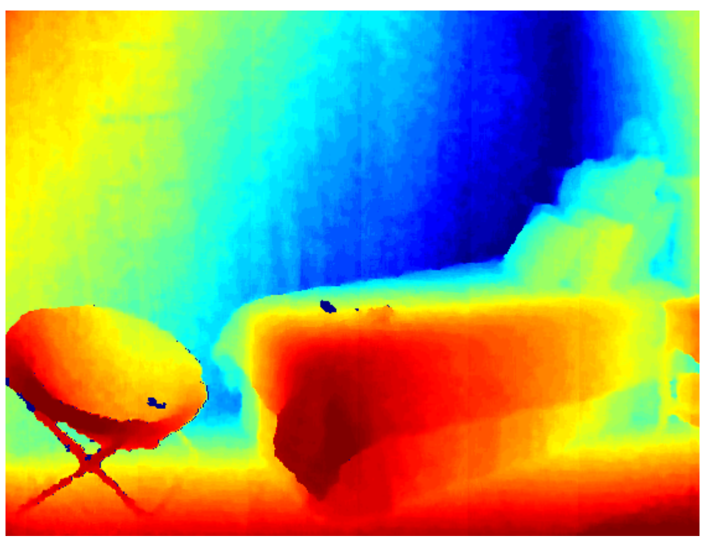


Bottom-Up Segmentation

Adapt the gPb-ucm machinery from Arbeláez et al. from RGB to RGB-D images



Input RGB Image



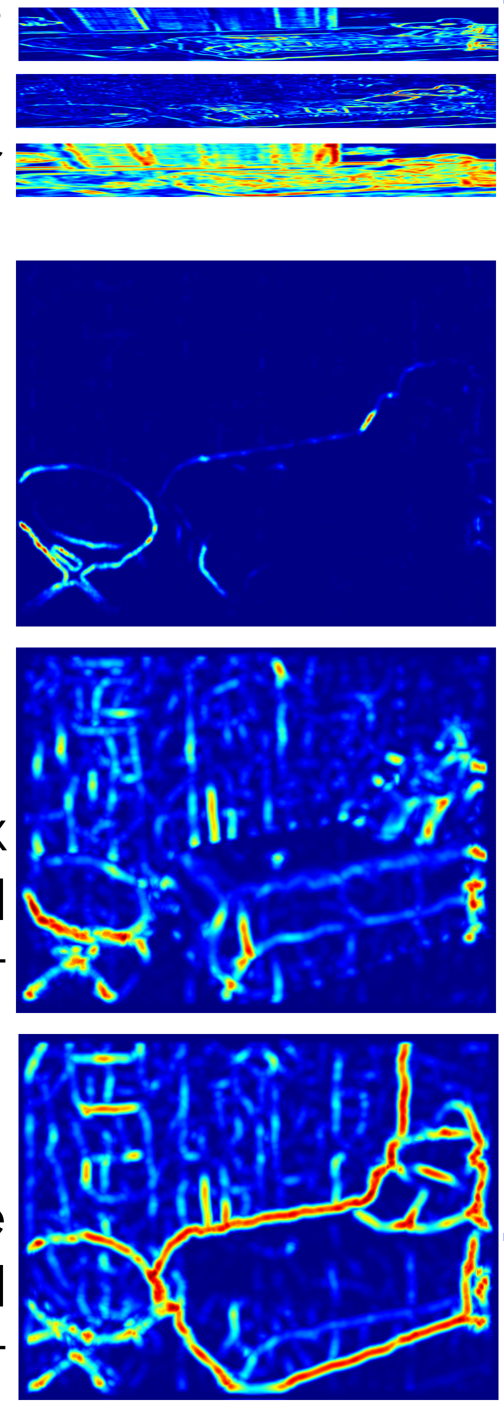
Input Depth Image

Gradient from Color Image

Depth Gradient

Convex Normal Gradient

Concave Normal Gradient

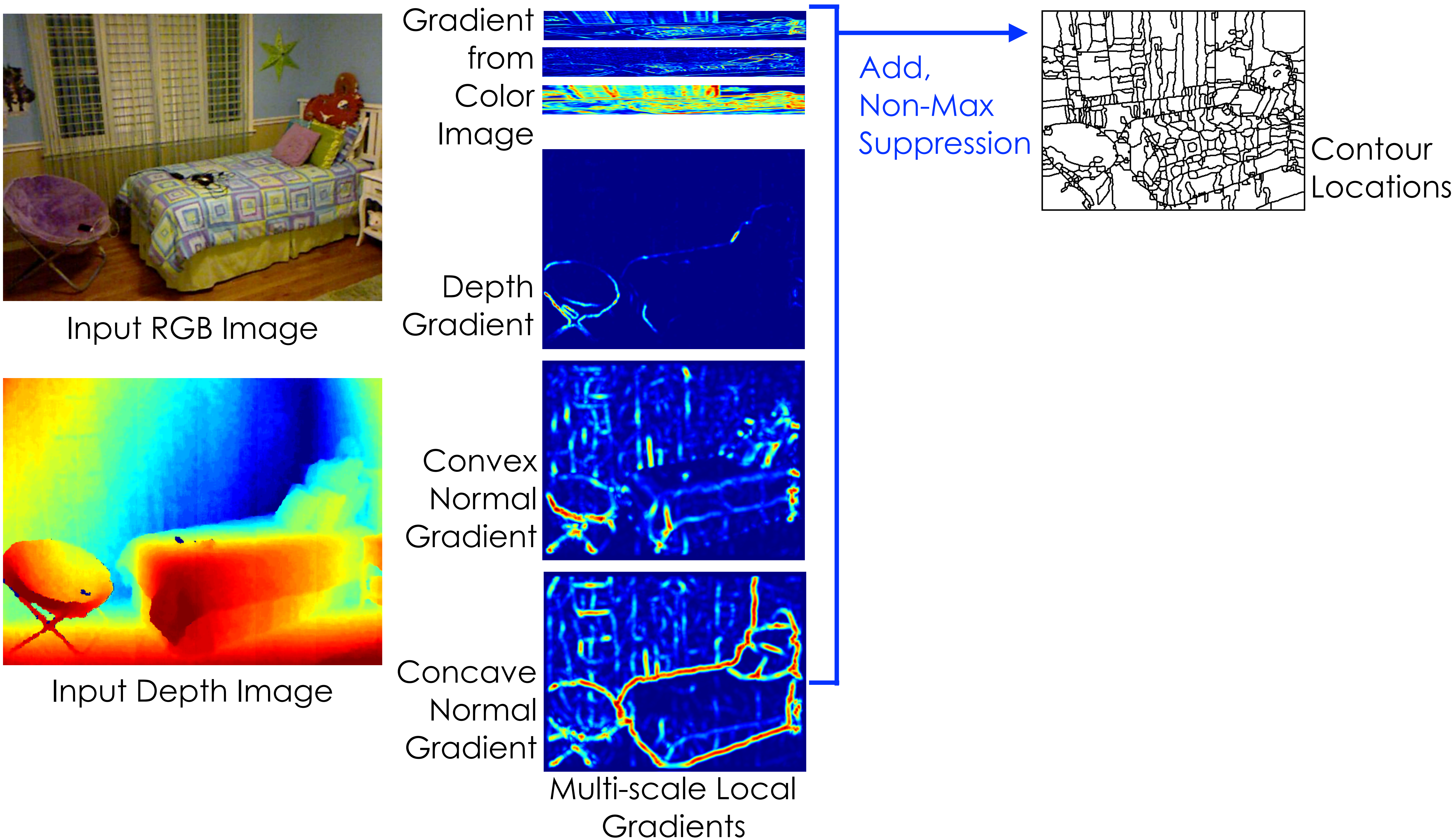


Multi-scale Local Gradients

Add, Non-Max Suppression

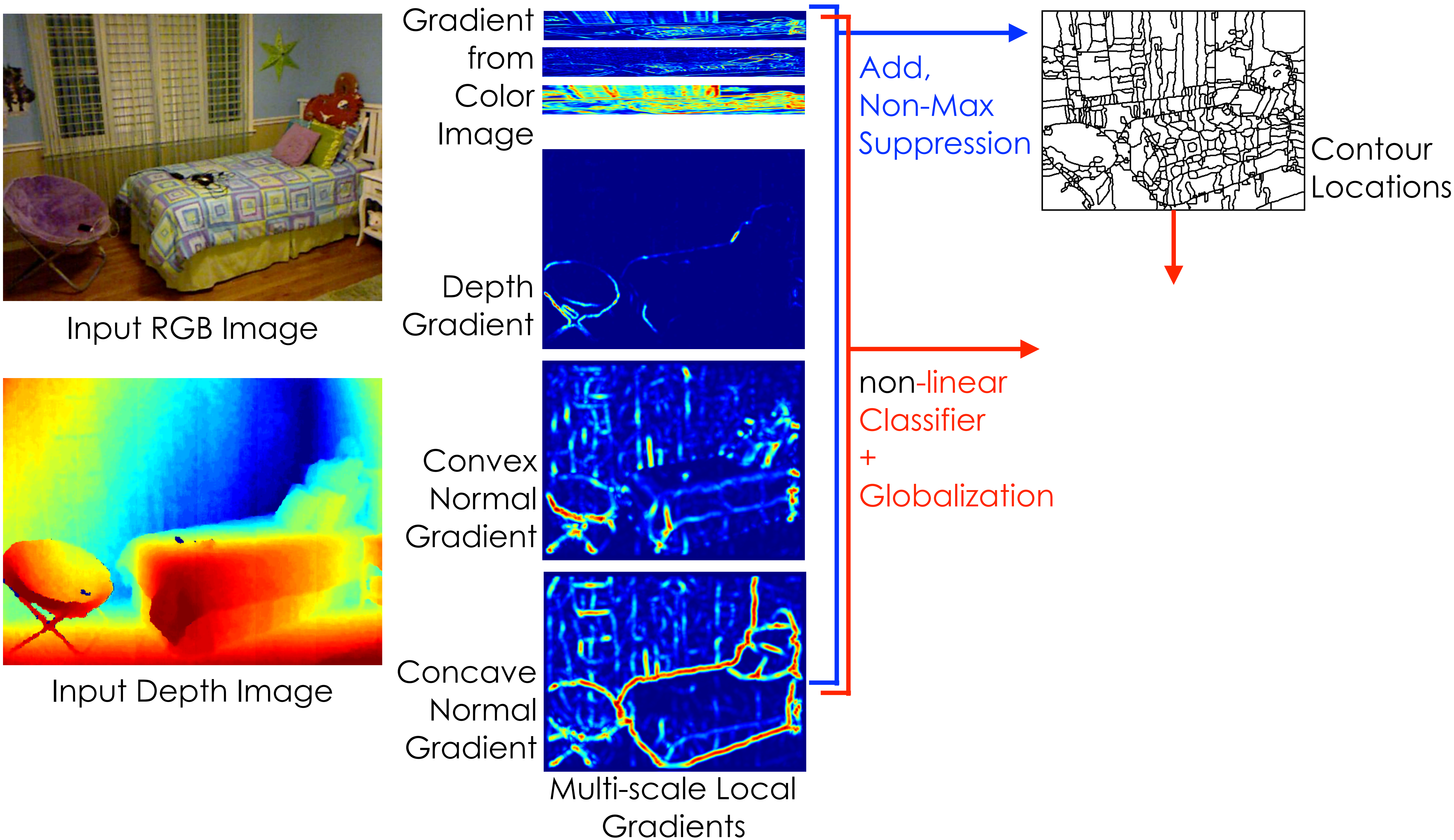
Bottom-Up Segmentation

Adapt the gPb-ucm machinery from Arbeláez et al. from RGB to RGB-D images



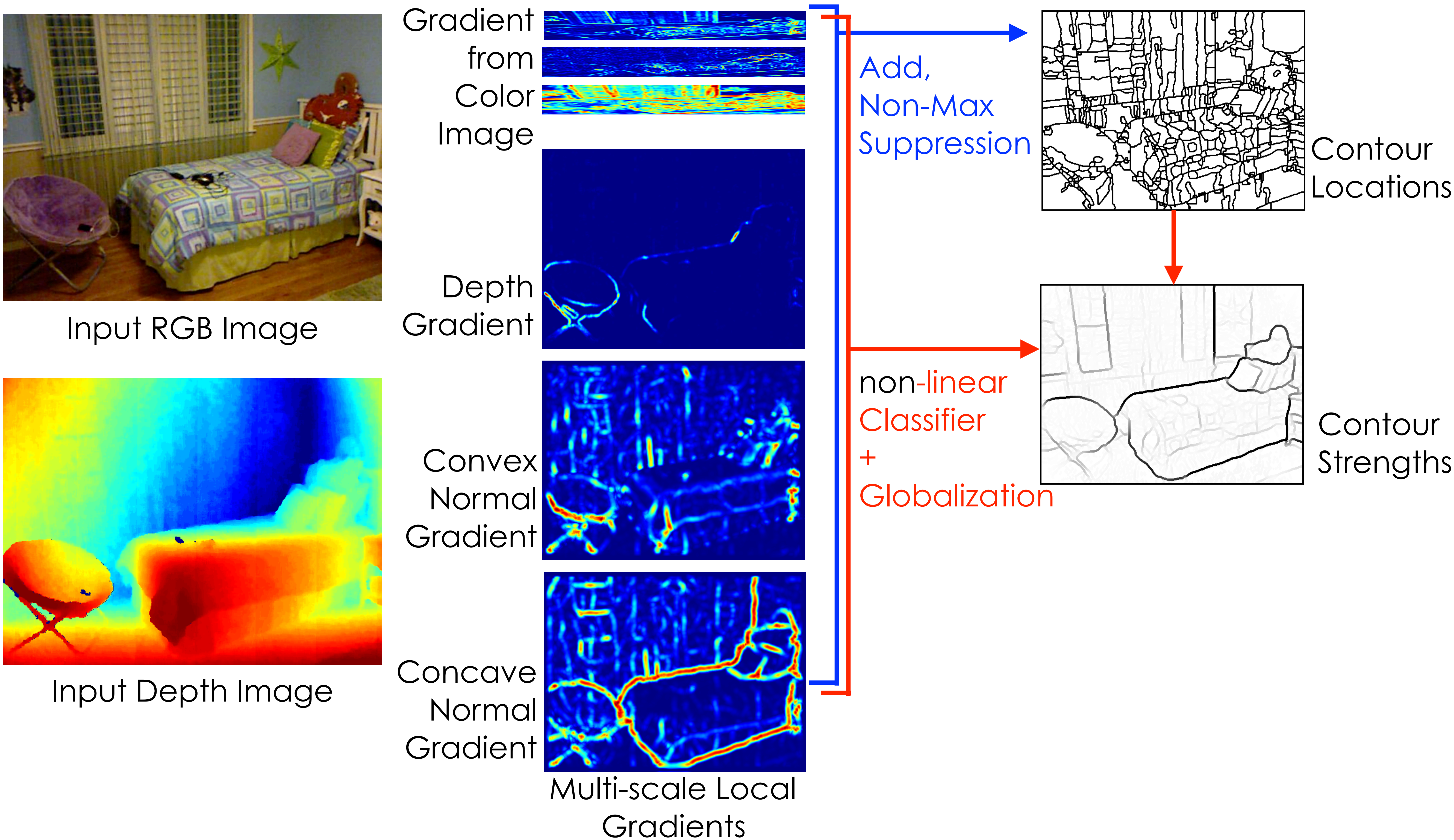
Bottom-Up Segmentation

Adapt the gPb-ucm machinery from Arbeláez et al. from RGB to RGB-D images



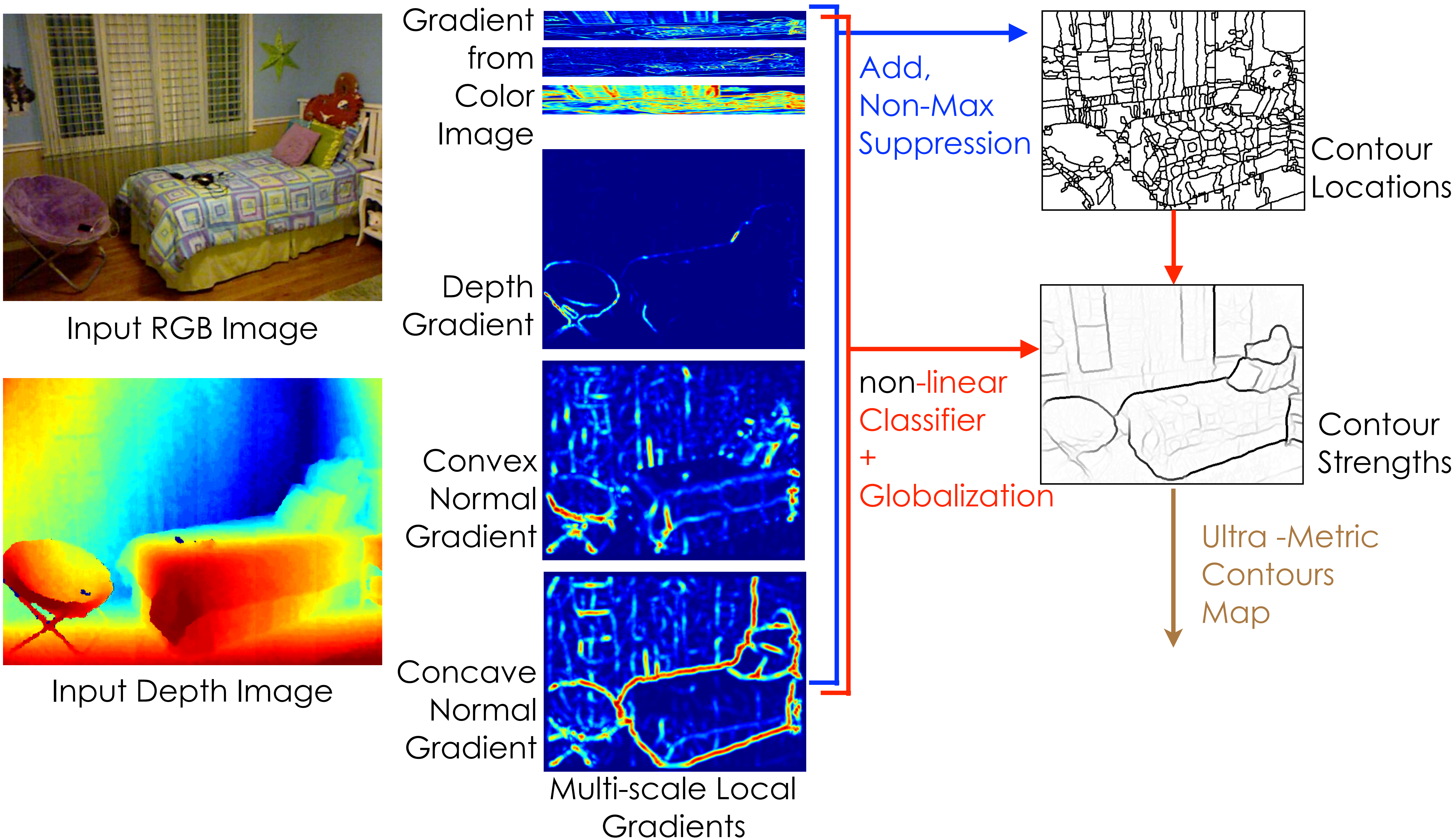
Bottom-Up Segmentation

Adapt the gPb-ucm machinery from Arbeláez et al. from RGB to RGB-D images



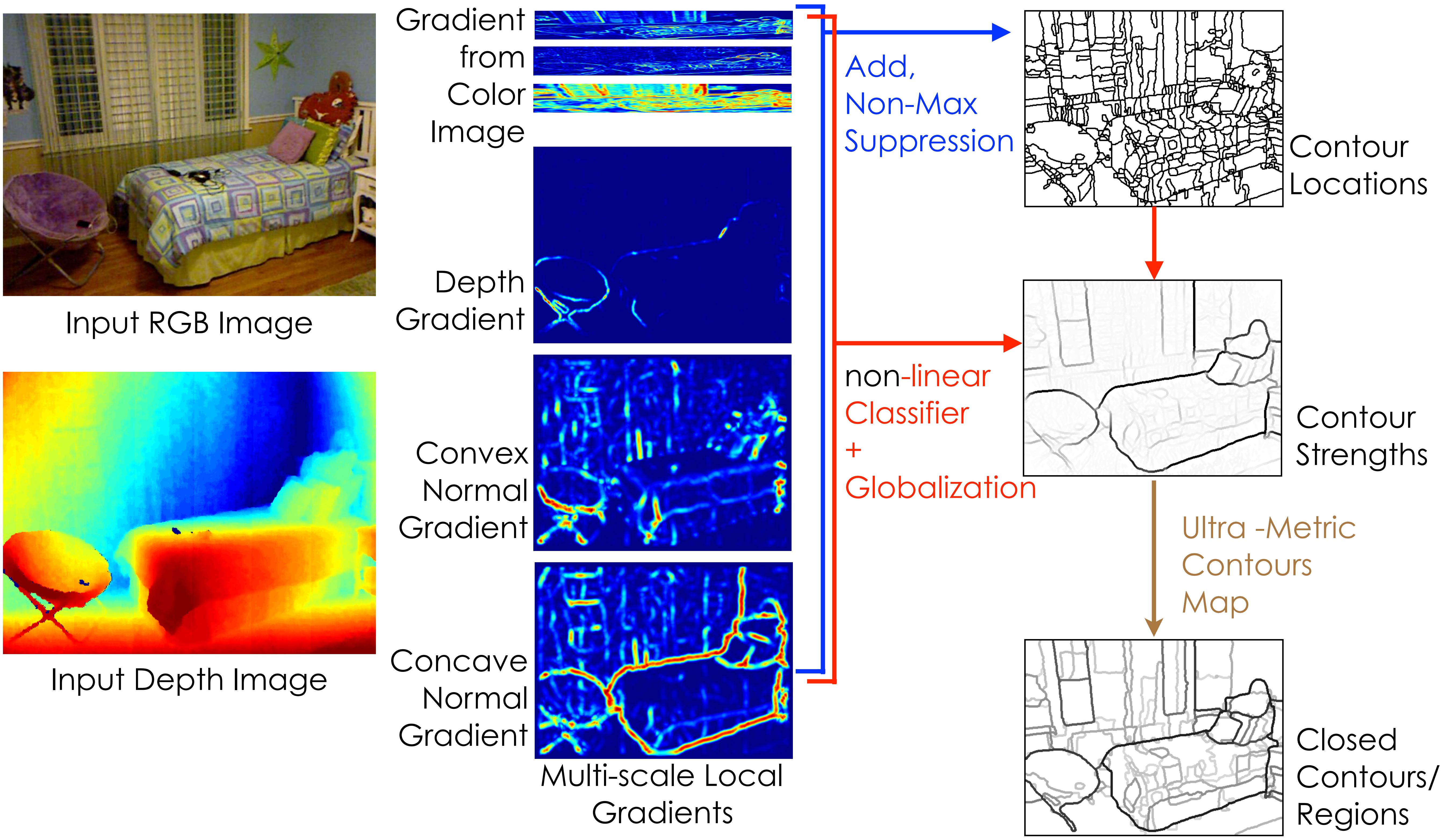
Bottom-Up Segmentation

Adapt the gPb-ucm machinery from Arbeláez et al. from RGB to RGB-D images



Bottom-Up Segmentation

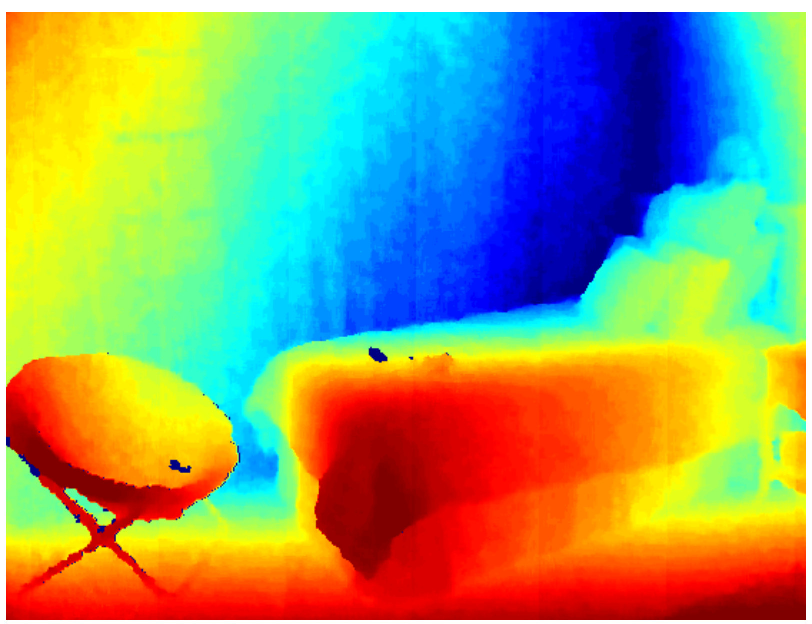
Adapt the gPb-ucm machinery from Arbeláez et al. from RGB to RGB-D images



Results

RGB

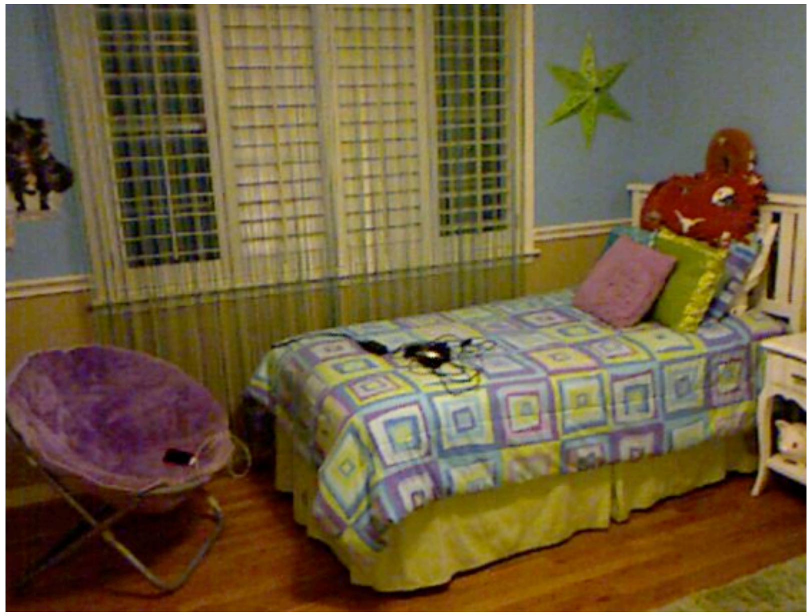
gPb-UCM(RGB)



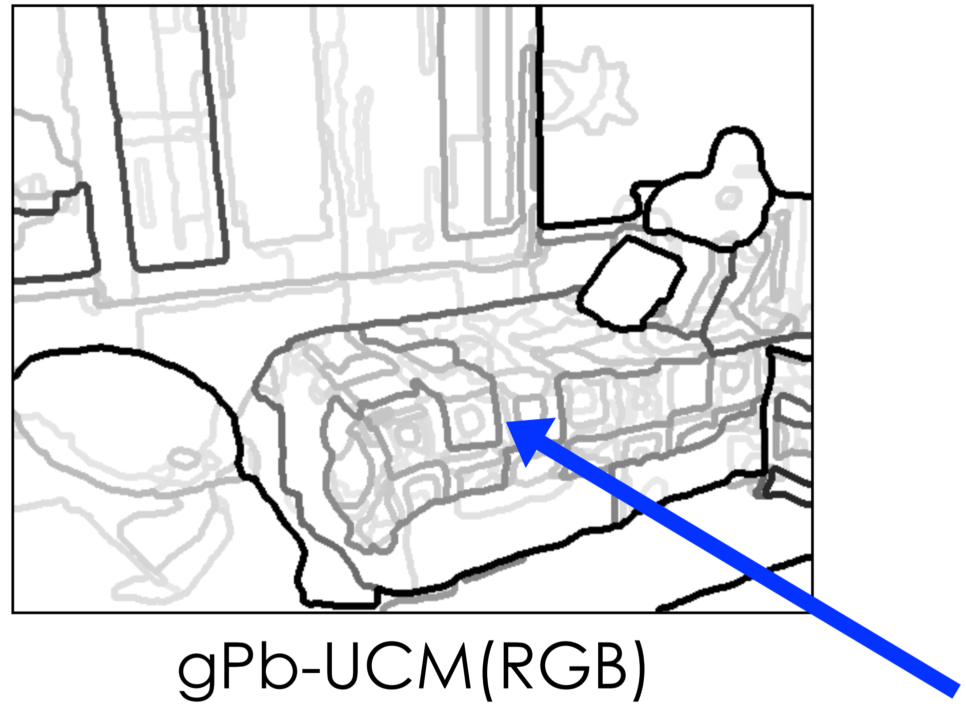
D

This Work (RGB-D)

Results

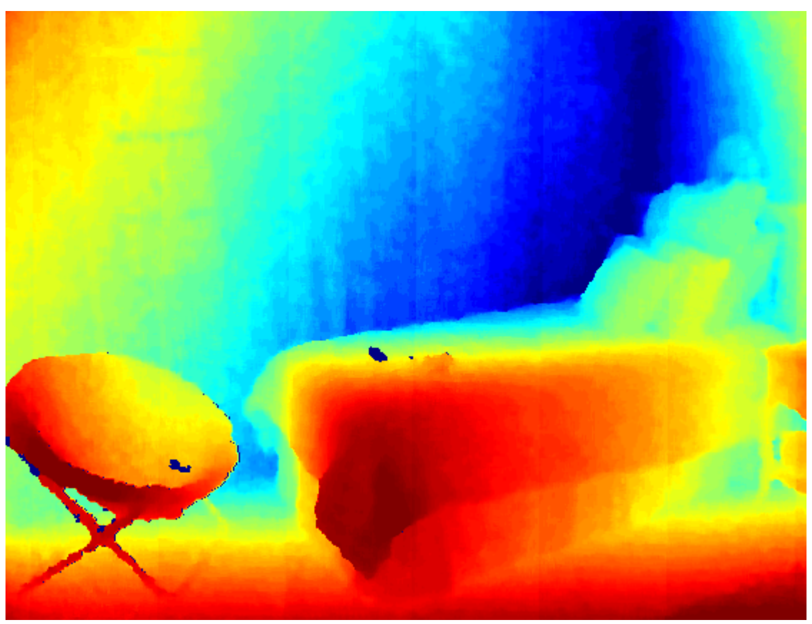


RGB

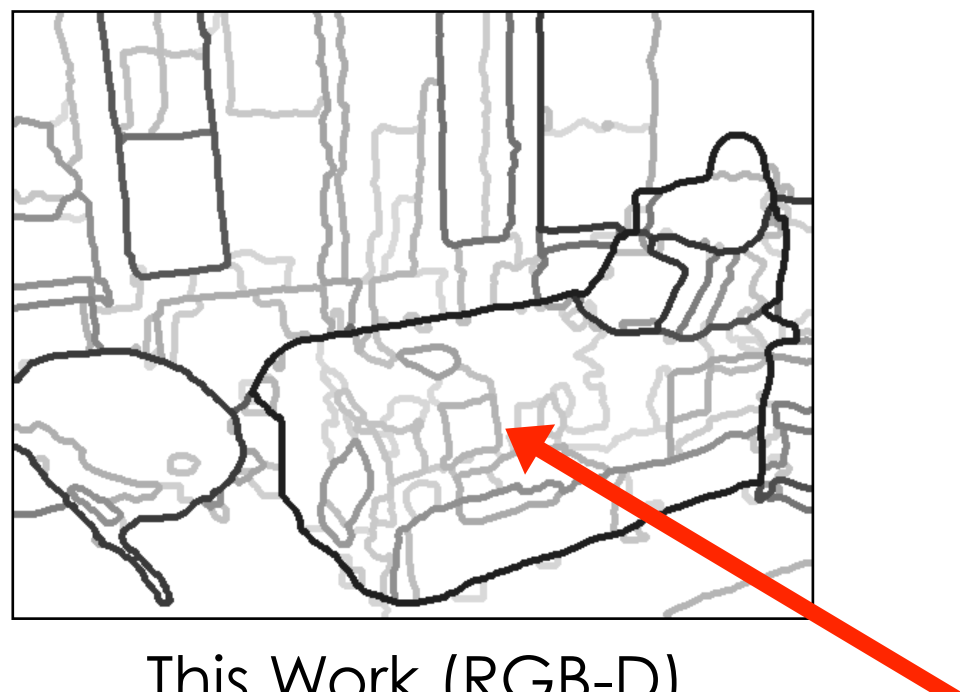


gPb-UCM(RGB)

Less distracted by albedo

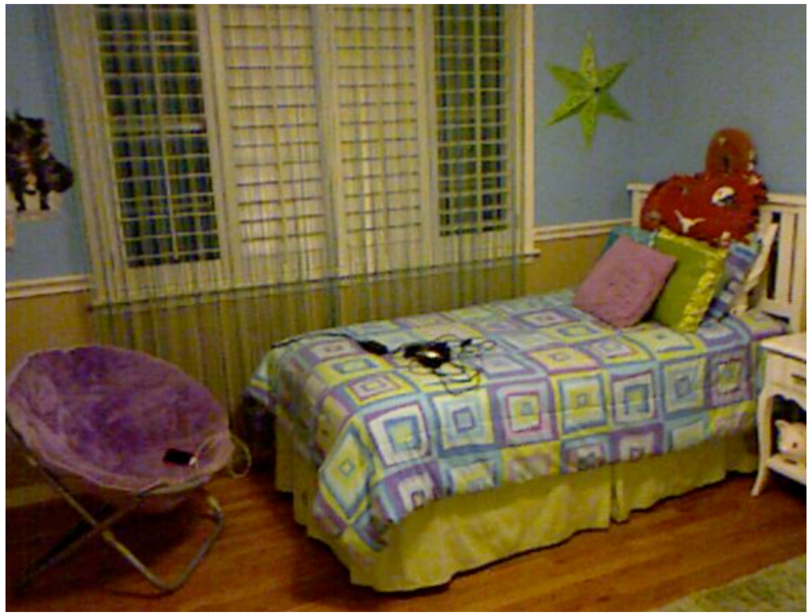


D



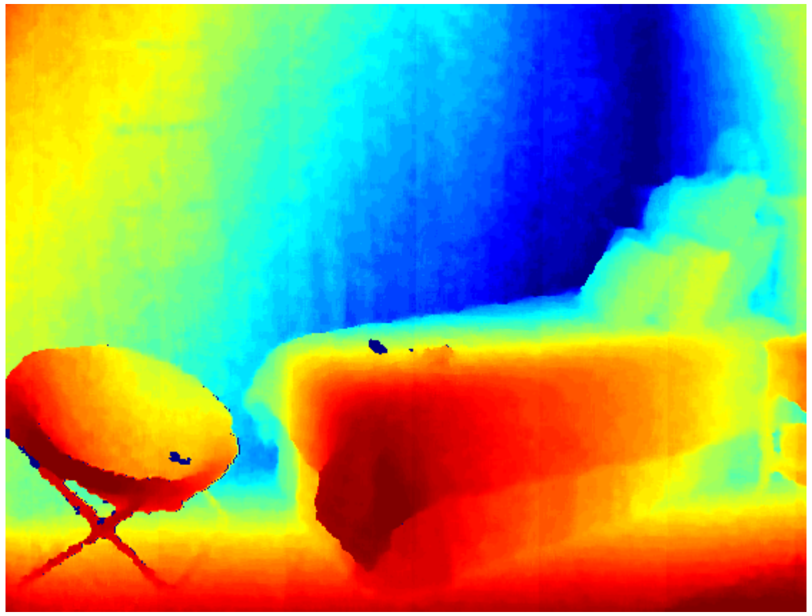
This Work (RGB-D)

Results

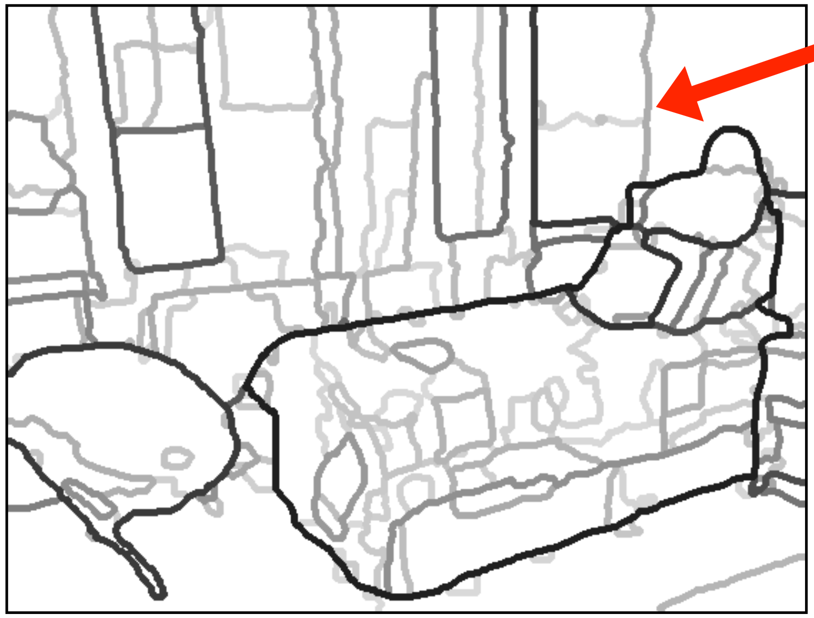


RGB

gPb-UCM(RGB)



D



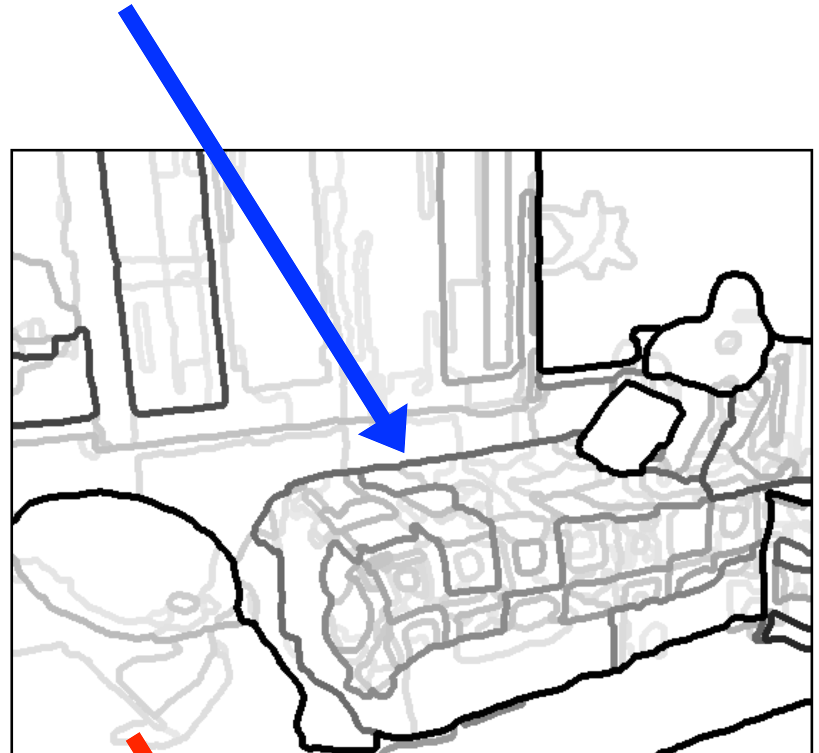
This Work (RGB-D)

Less distracted by albedo

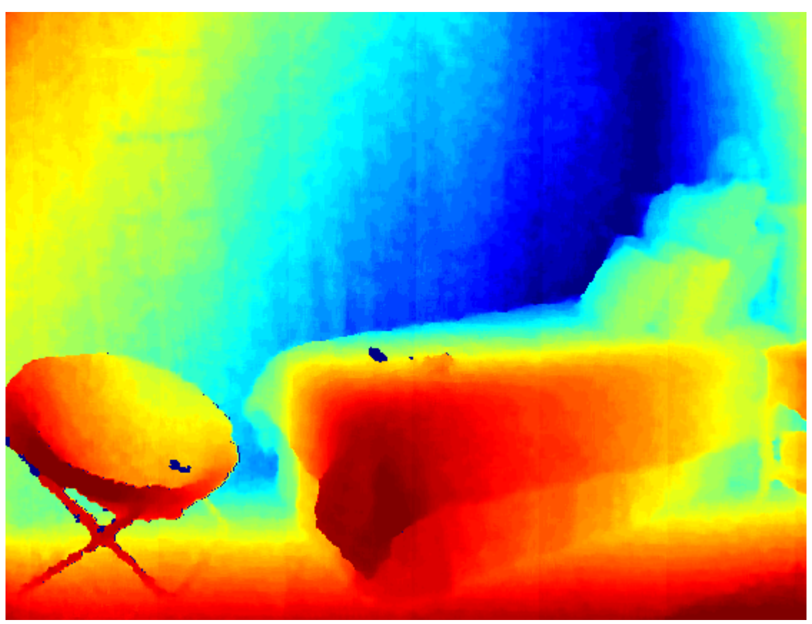
Higher Recall

Results

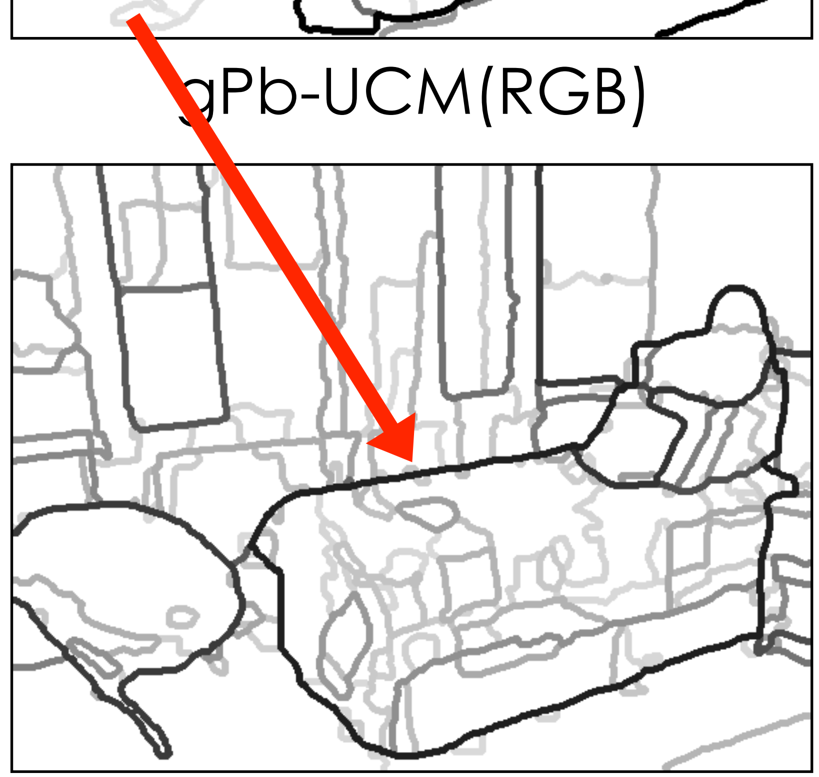
RGB



gPb-UCM(RGB)



D



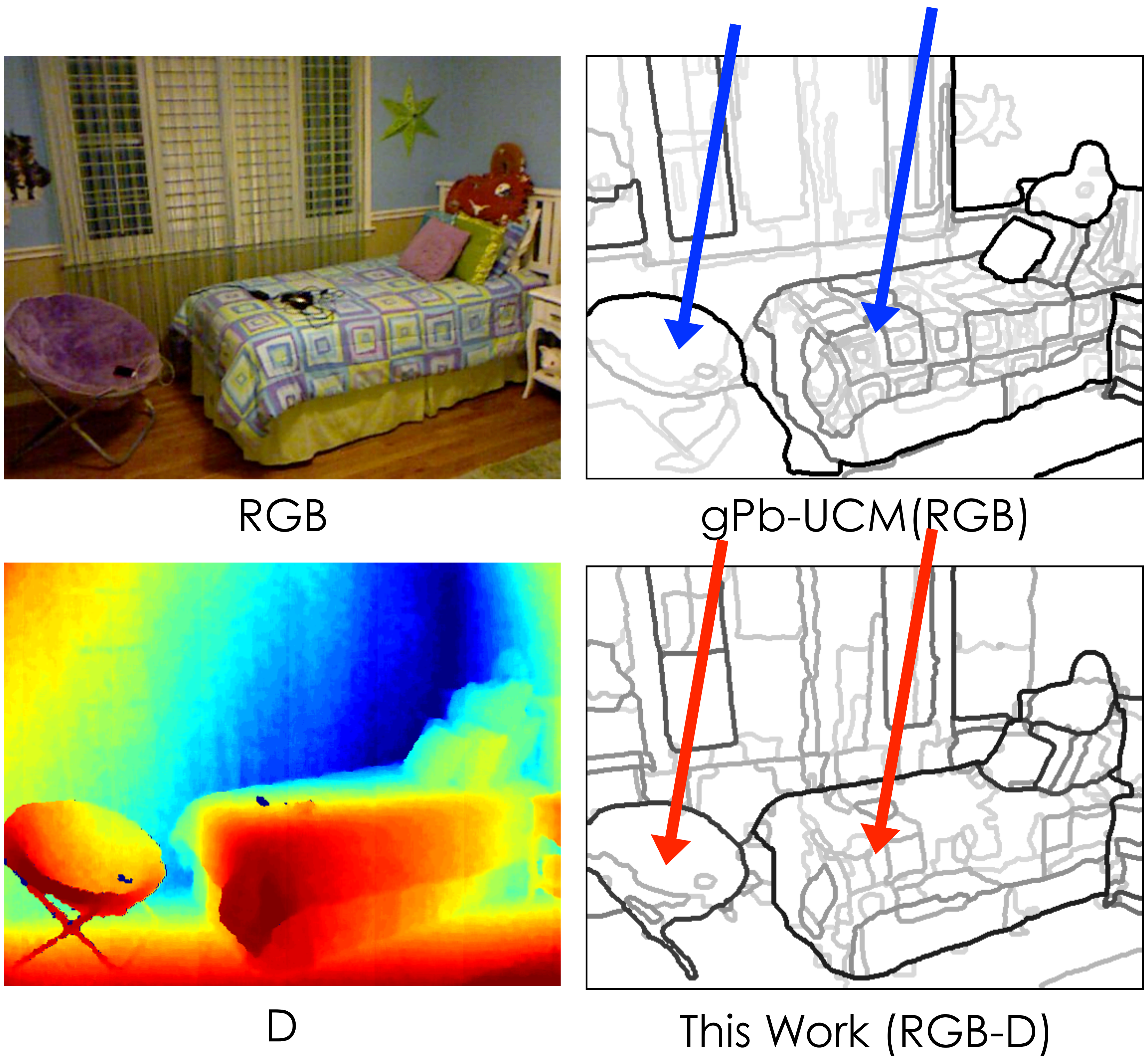
This Work (RGB-D)

Less distracted by albedo

Higher Recall

Higher Precision

Results



Less distracted by albedo

Higher Recall

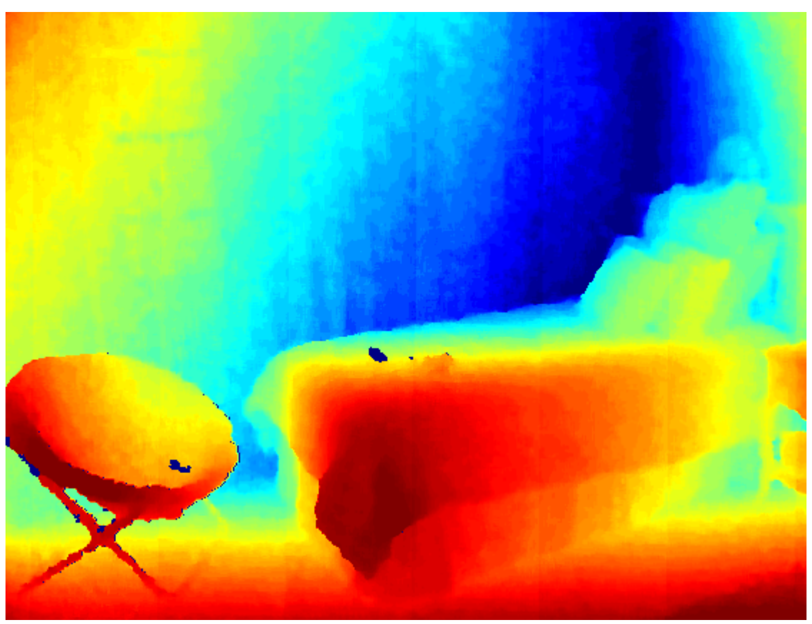
Higher Precision

More Complete Objects

Results

RGB

gPb-UCM(RGB)



D

This Work (RGB-D)

Less distracted by albedo

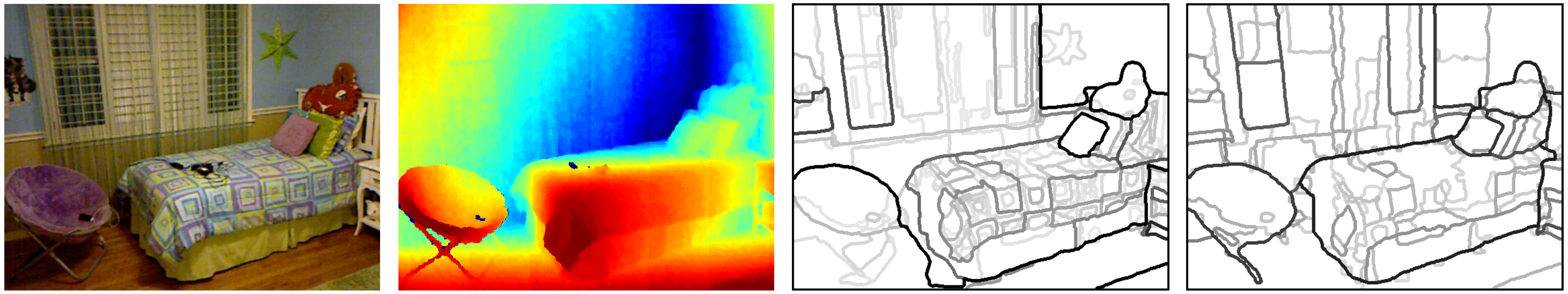
Higher Recall

Higher Precision

More Complete Objects

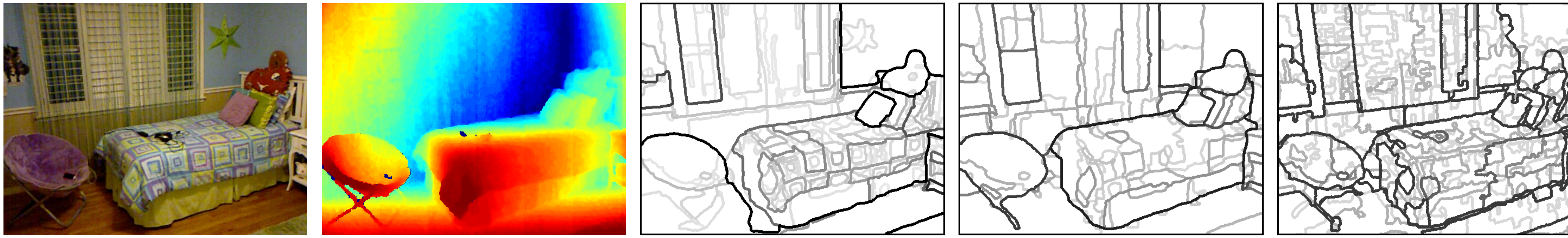
Results

RGB | Depth | gPb-ucm (RGB) | This Work (RGB-D)



Results

RGB | Depth | gPb-ucm (RGB) | This Work (RGB-D) | Silberman et al. (RGB-D)



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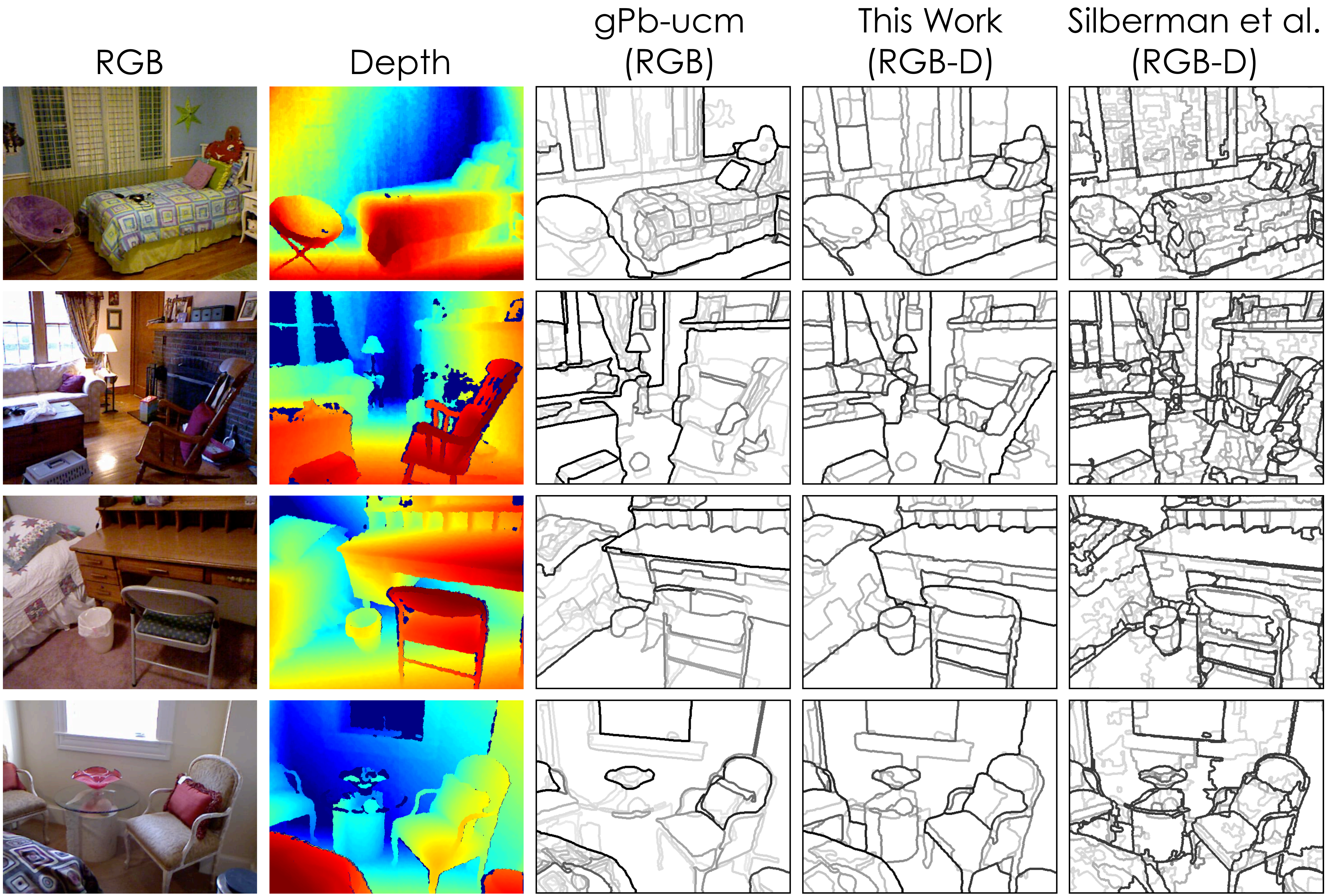


Bottom Up Segmentation

Performance

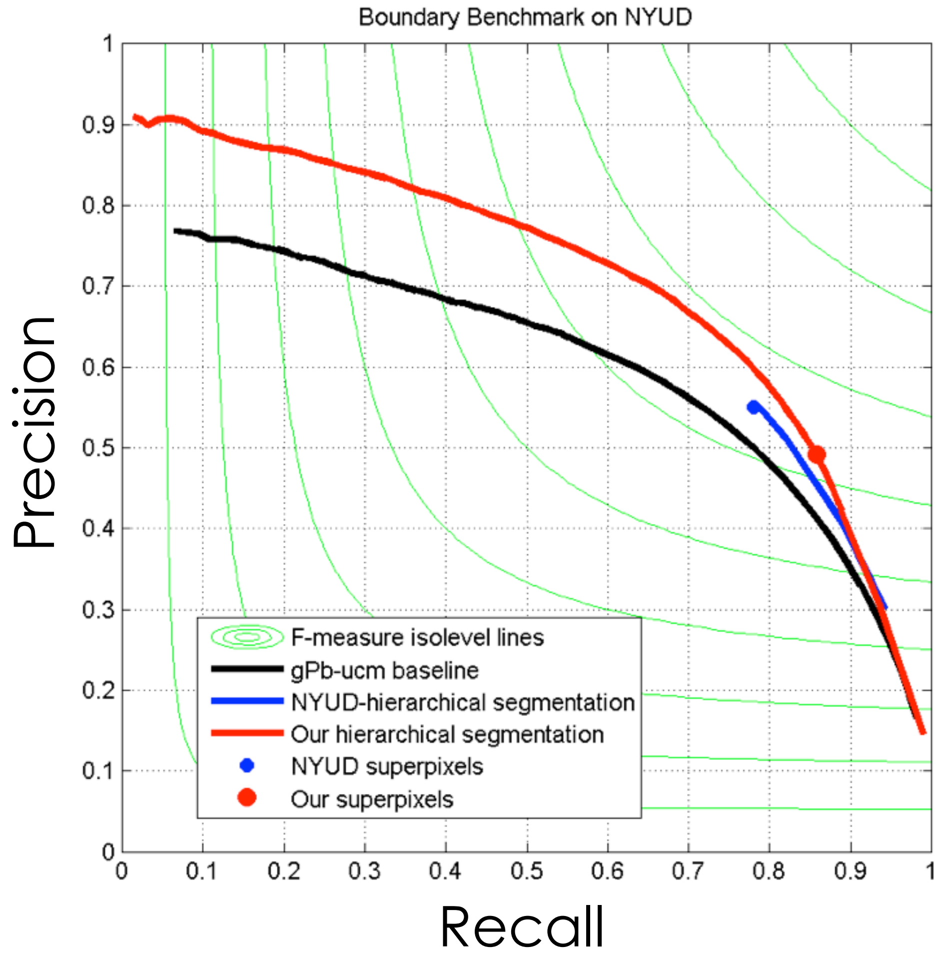
Arbeláez et al., PAMI 2011, Contour Detection and Hierarchical Image Segmentation.
Silberman et al., ECCV12, Indoor segmentation and support inference from RGBD images.

Bottom Up Segmentation

Performance

Contours

		ODS	OIS	AP
Arbeláez et al.	RGB	0.62	0.65	0.55
Silberman et al.	RGB-D	0.65	0.65	-
This Work	RGB-D	**0.69**	**0.71**	0.70



Precision Recall Curve on Contours

Arbeláez et al., PAMI 2011, Contour Detection and Hierarchical Image Segmentation.
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Bottom Up Segmentation

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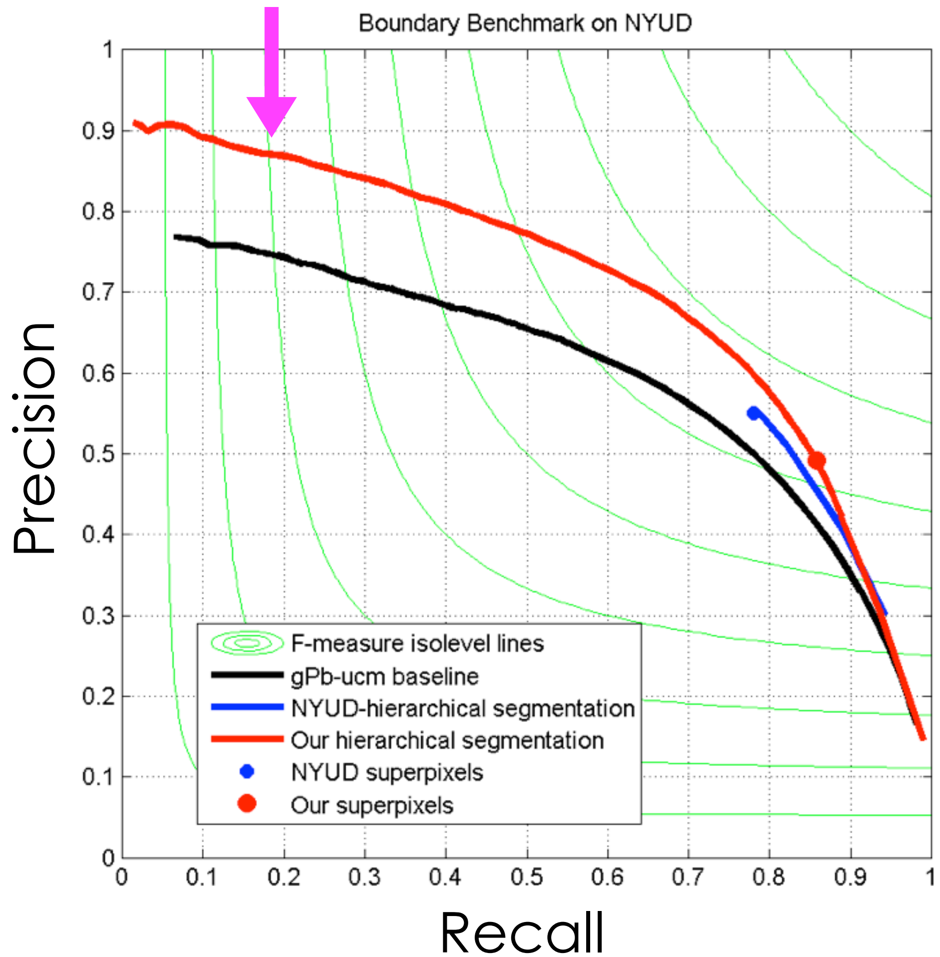

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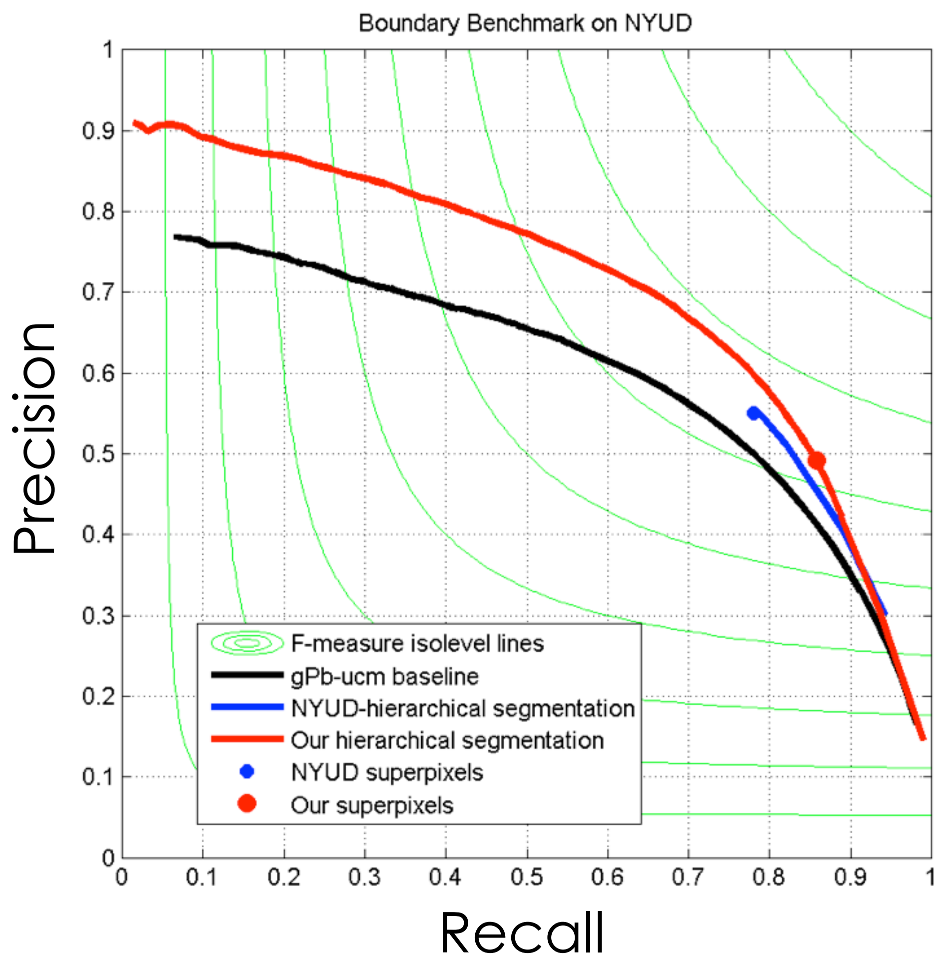

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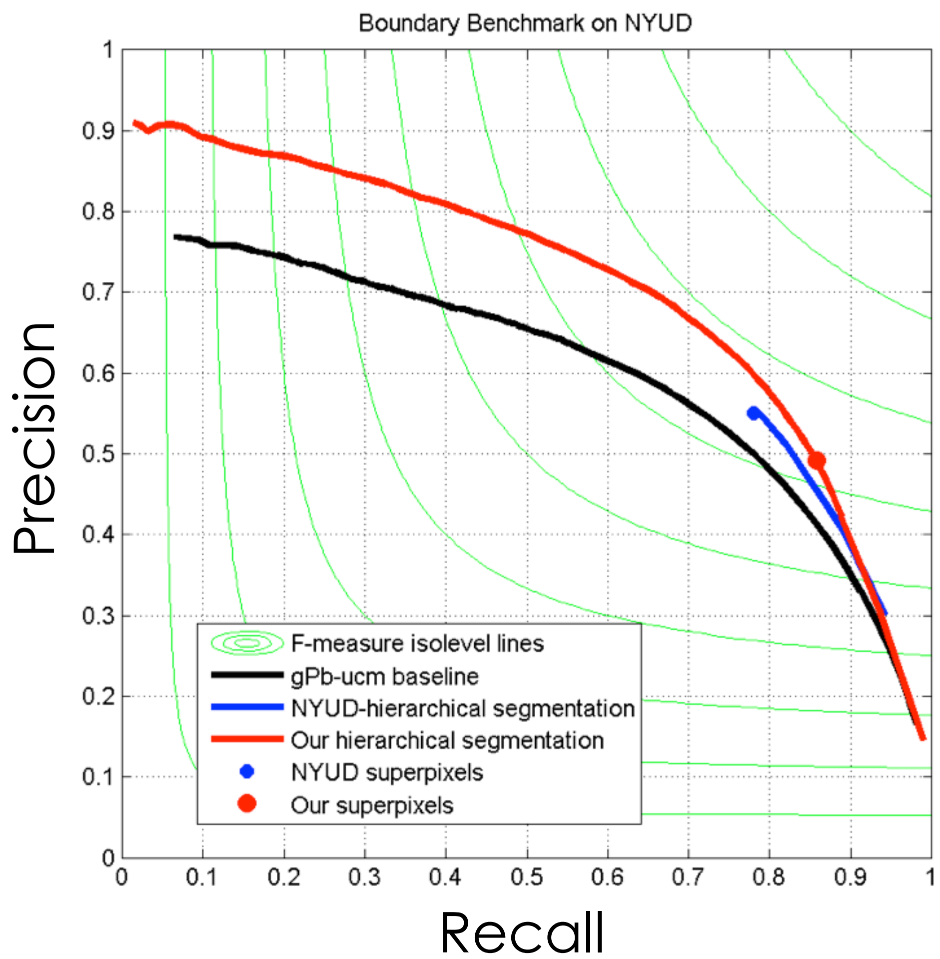

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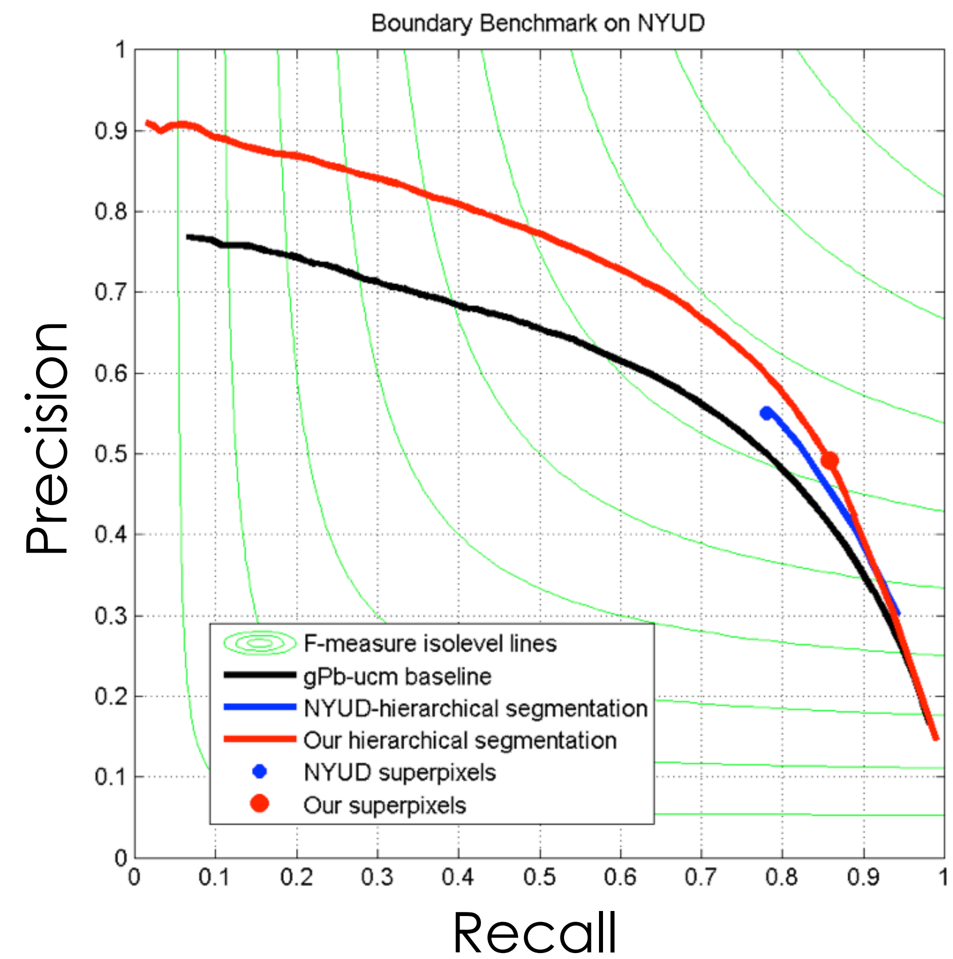

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Bottom Up Segmentation

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Regions

		ODS	OIS	bestC
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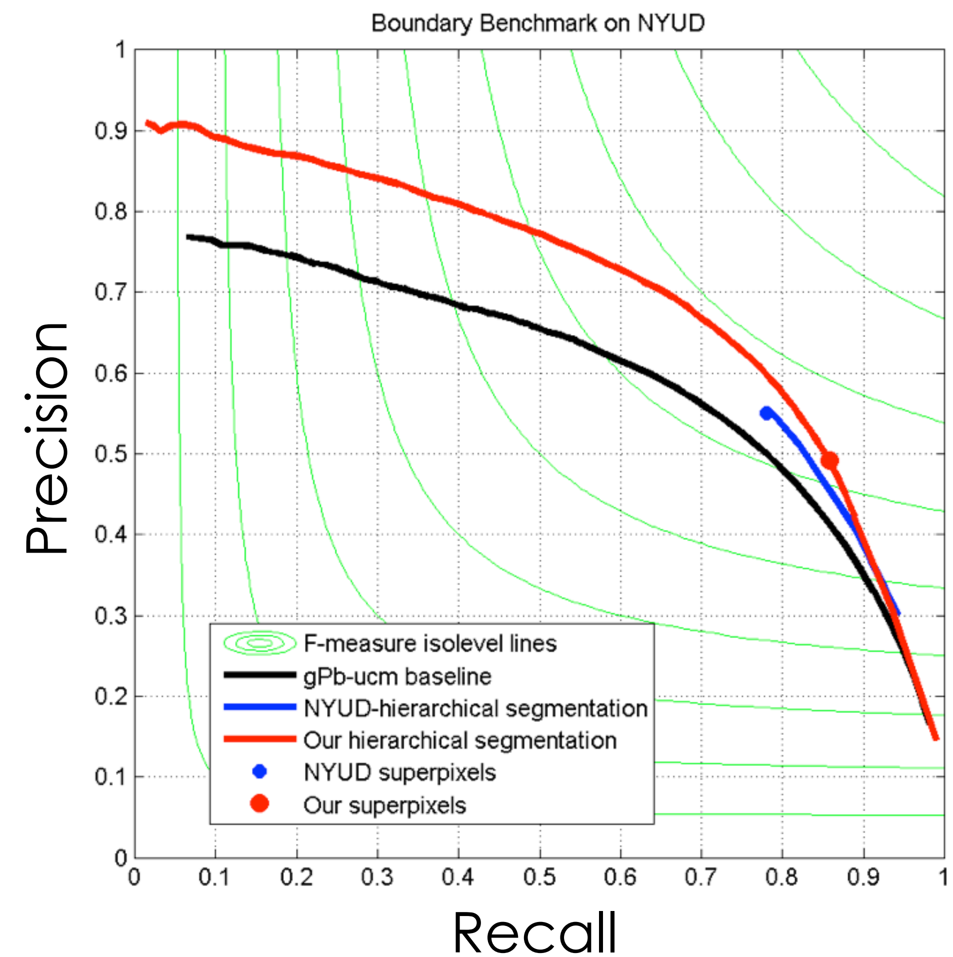

Precision Recall Curve on Contours

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Bottom Up Segmentation

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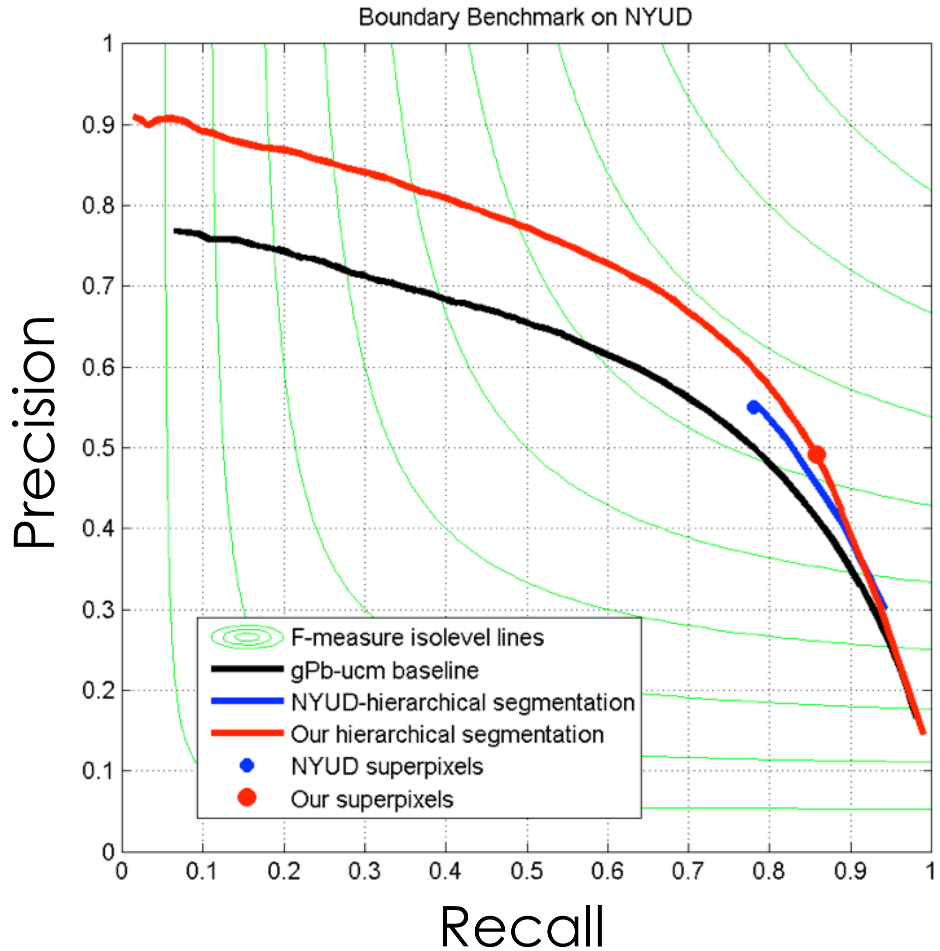

Precision Recall Curve on Contours

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Bottom Up Segmentation

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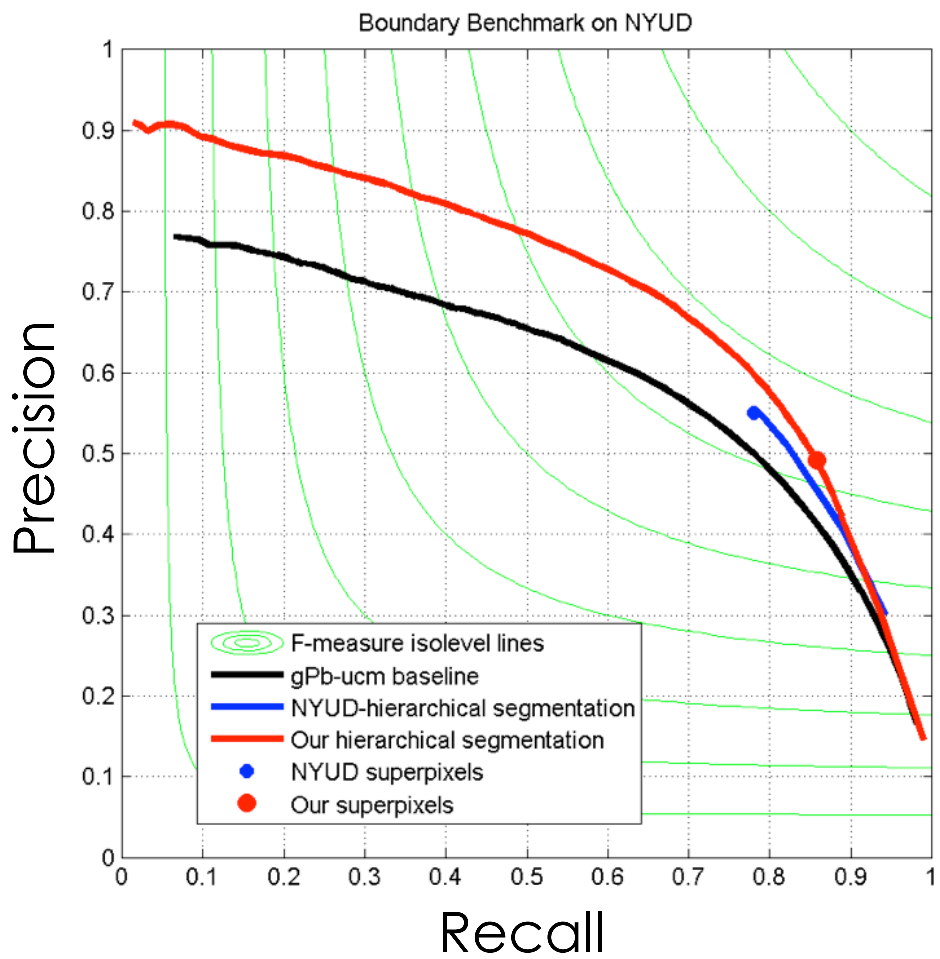

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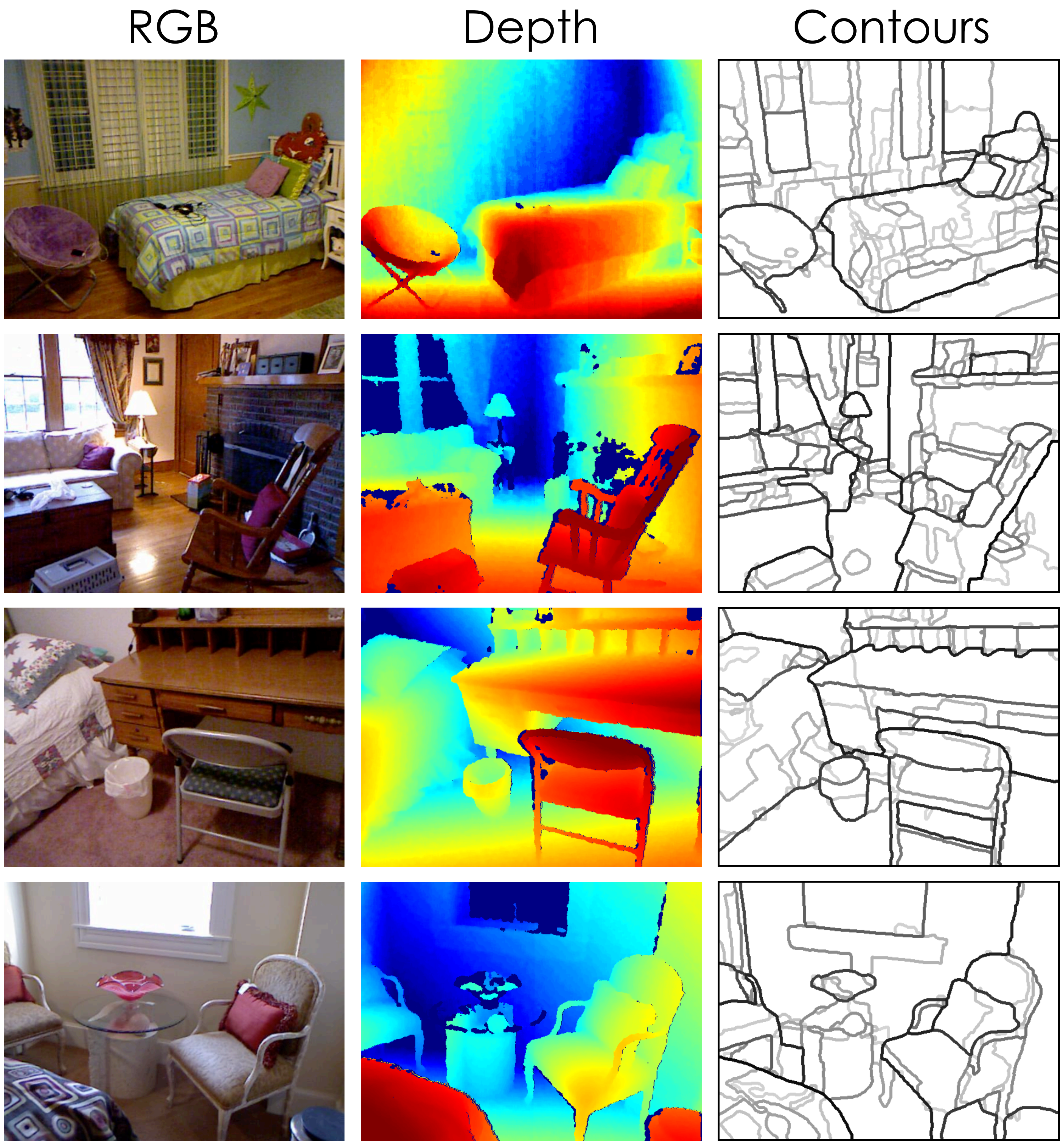
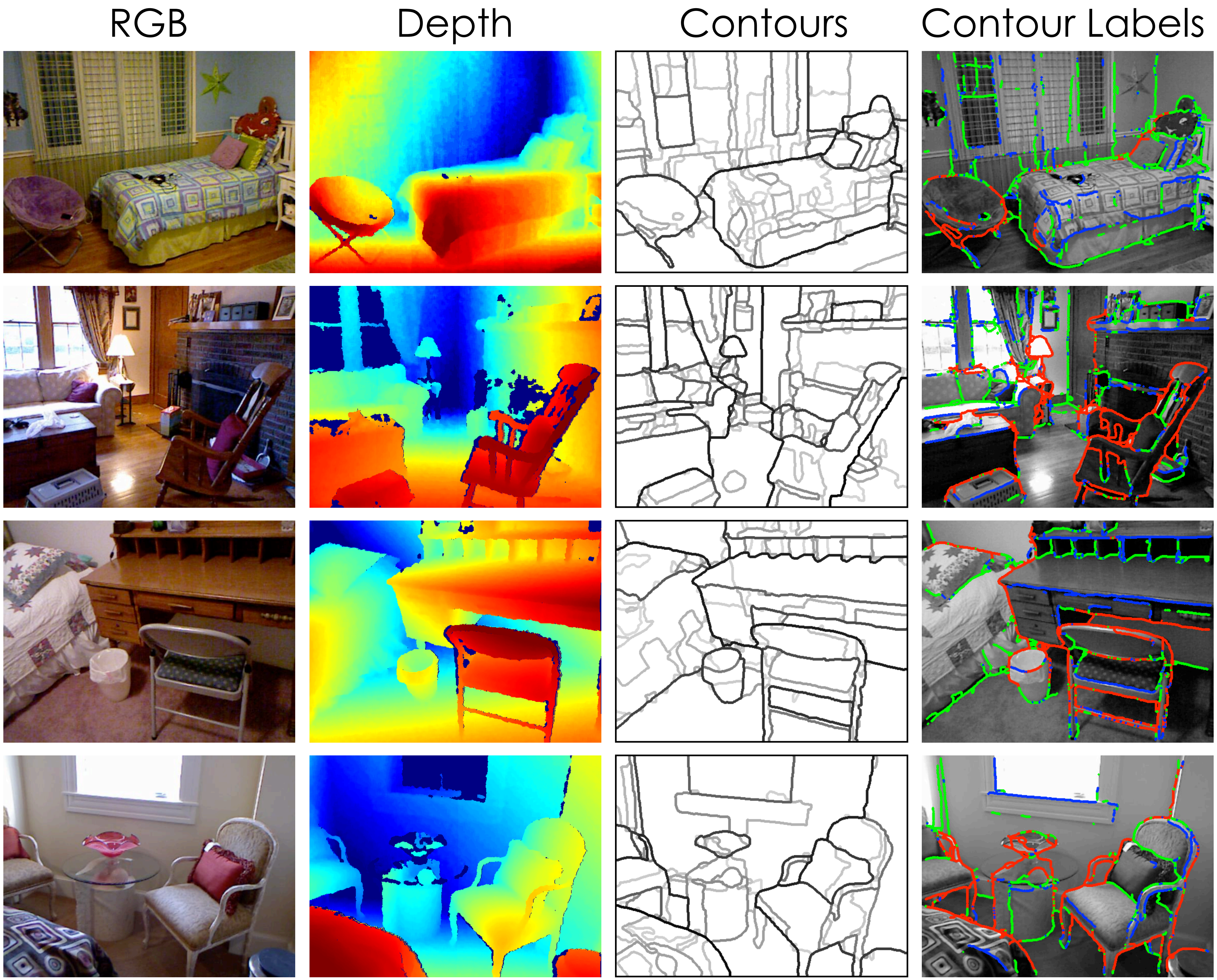
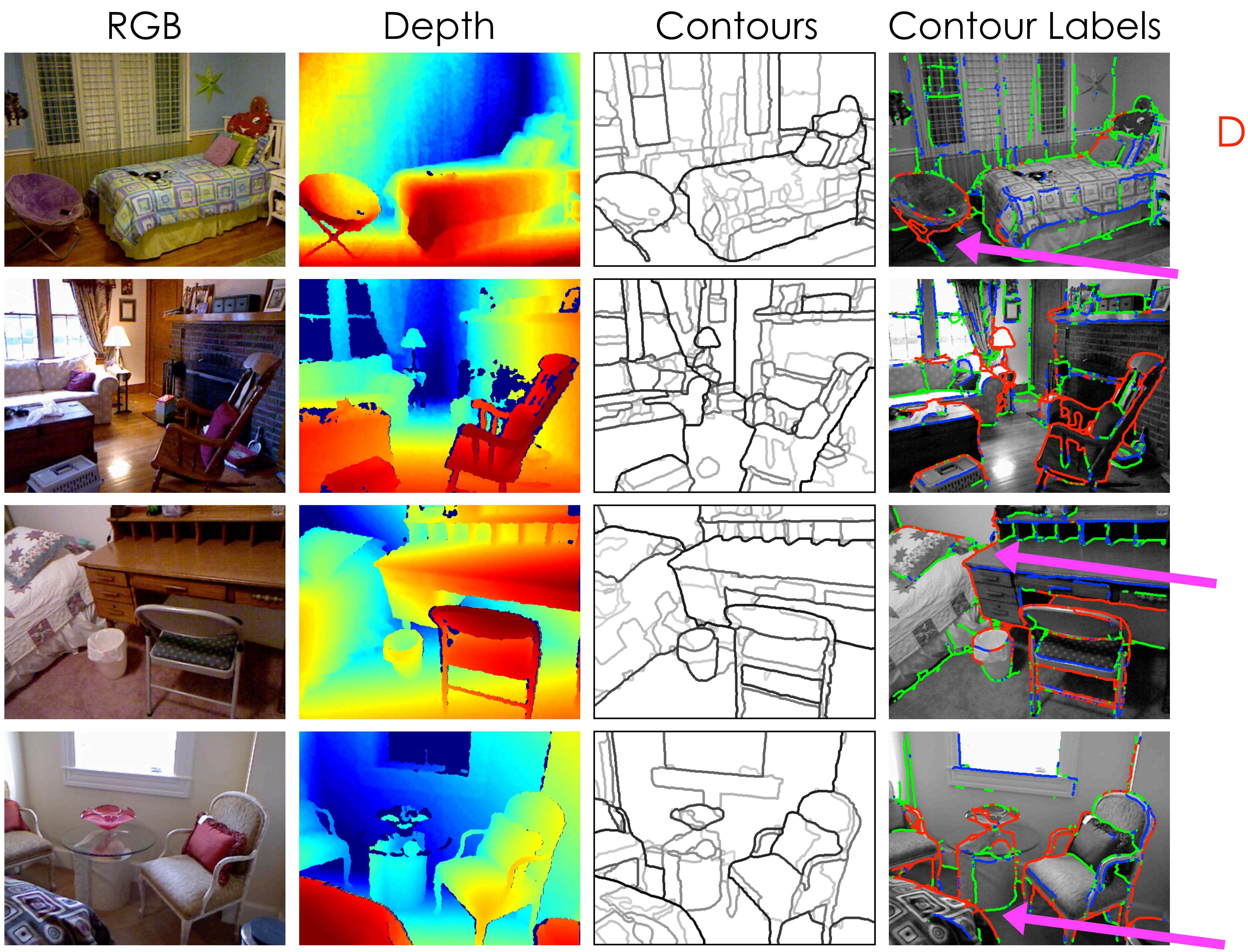
Results



Results

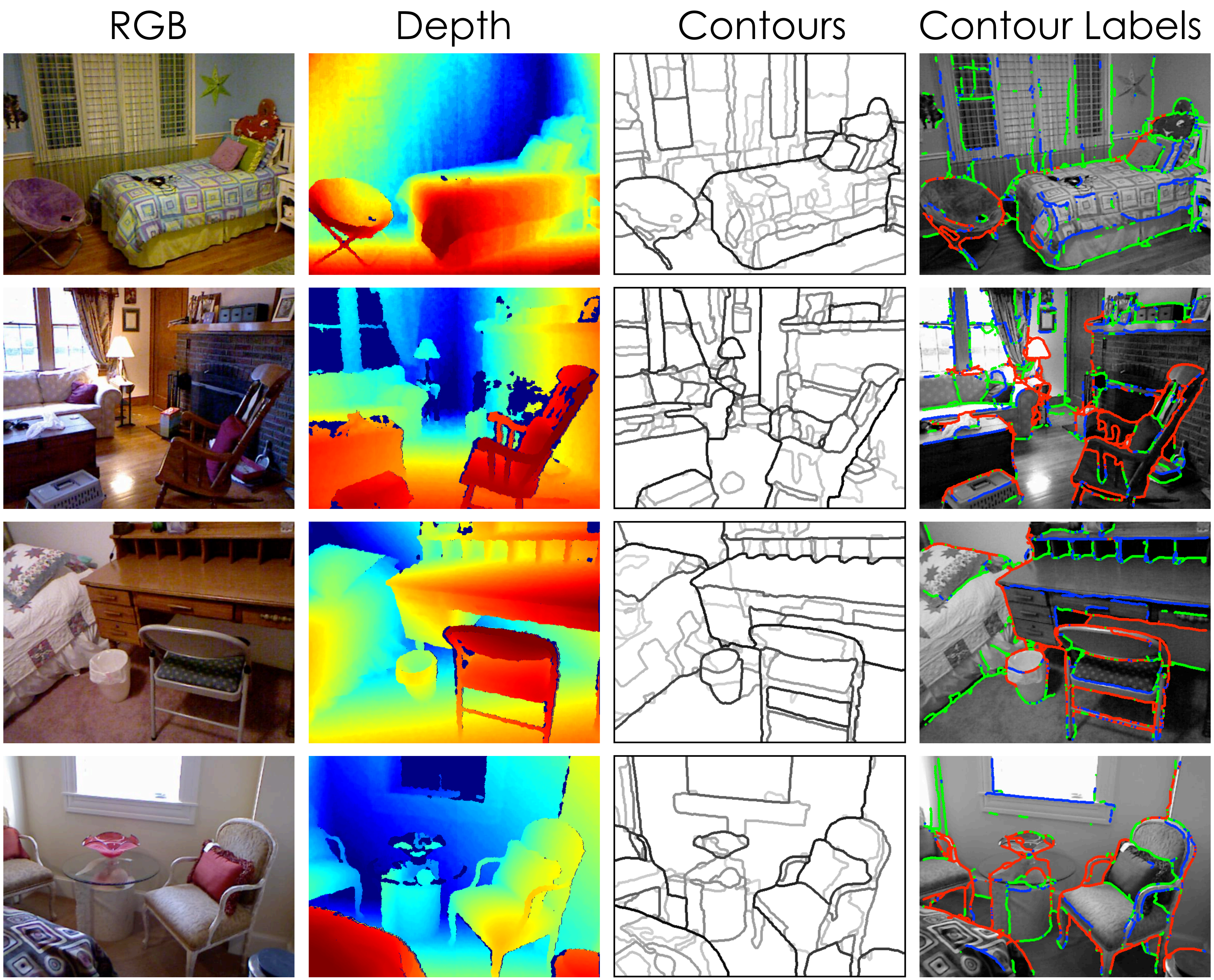


Results



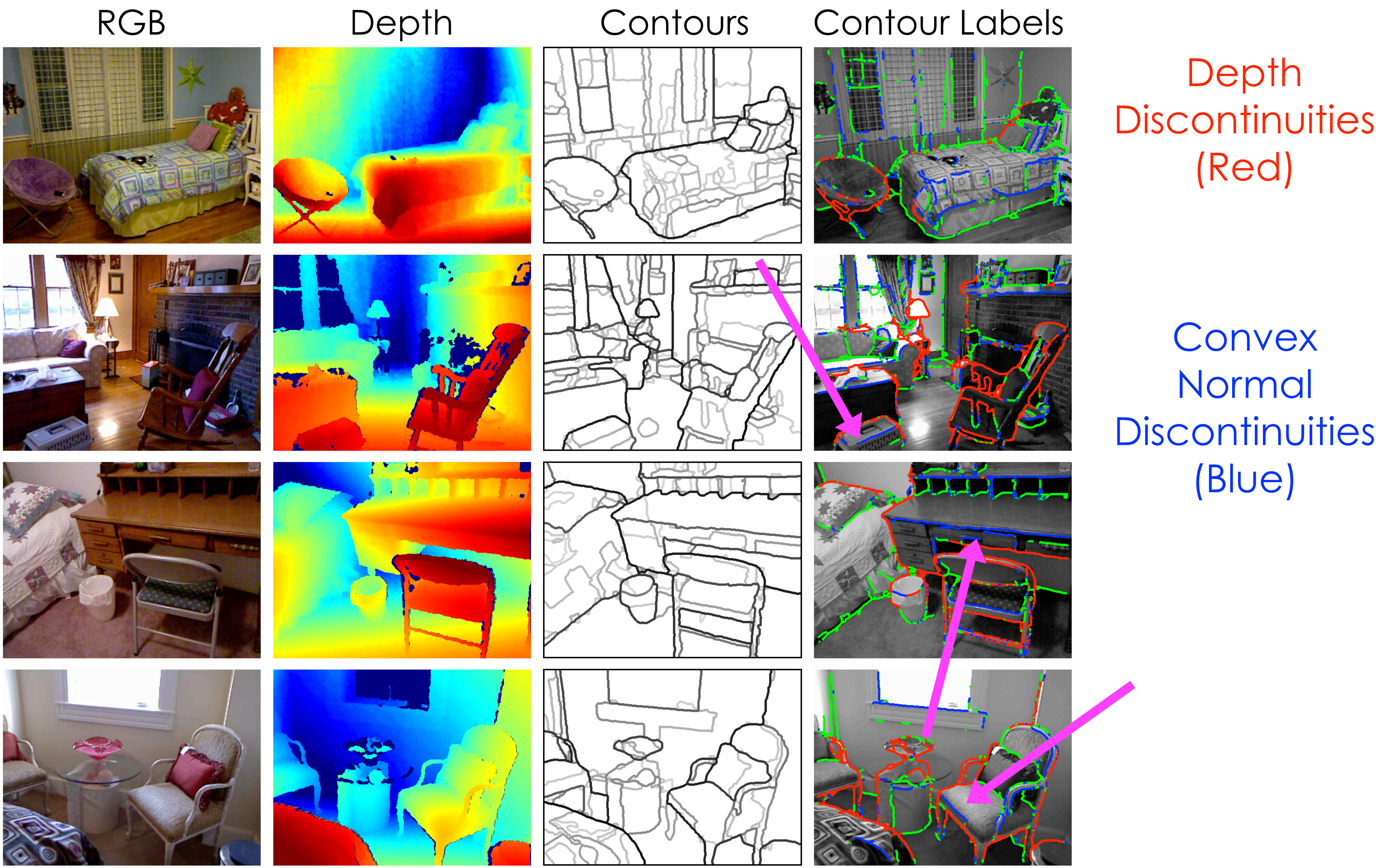
RGB
Depth
Contours
Contour Labels
Depth
Discontinuities
(Red)

Results



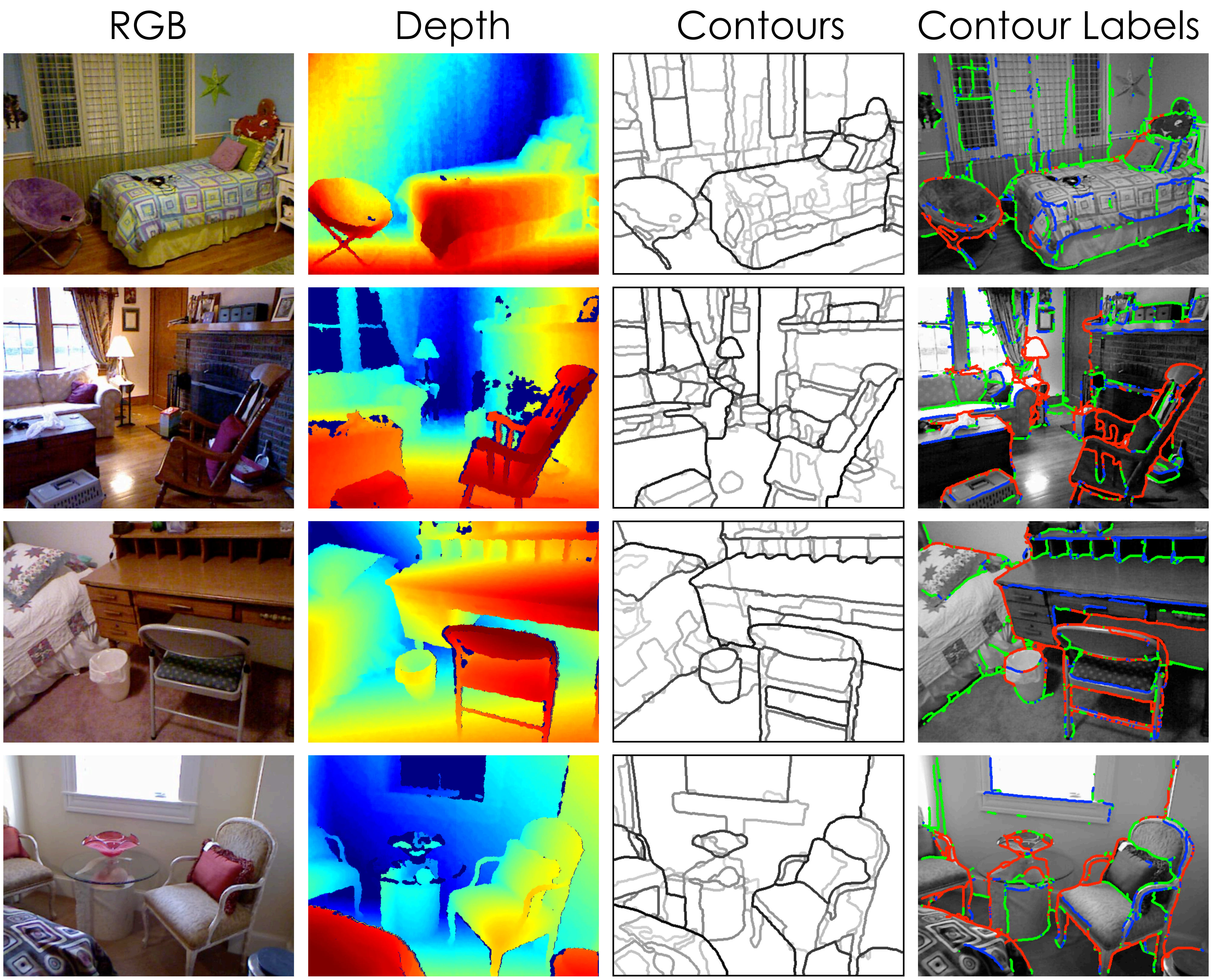
Depth Discontinuities (Red)

Results



RGB
Depth
Contours
Contour Labels
Depth Discontinuities (Red)
Convex Normal Discontinuities (Blue)

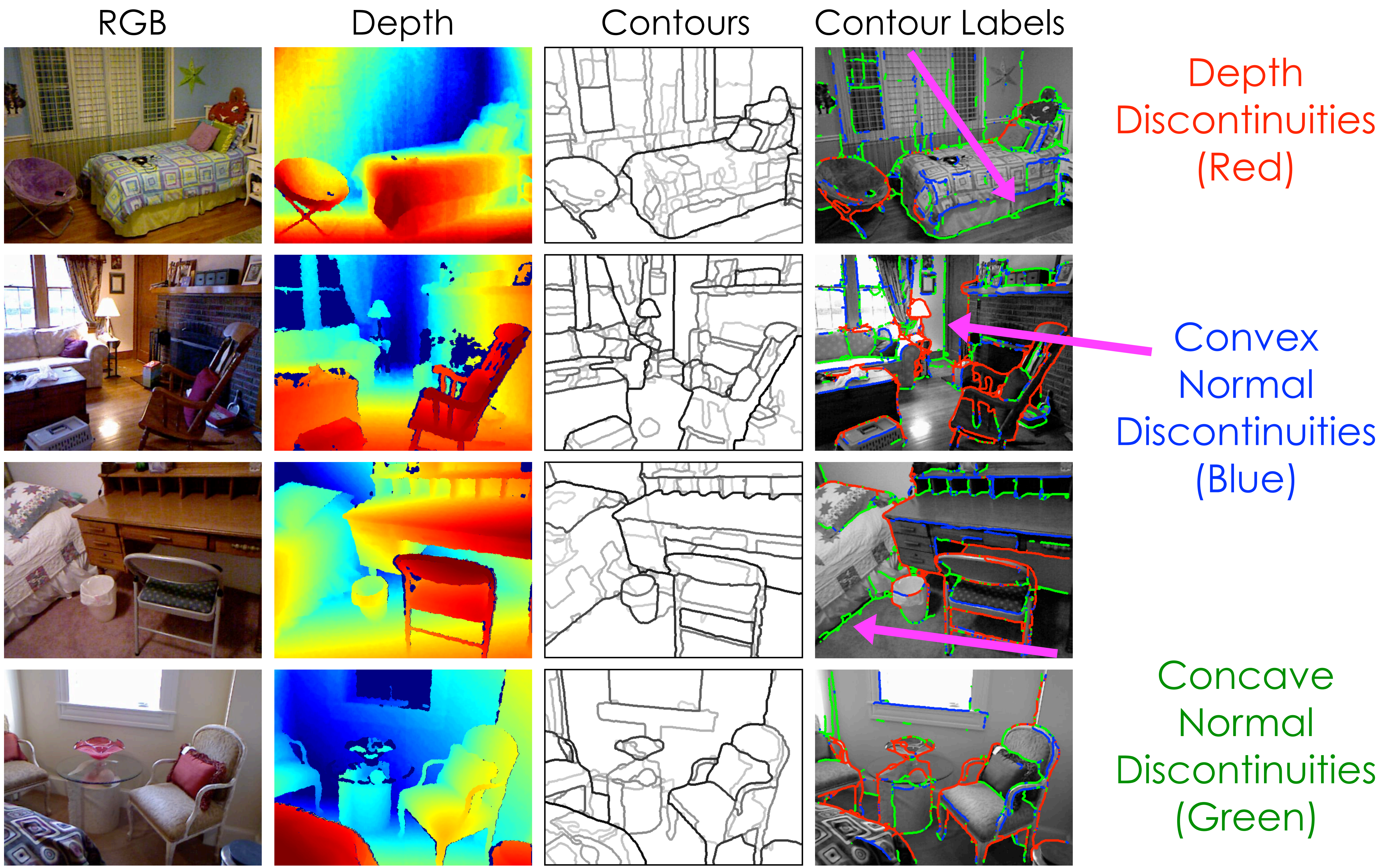
Results



Depth Discontinuities (Red)

Convex Normal Discontinuities (Blue)

Results


RGB
Depth
Contours
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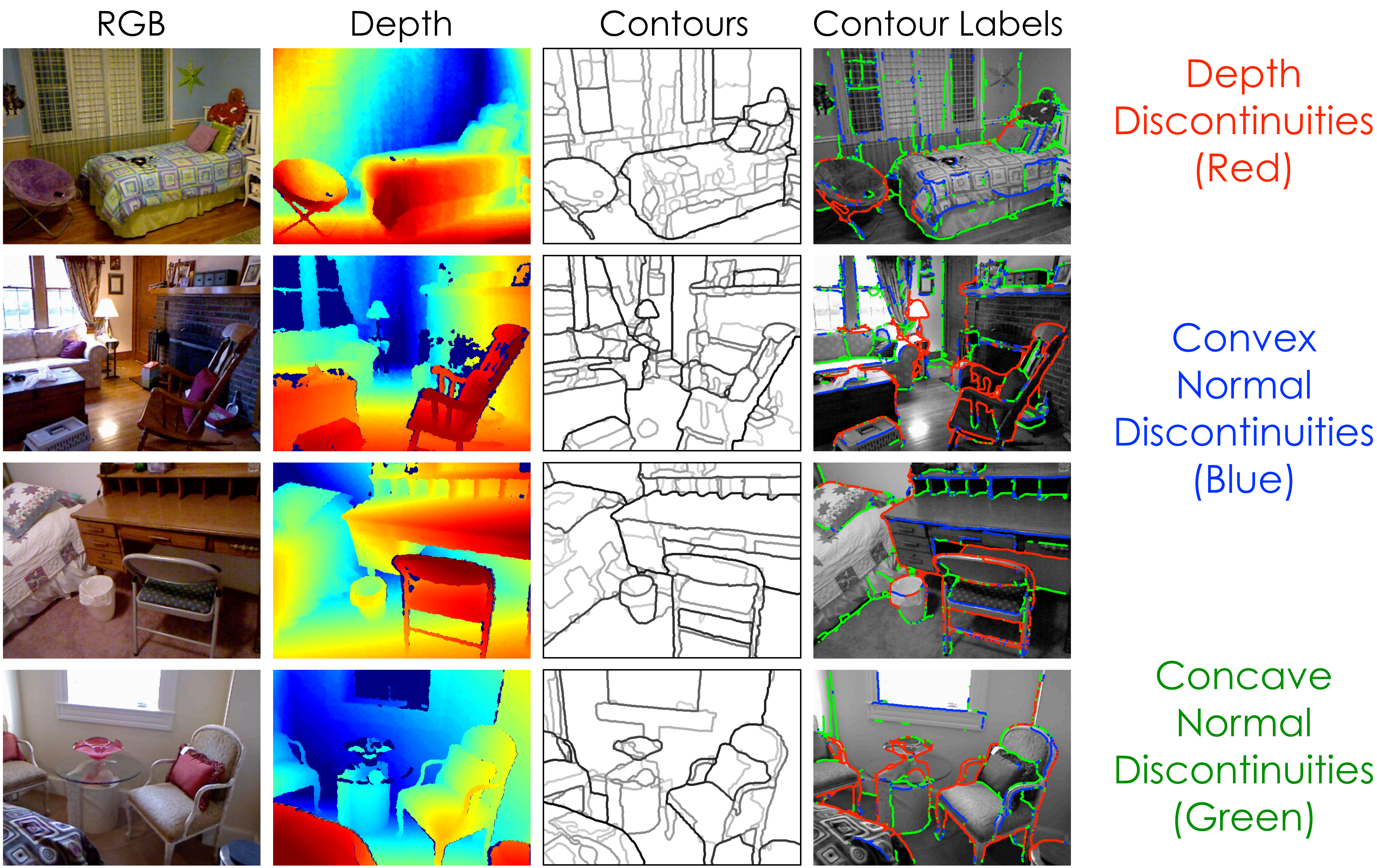
Concave Normal Discontinuities (Green)

Results


RGB
Depth
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Depth Discontinuities (Red)
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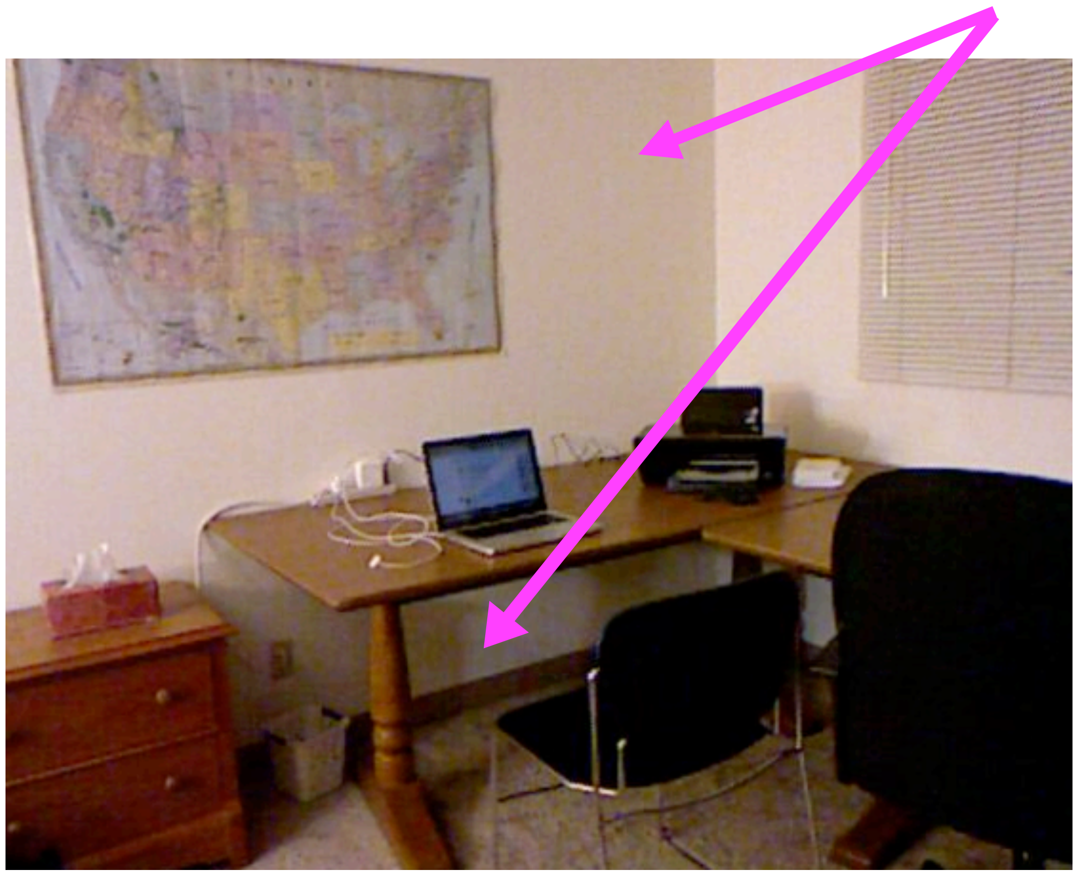
Amodal Completion

Completing contiguous surfaces behind occluders

Kanizsa et al., Praeger Publishers, 1979, Organization in Vision: Essays on Gestalt Perception.

Amodal Completion

Completing contiguous surfaces behind occluders



Wall

Kanizsa et al., Praeger Publishers, 1979, Organization in Vision: Essays on Gestalt Perception.

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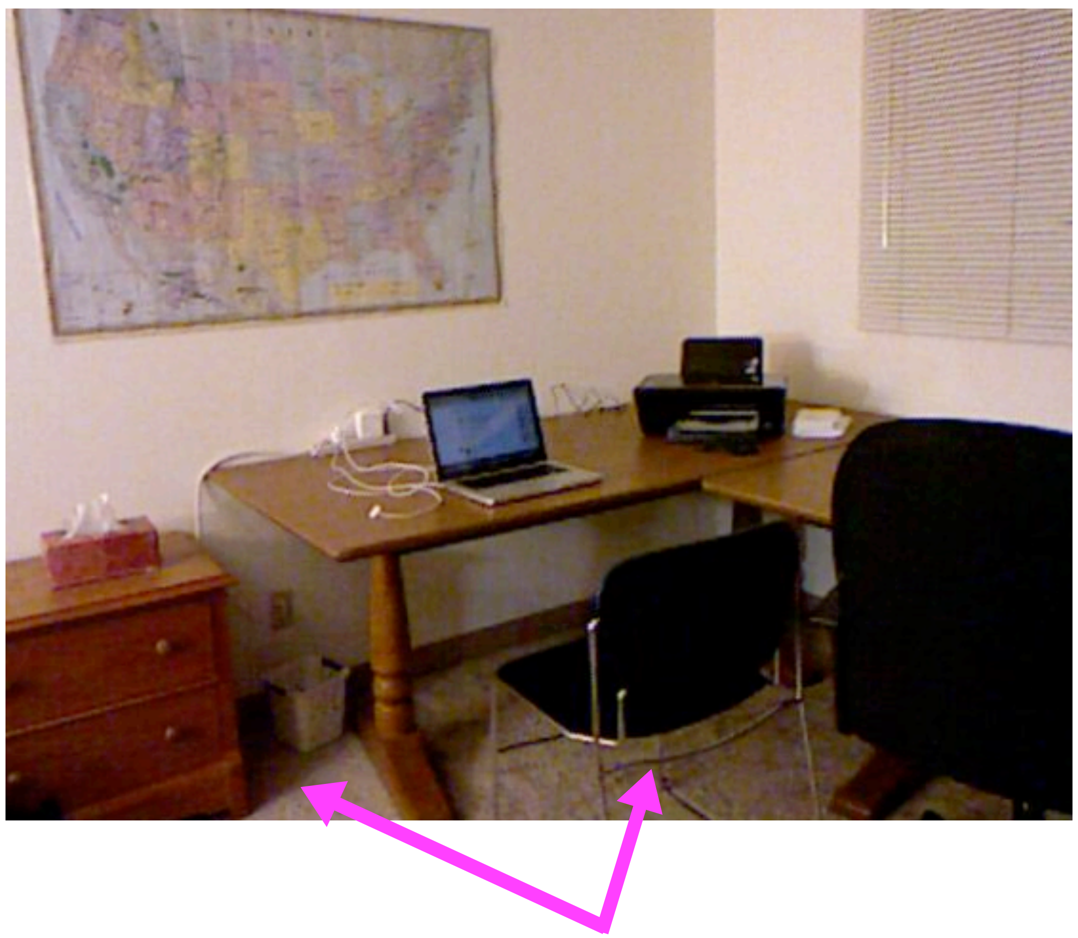

Floor

Kanizsa et al., Praeger Publishers, 1979, Organization in Vision: Essays on Gestalt Perception.

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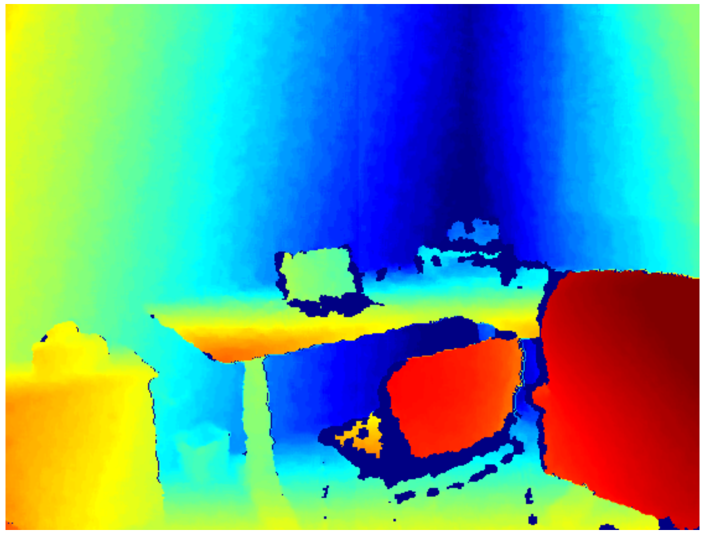

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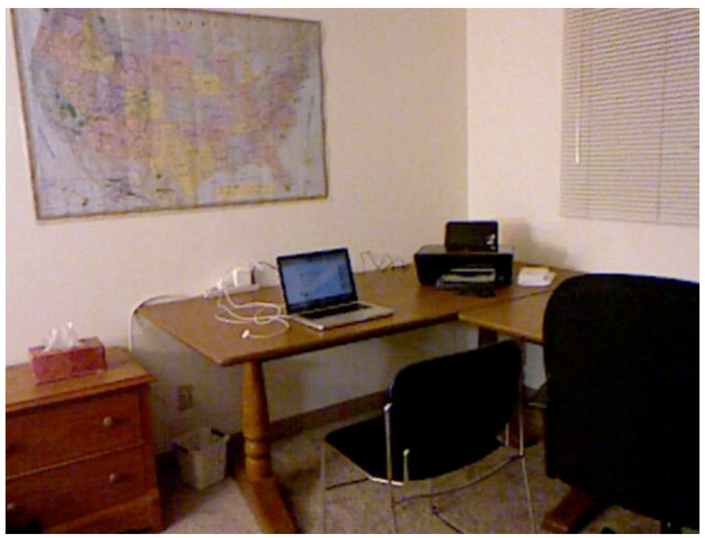

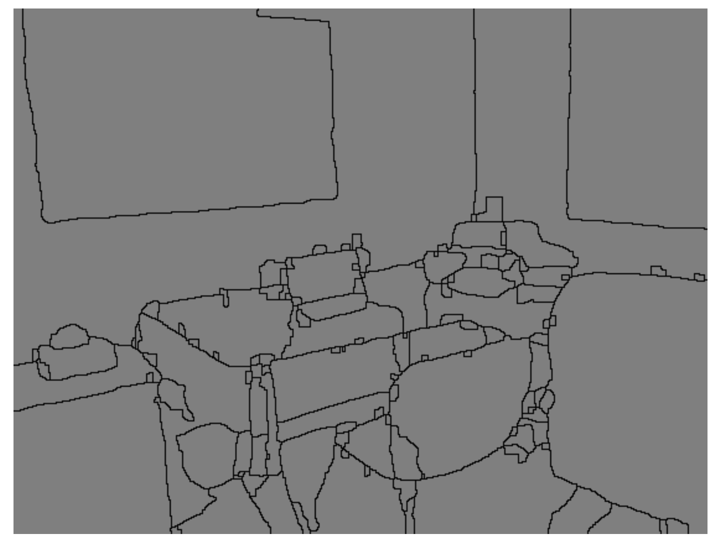

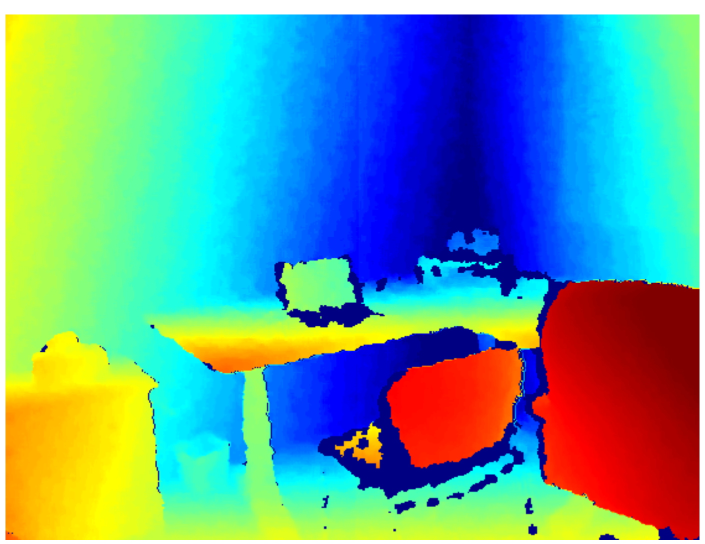

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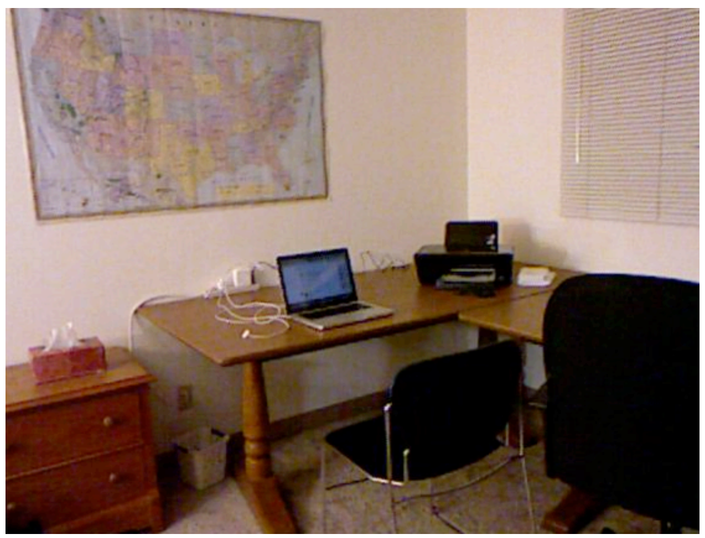

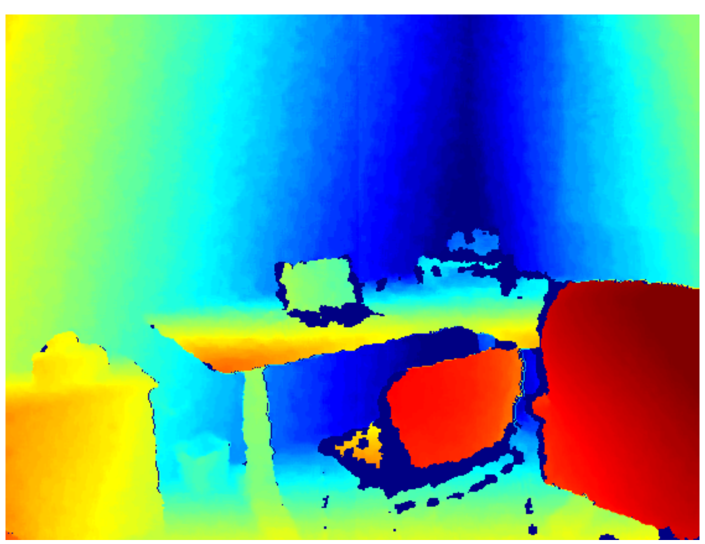

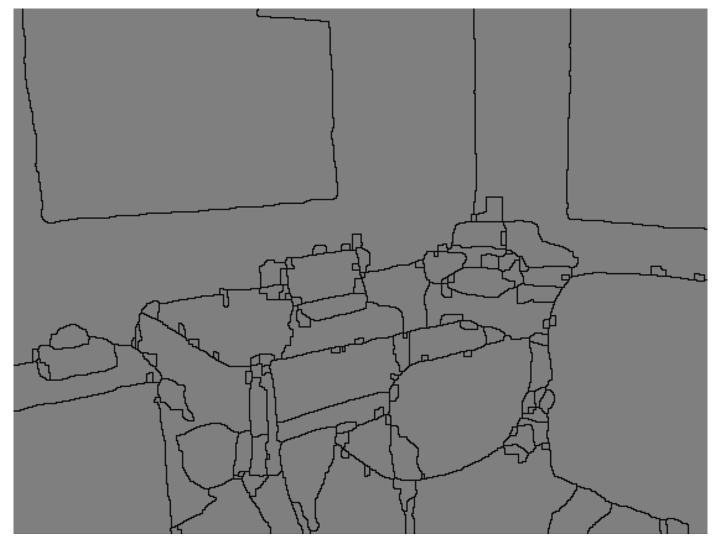

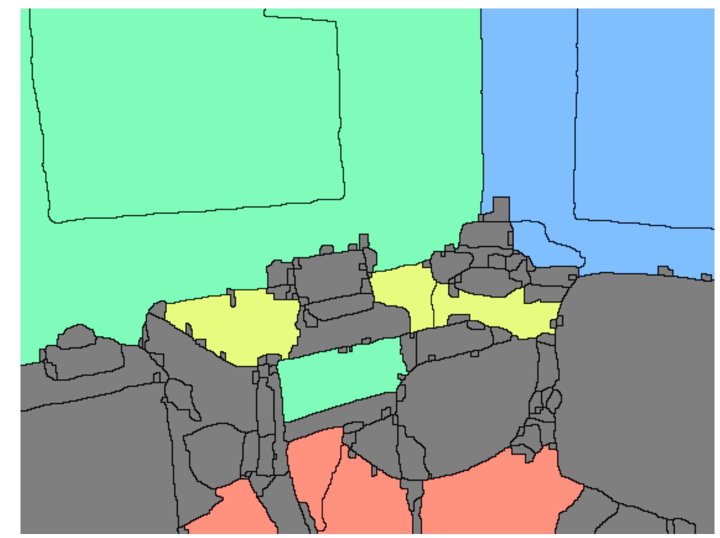

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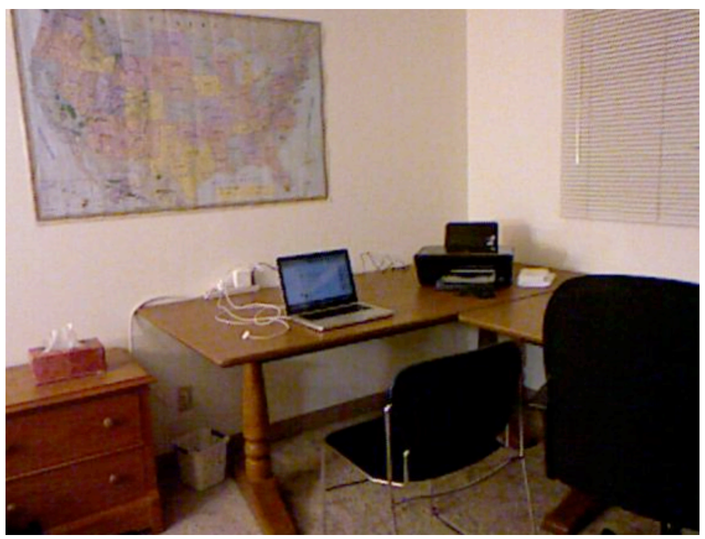

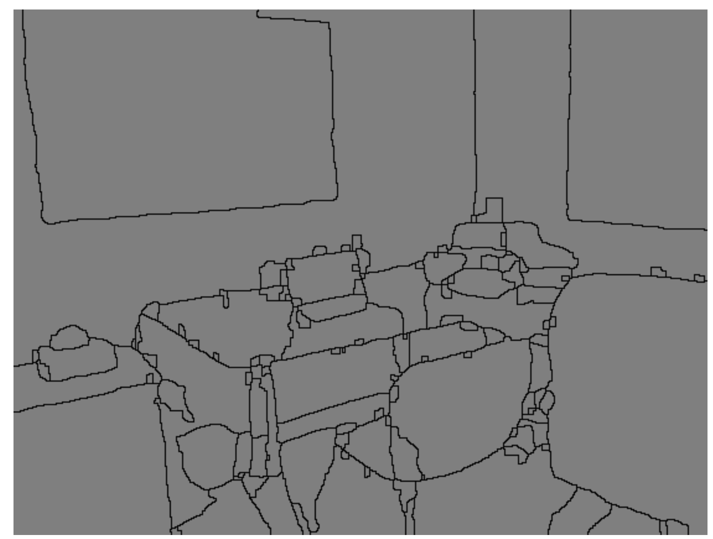

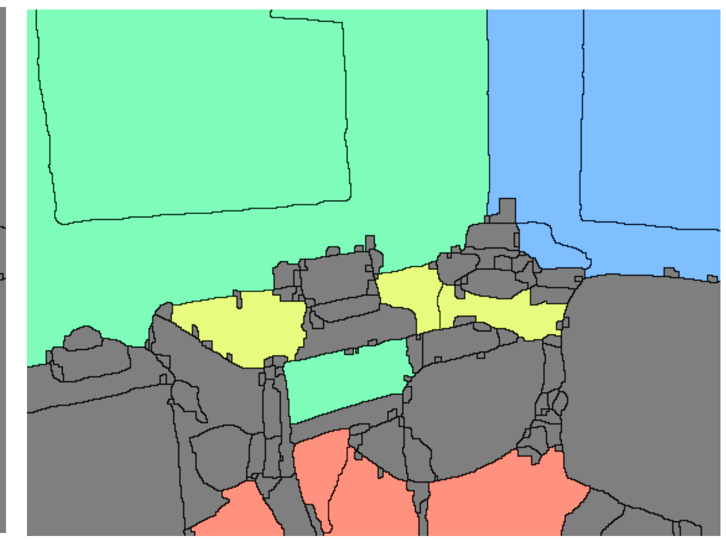

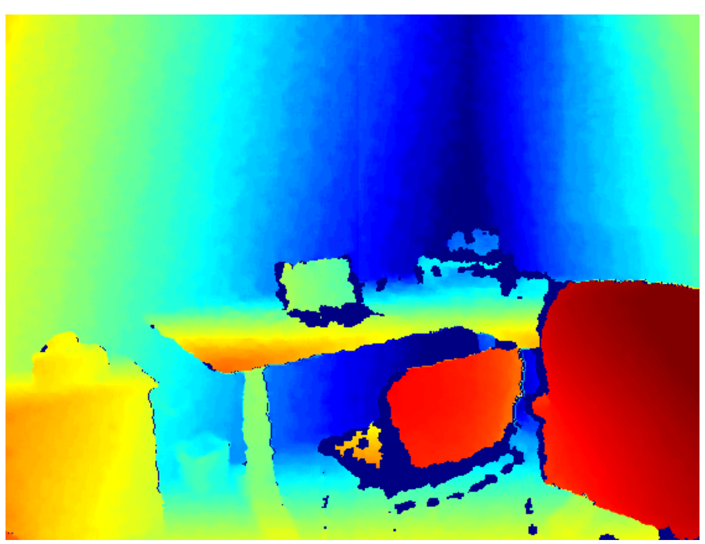

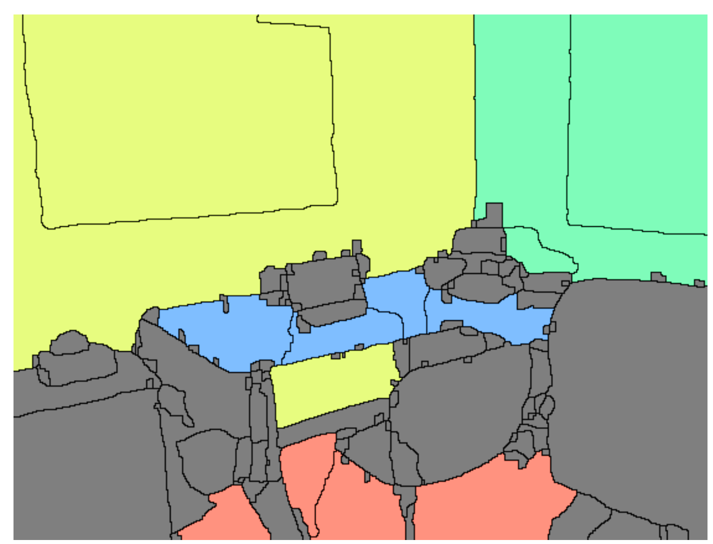

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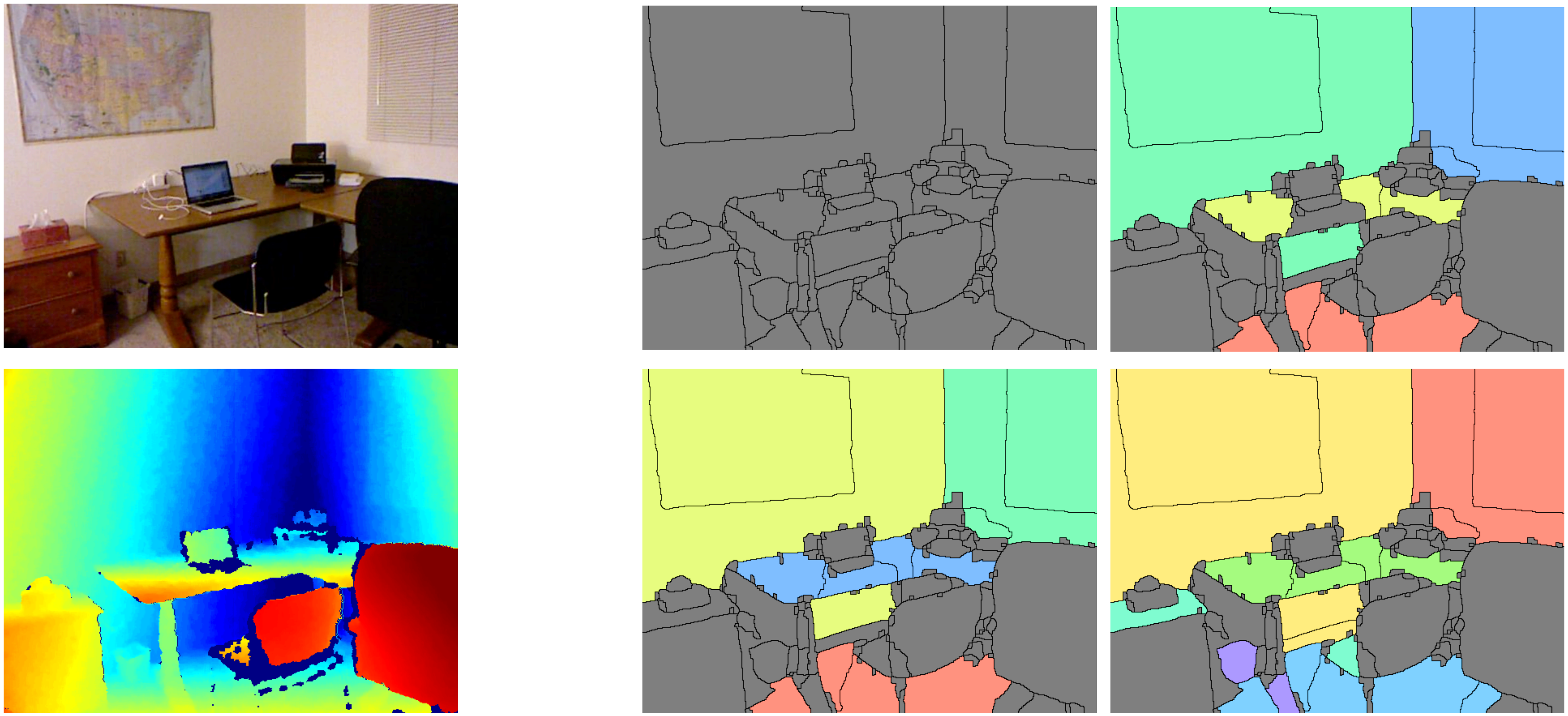
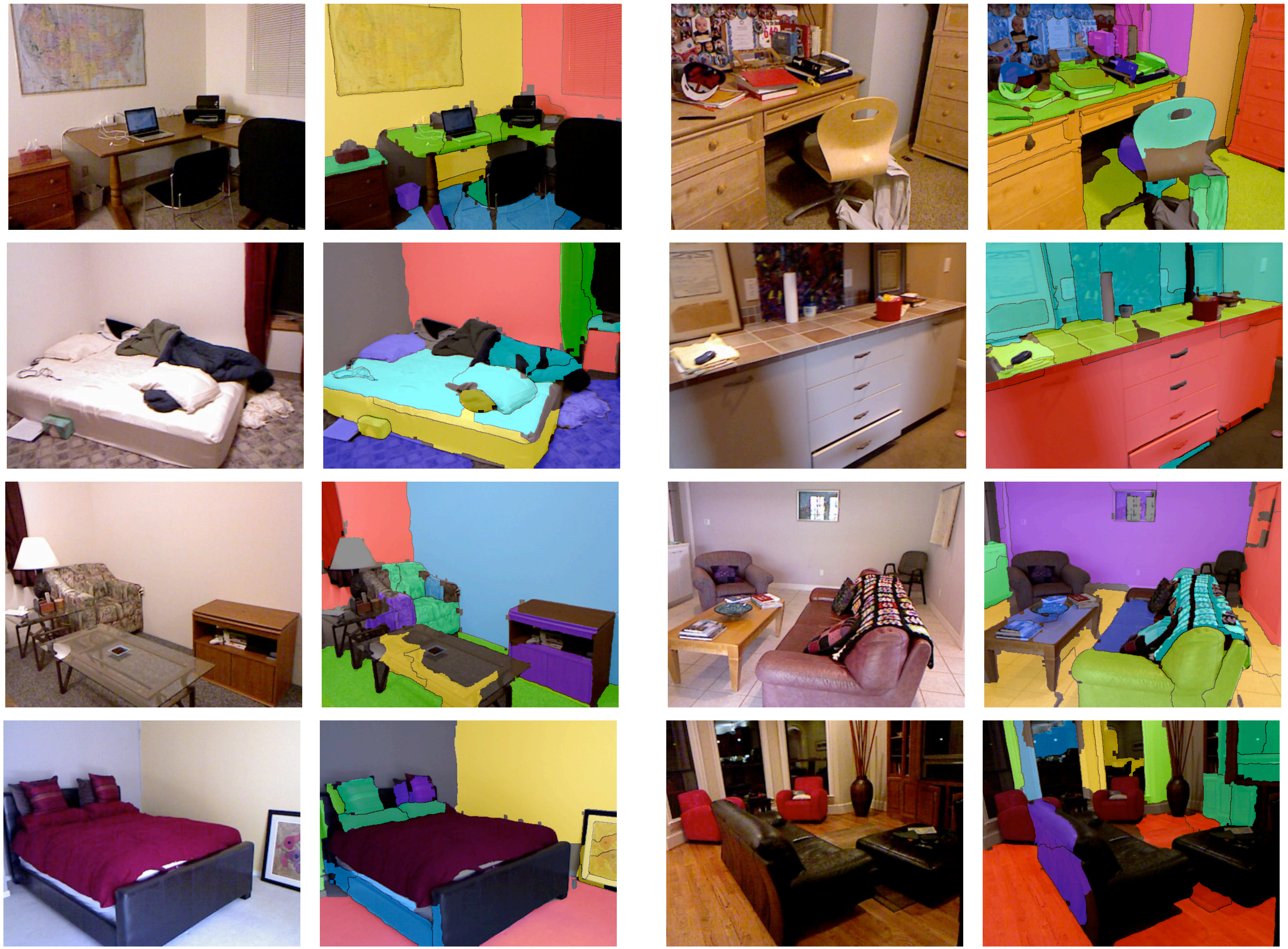


Results

Image | Completions | Image | Completions



Specially useful for floors and tables which are often interrupted by occluders

Results

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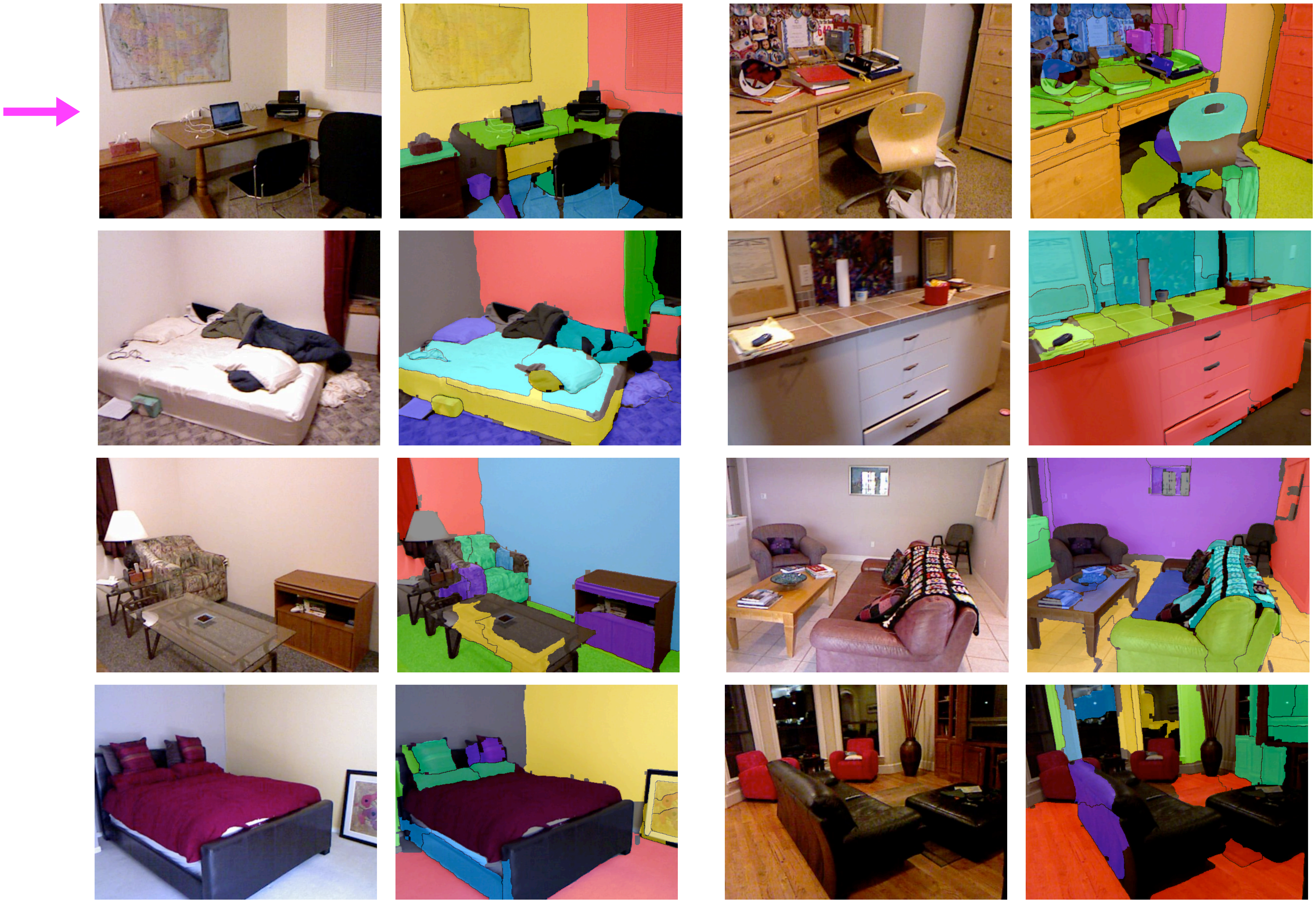

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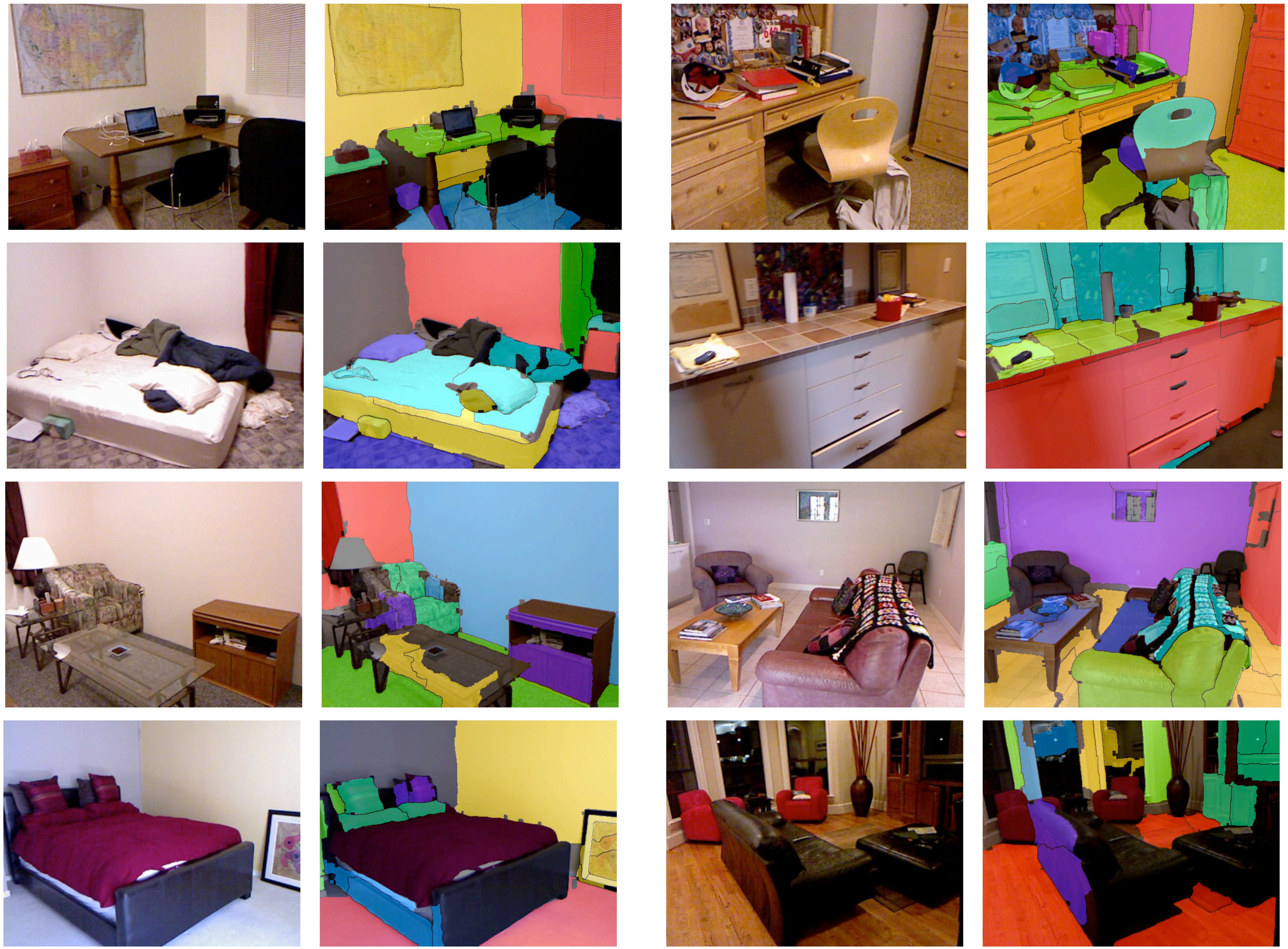

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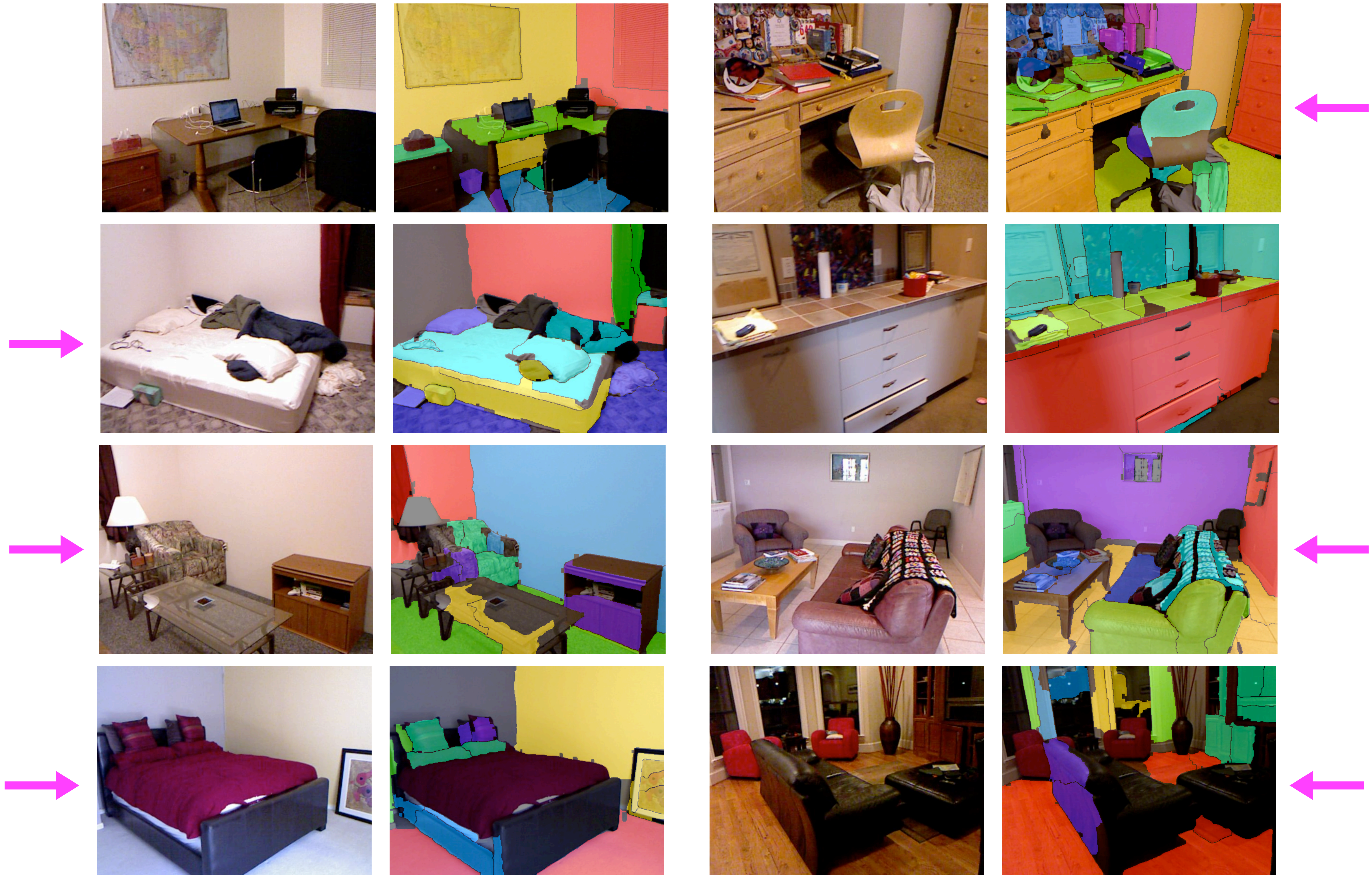

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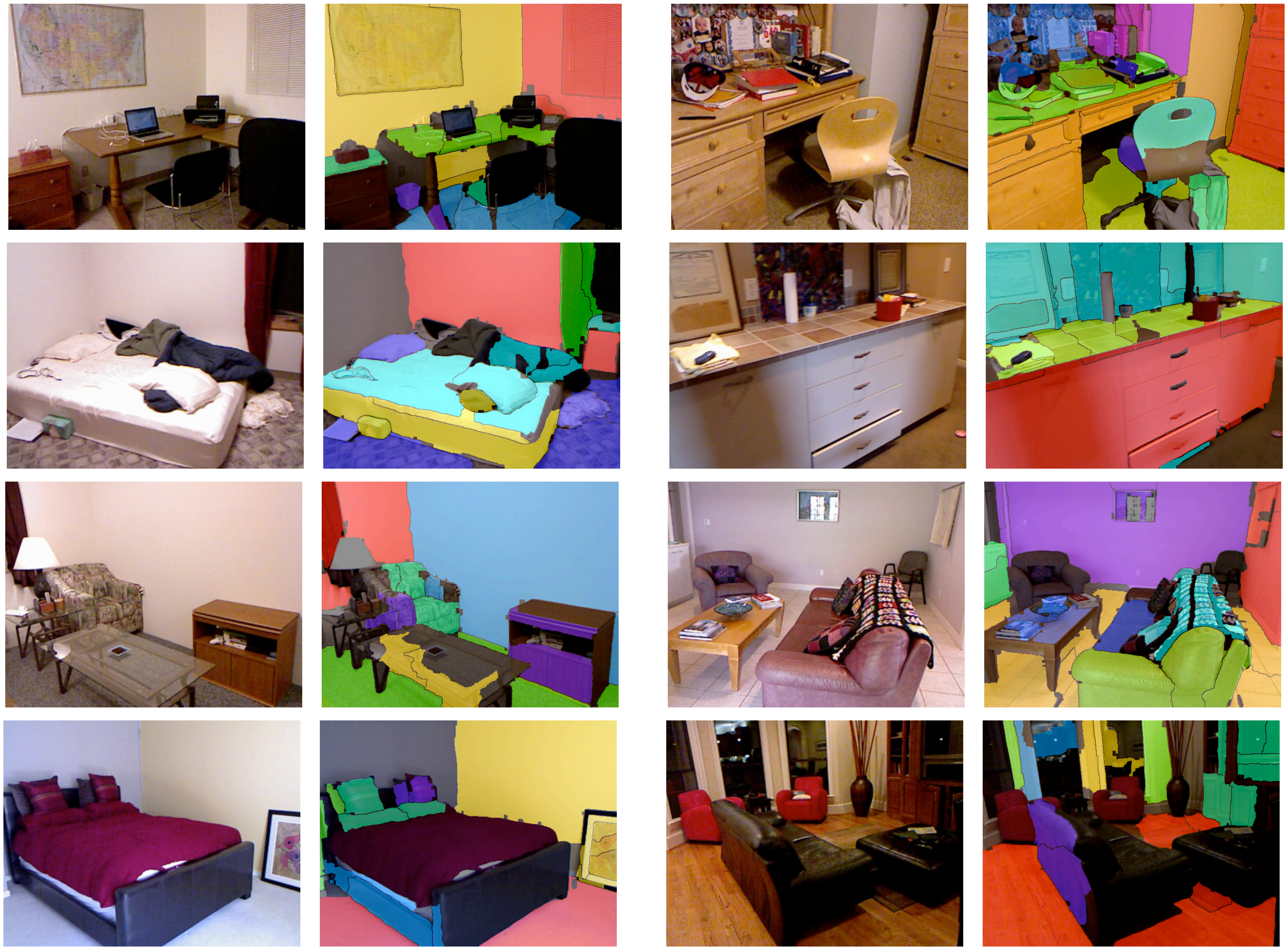

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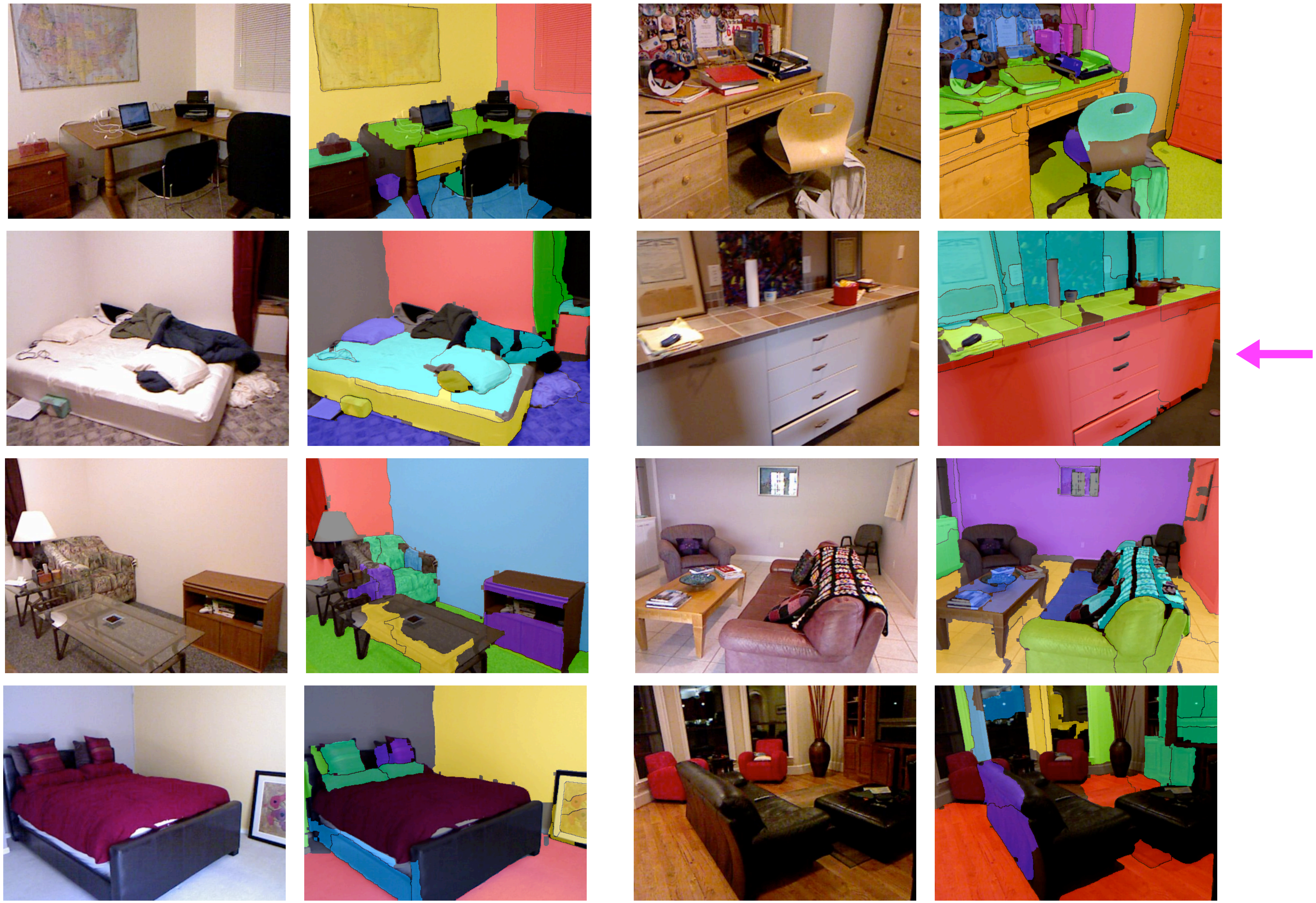

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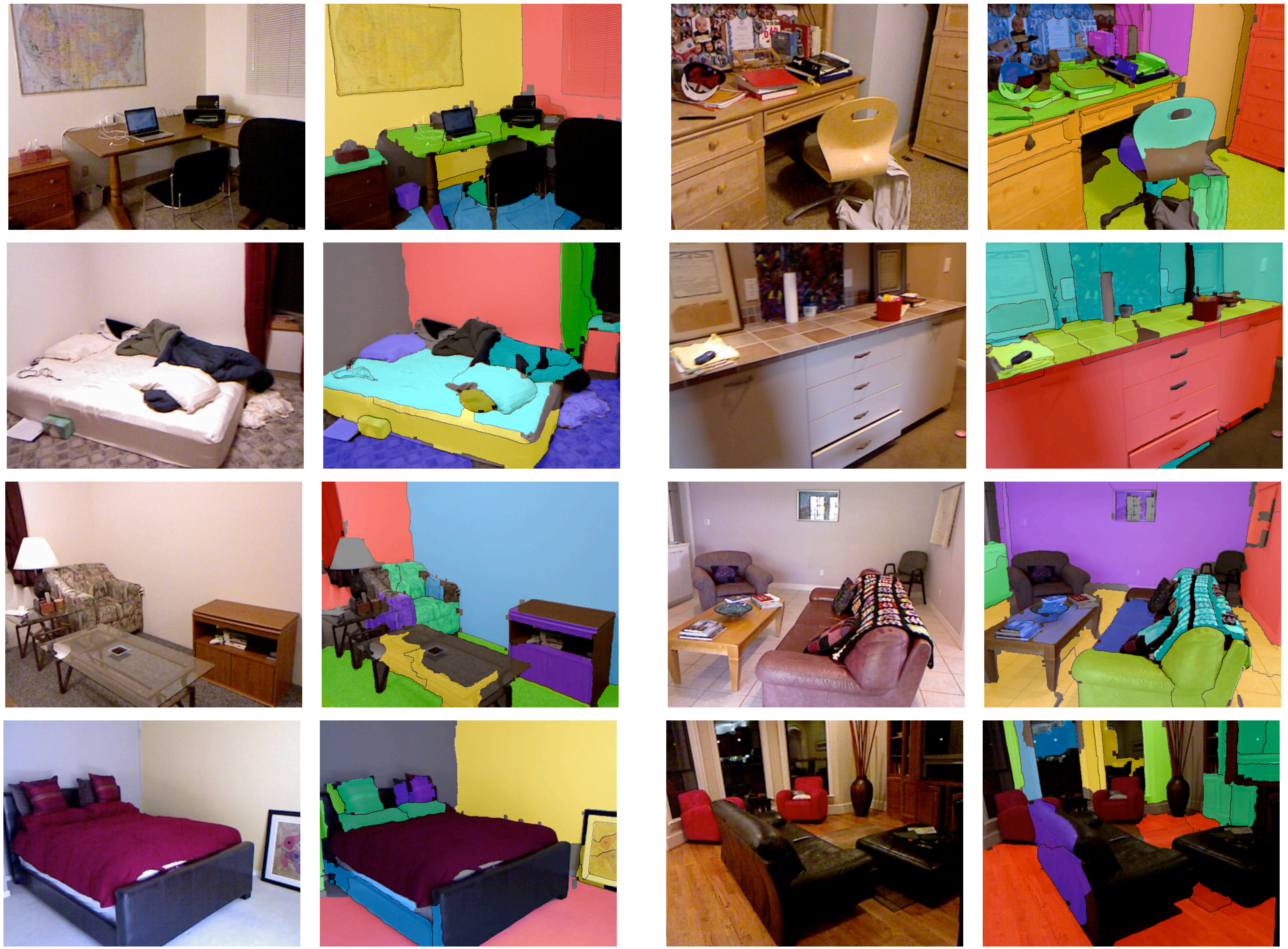

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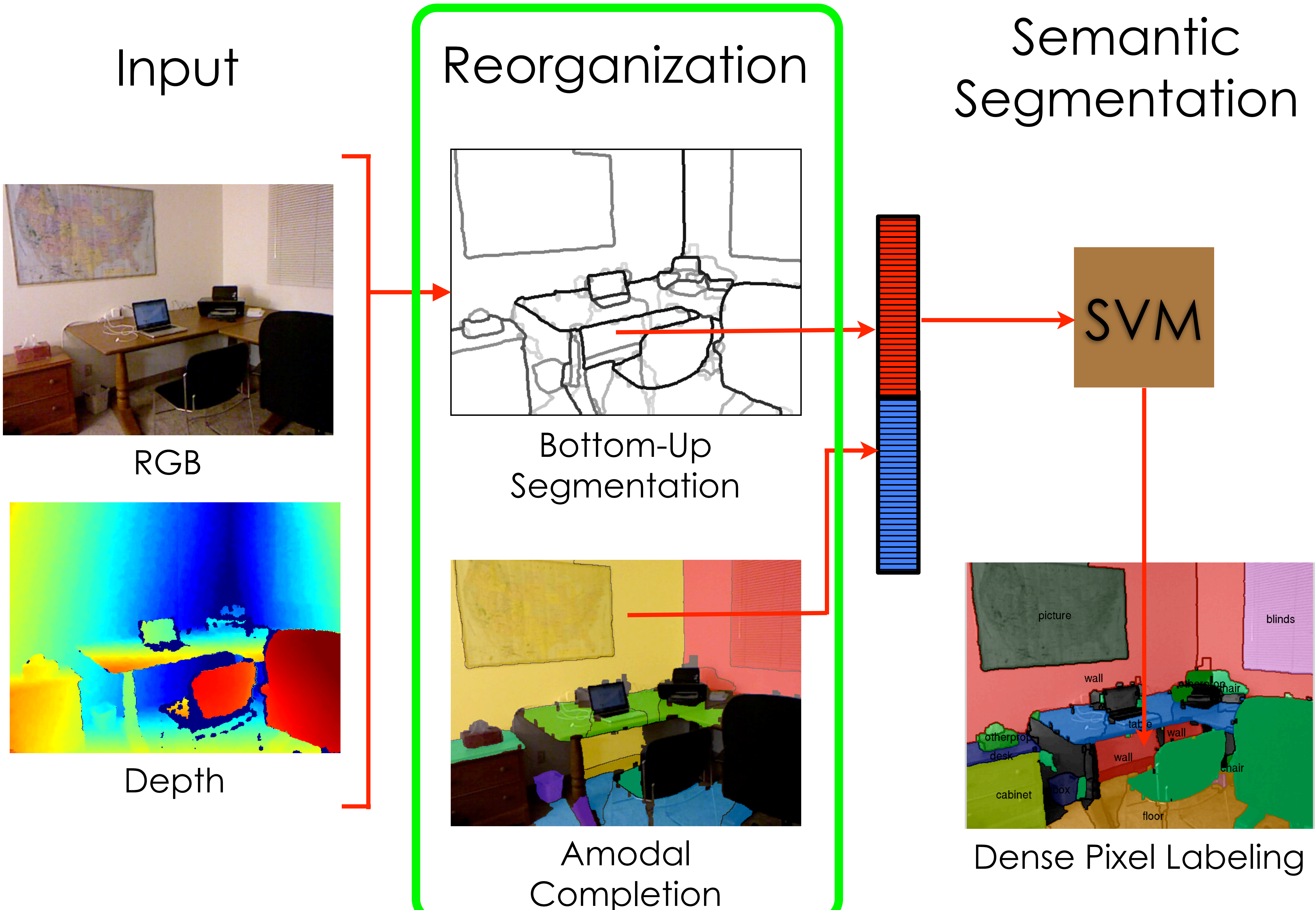
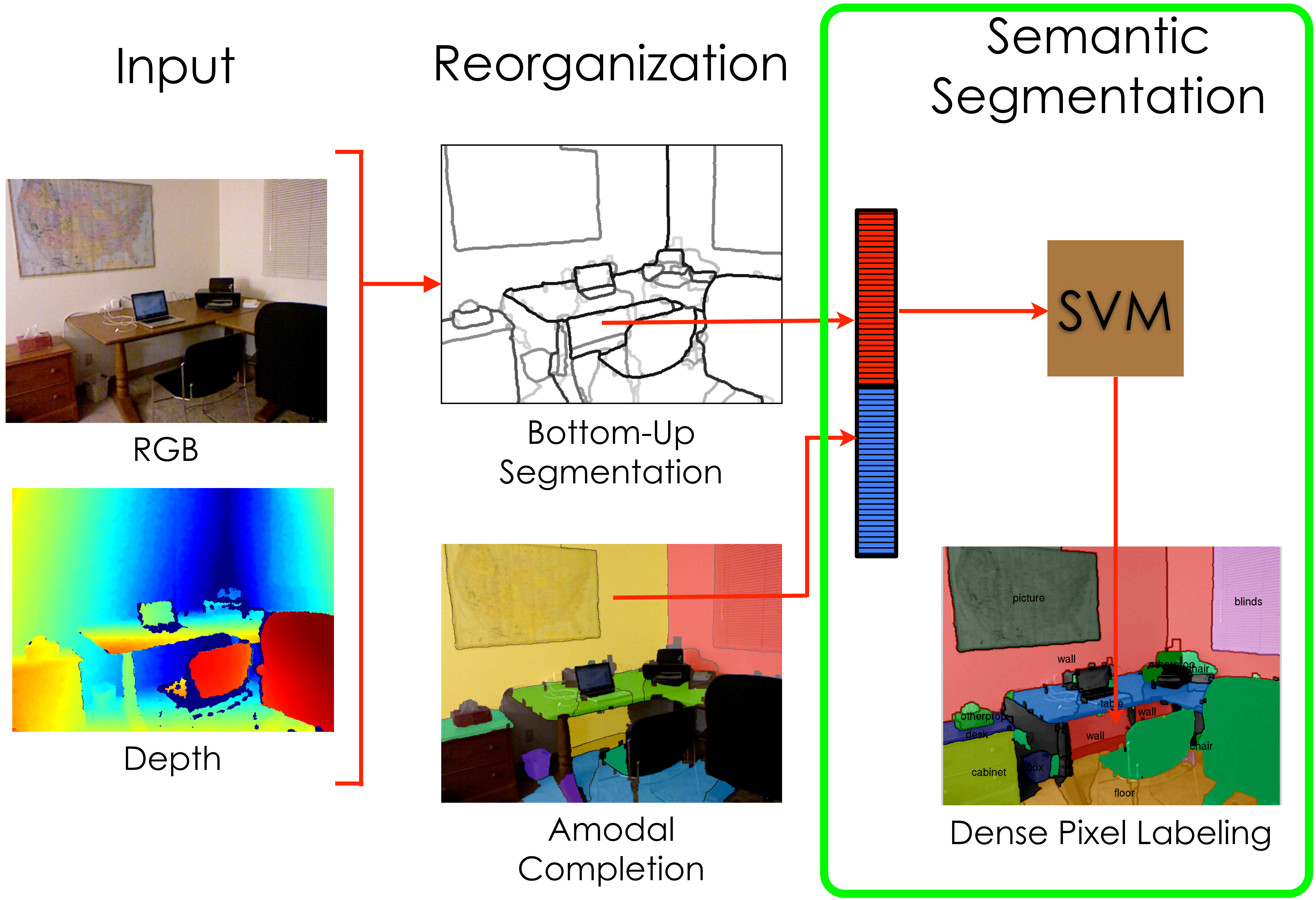
Semantic Segmentation with RGB-D



Semantic Segmentation with RGB-D



Semantic Segmentation

Task

Silberman et al., ECCV12, Indoor segmentation and support inference from RGBD images.

Semantic Segmentation

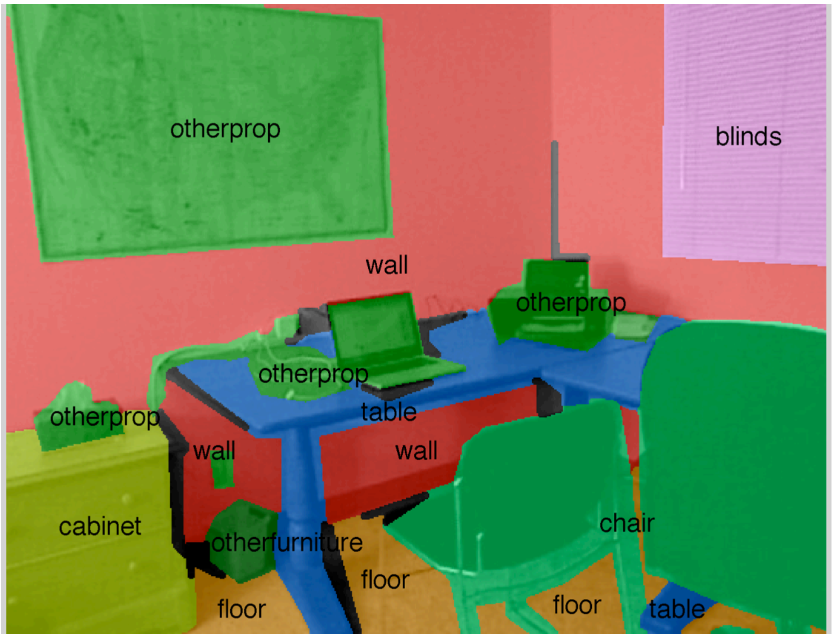
Task

40 Class Task

Scene Surfaces - Floors, walls, ceiling, windows, doors, ...

Furniture - Beds, chairs, sofa, table, desks, ...

Objects - Pillow, books, towel, box, ...



Ground Truth 40 Class

Silberman et al., ECCV12, Indoor segmentation and support inference from RGBD images.

Semantic Segmentation

Task

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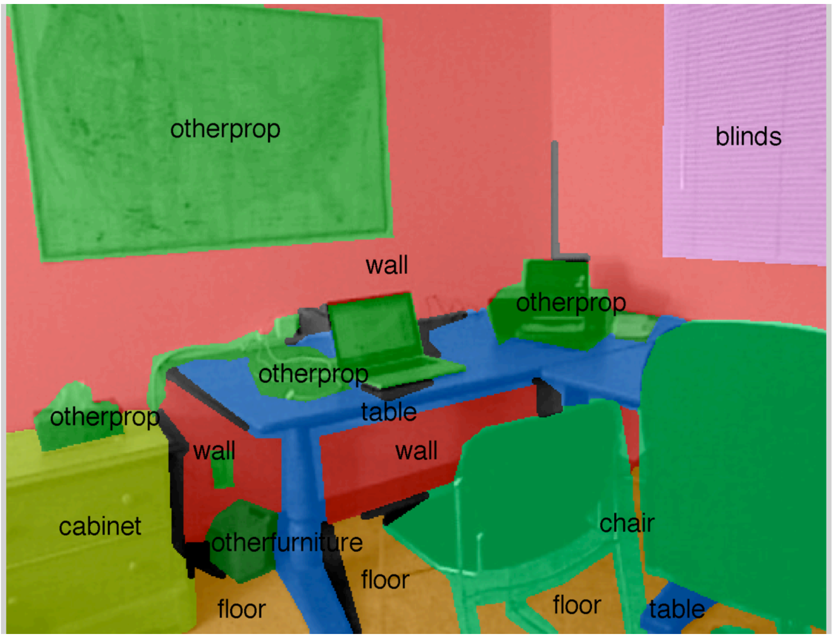
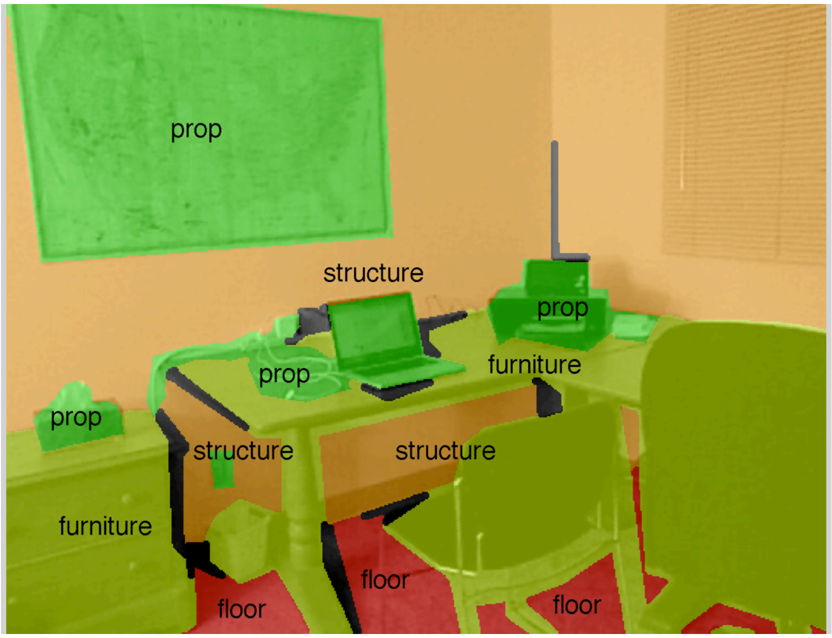


Ground Truth 40 Class

Original 4 Class Task

(as introduced by Silberman et al. ECCV 12)

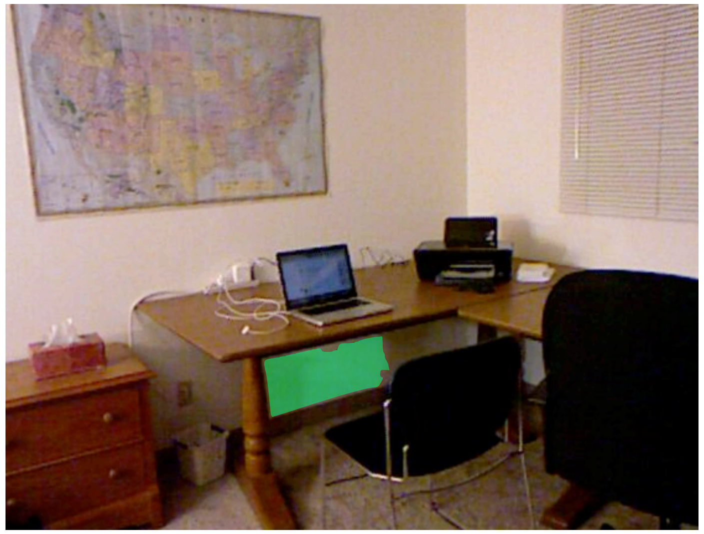
Floor, Structure, Furniture and Objects



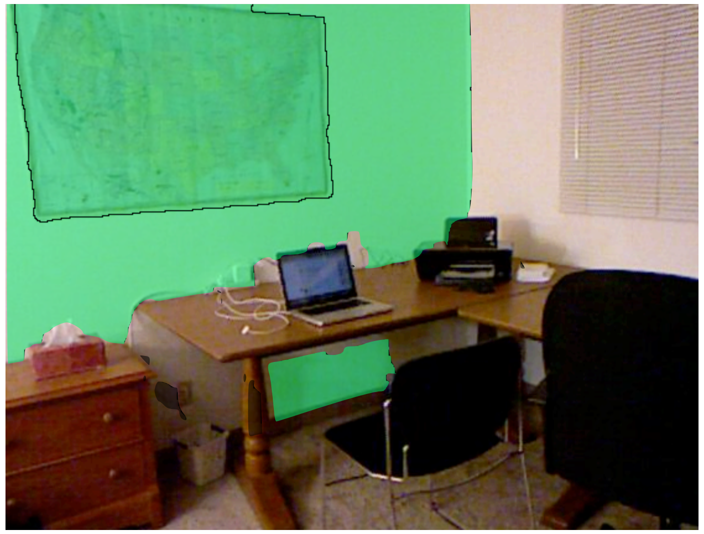
Ground Truth 4 Class

Silberman et al., ECCV12, Indoor segmentation and support inference from RGBD images.

Semantic Segmentation

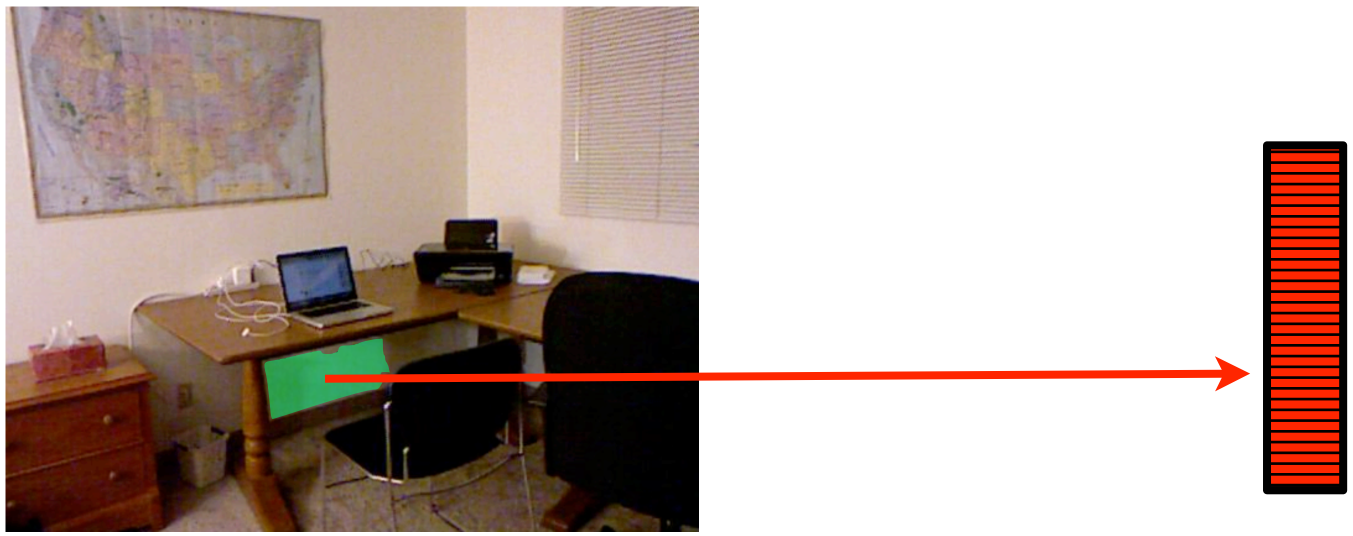


Superpixels

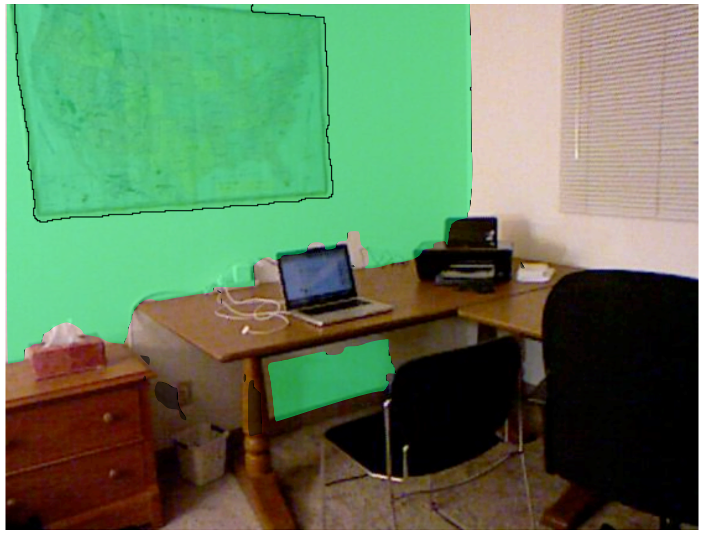


Amodal Completion

Semantic Segmentation



Superpixels



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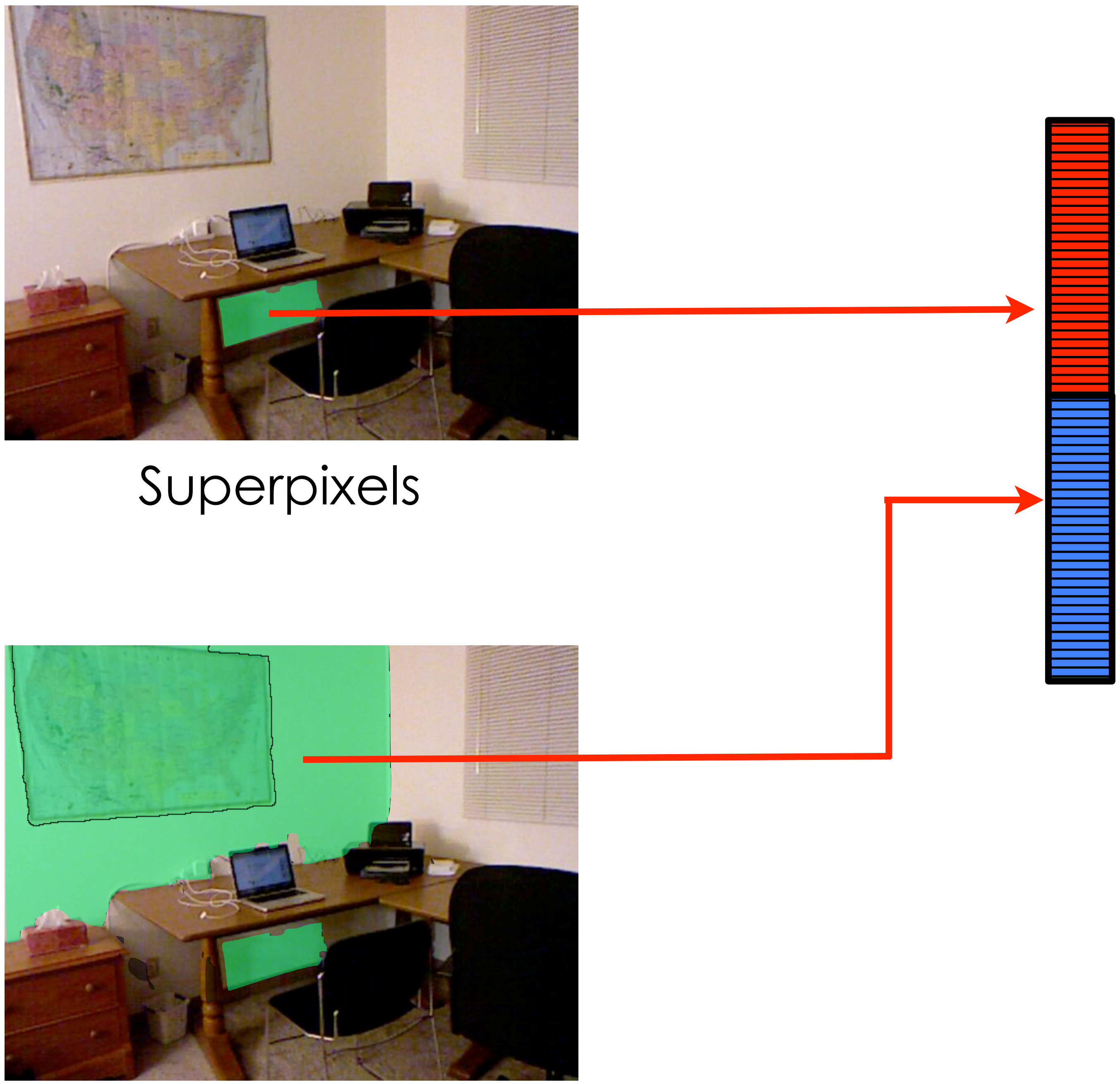

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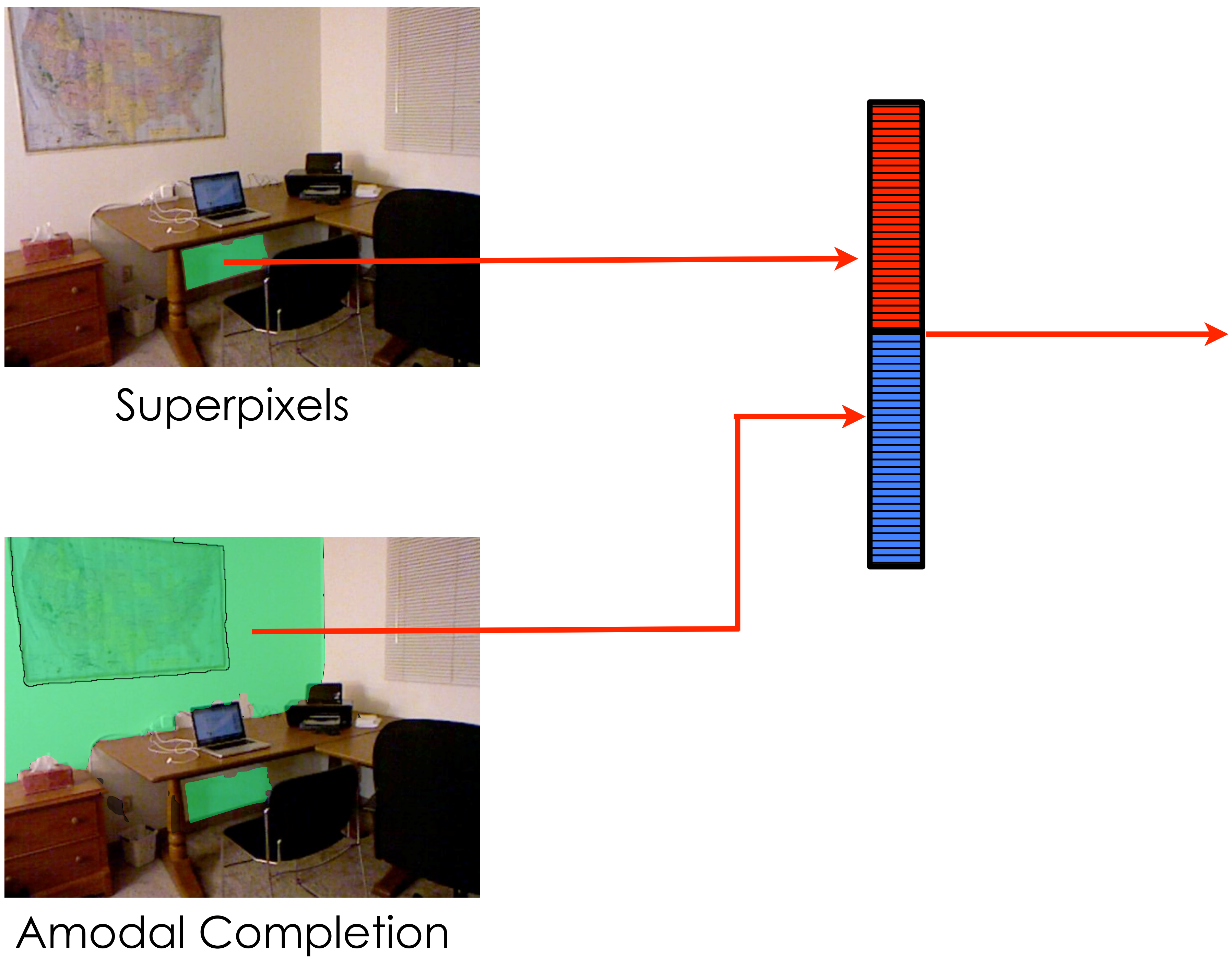

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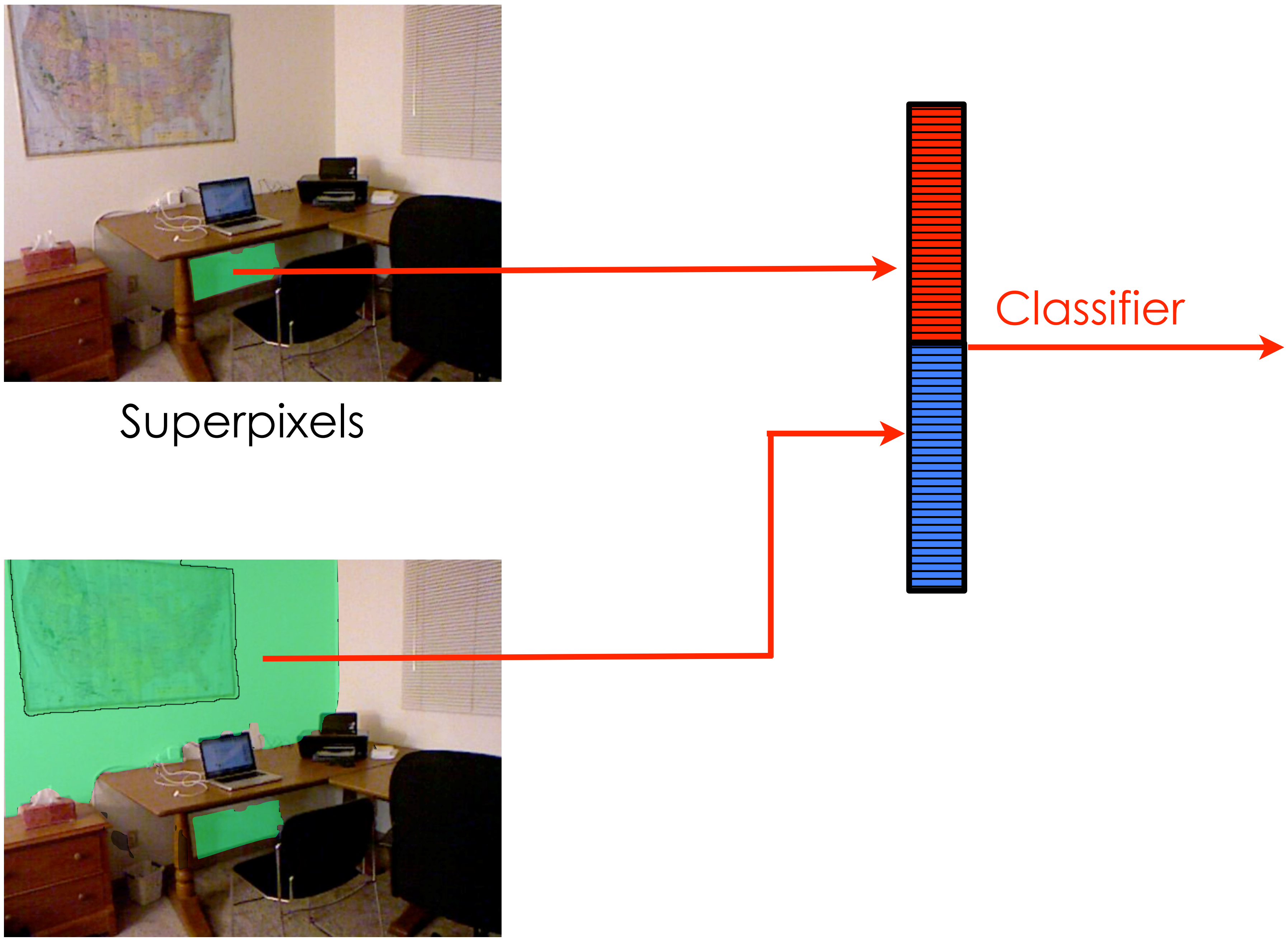

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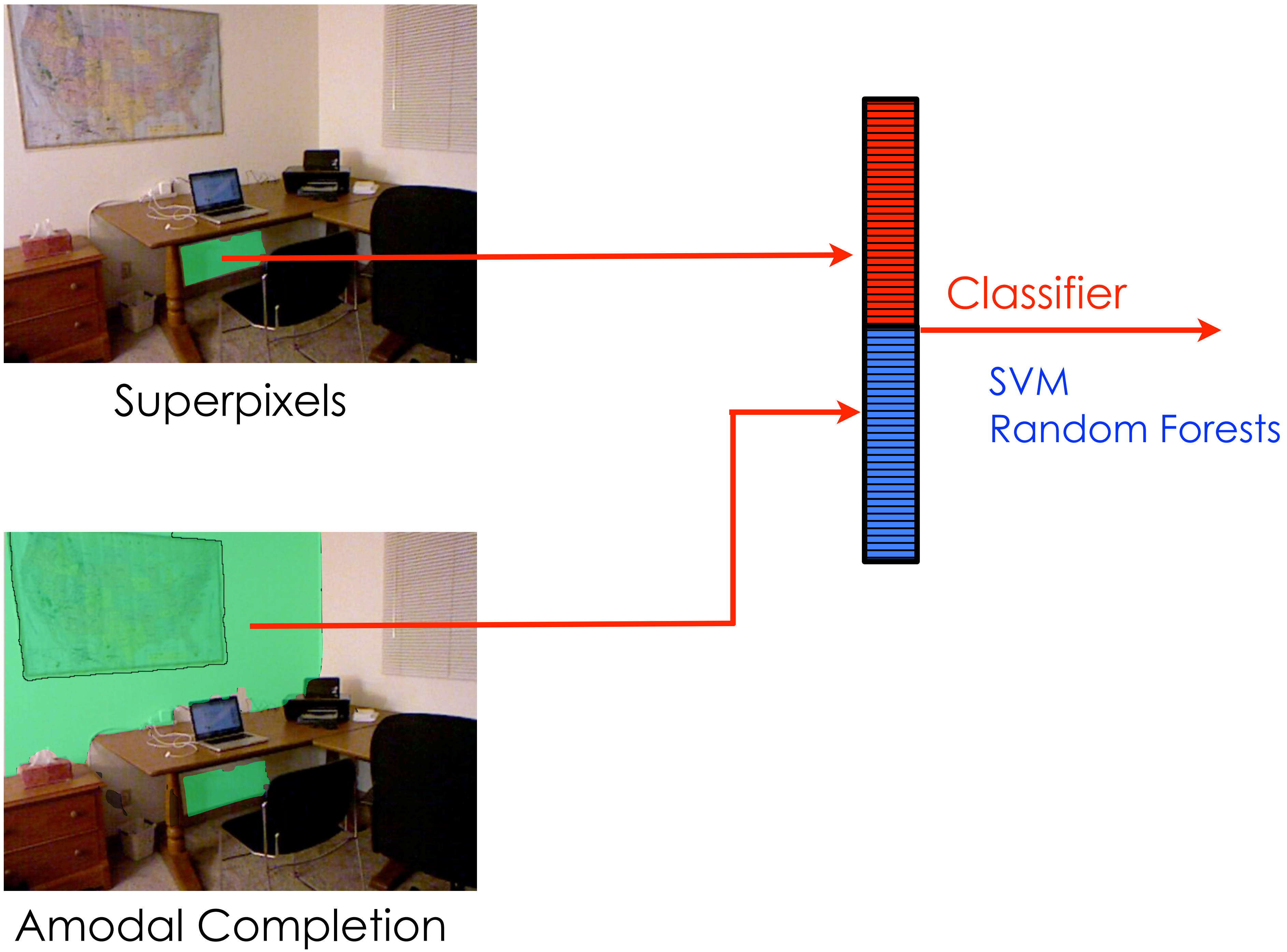
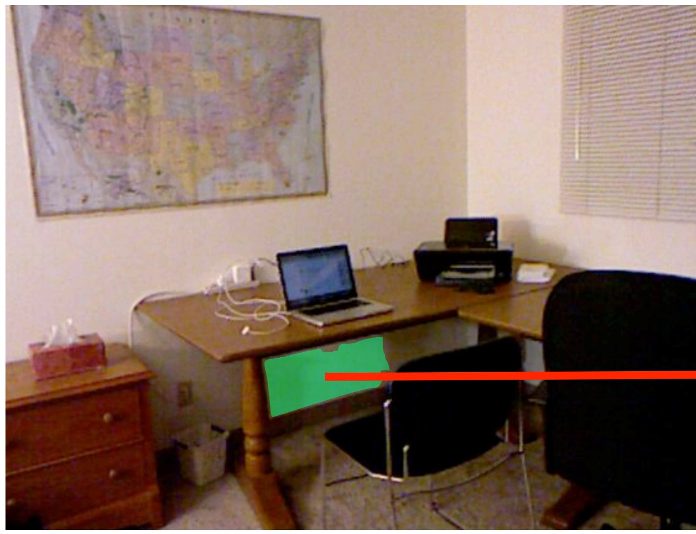
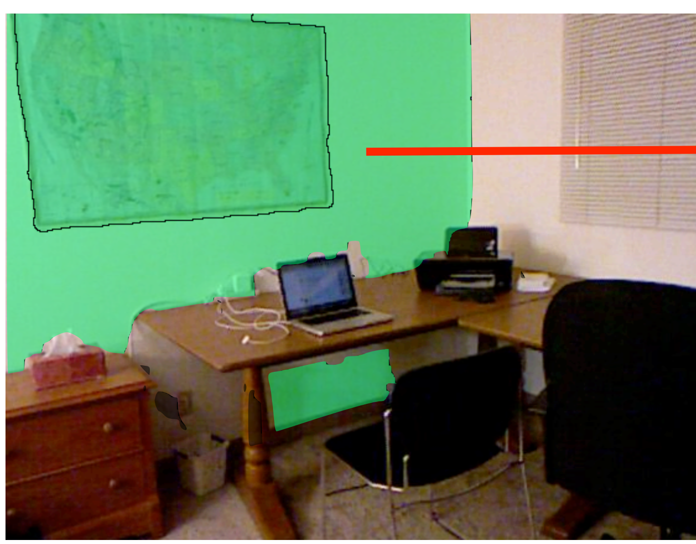


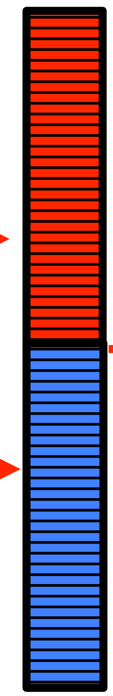
Semantic Segmentation



Superpixels



Amodal Completion



Classifier

SVM
Random Forests

category	prob
wall	0.90
cabinet	0.05
window	0.05
chair	0.0
table	0.0
-	
-	

Semantic Segmentation

Features

Semantic Segmentation

Features

- Appearance - SIFT on CIE-LAB, oriented edge energy
- Geometry - Absolute size, height above ground and angle with gravity ...

Semantic Segmentation

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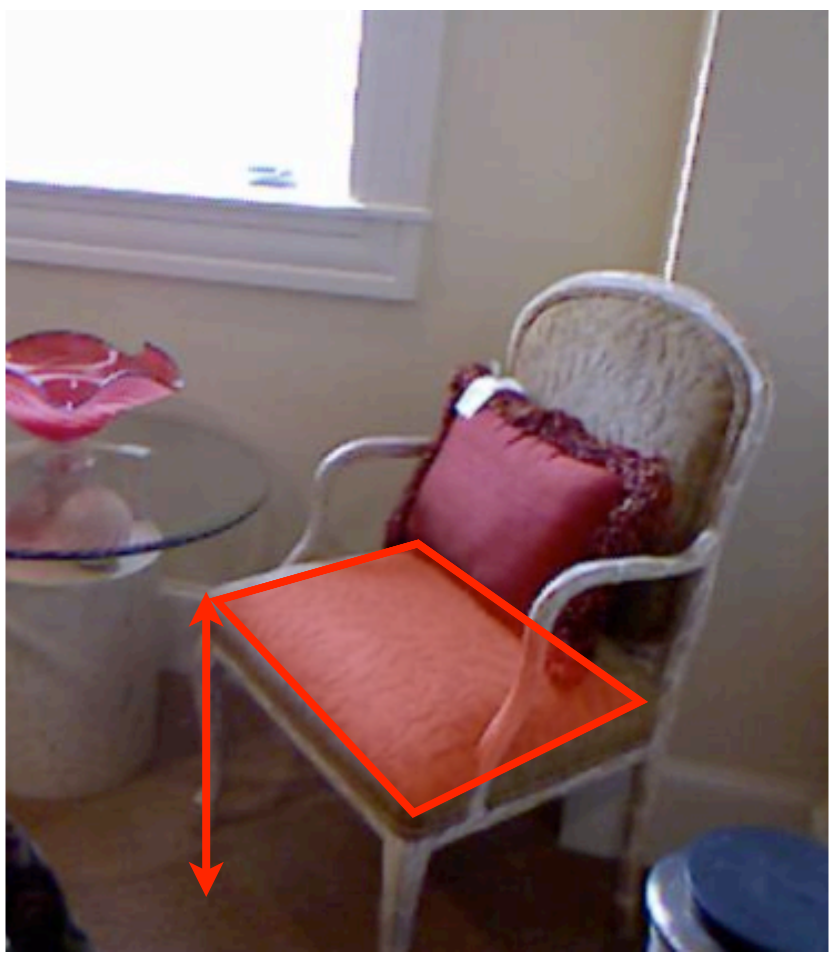

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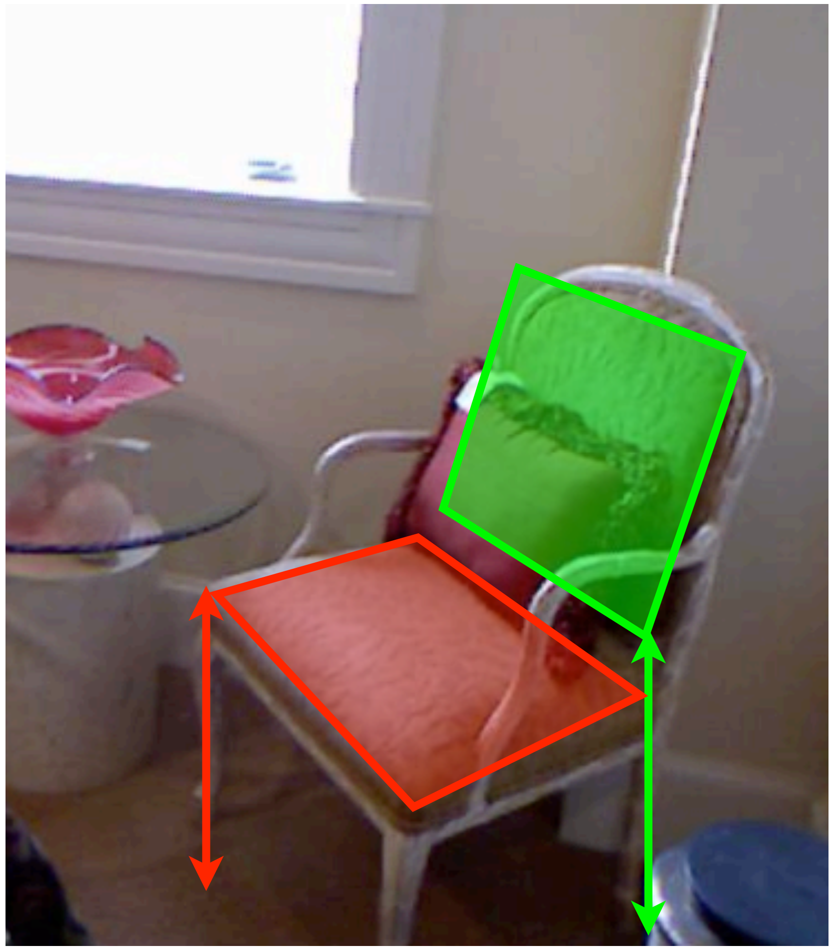

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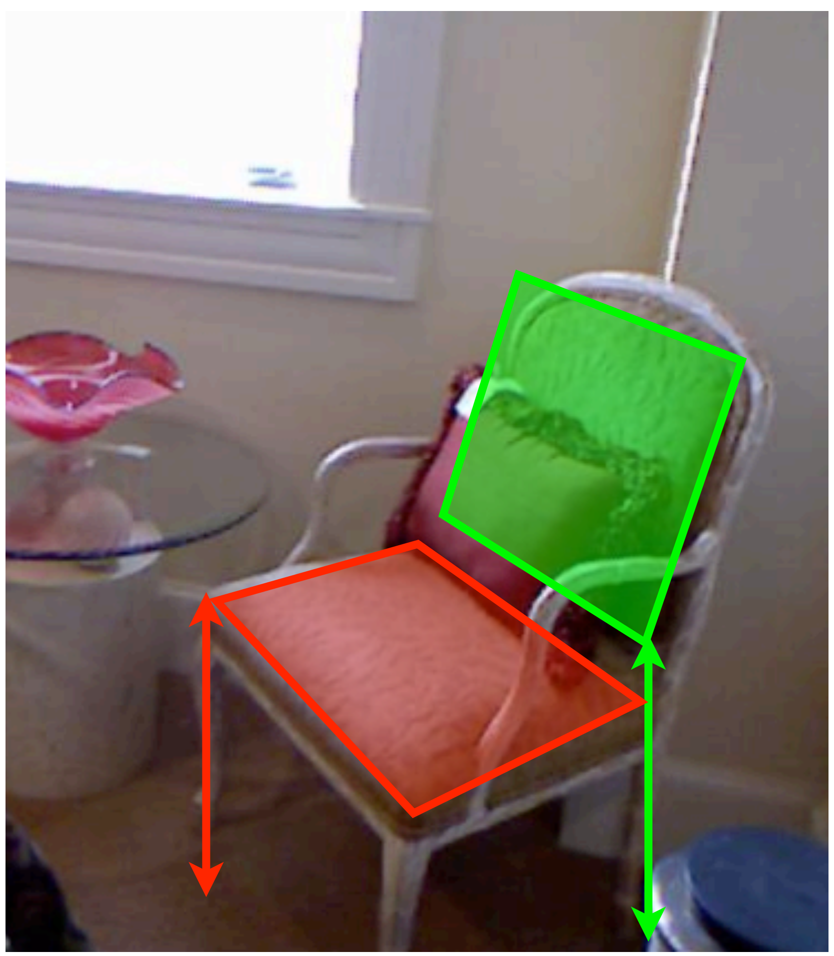
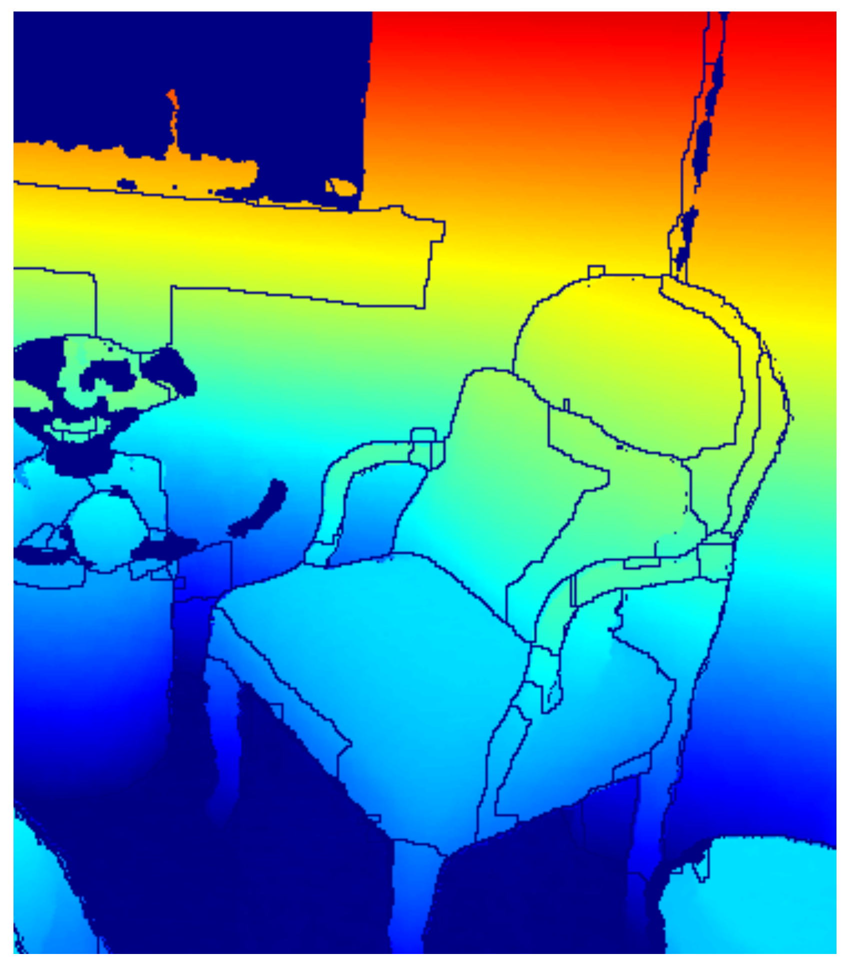
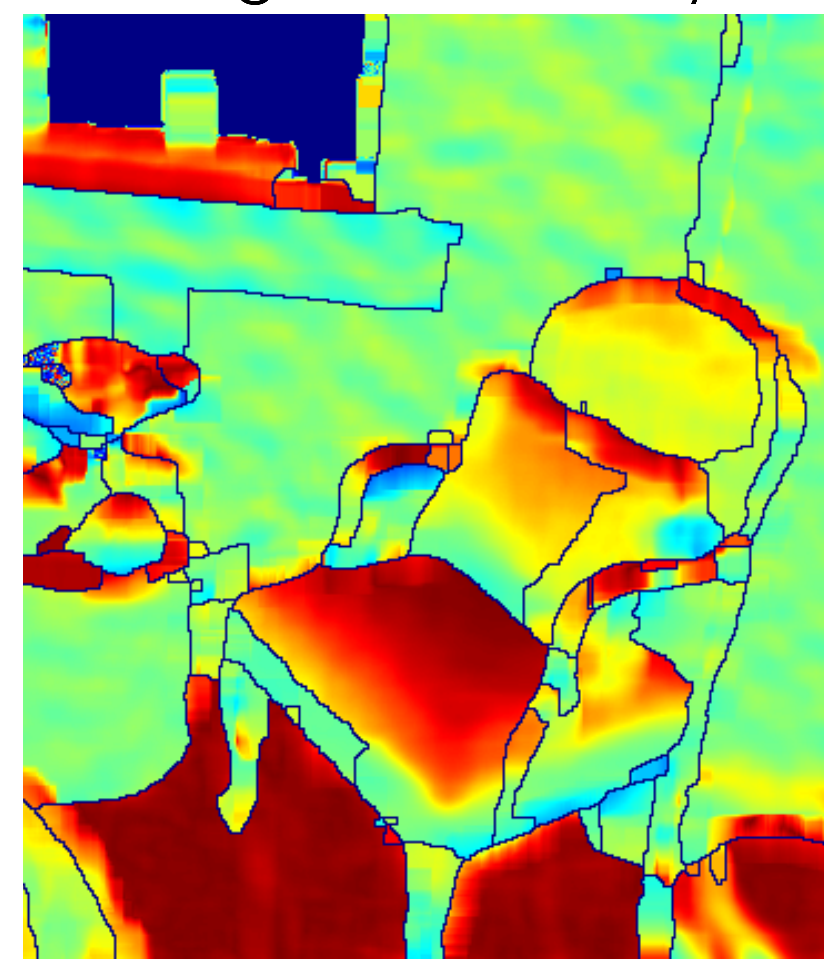


Height above Ground



Angle with Gravity



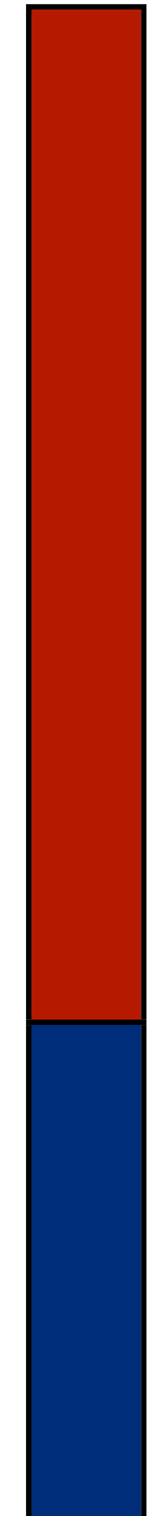
Joint Histogram to give **Geocentric Textons**

Semantic Segmentation

Features

Semantic Segmentation

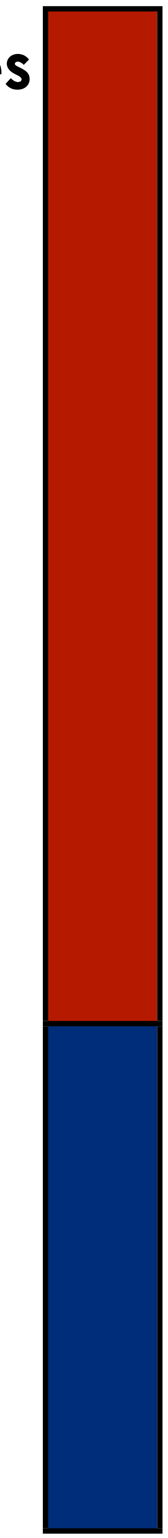
Features



Semantic Segmentation

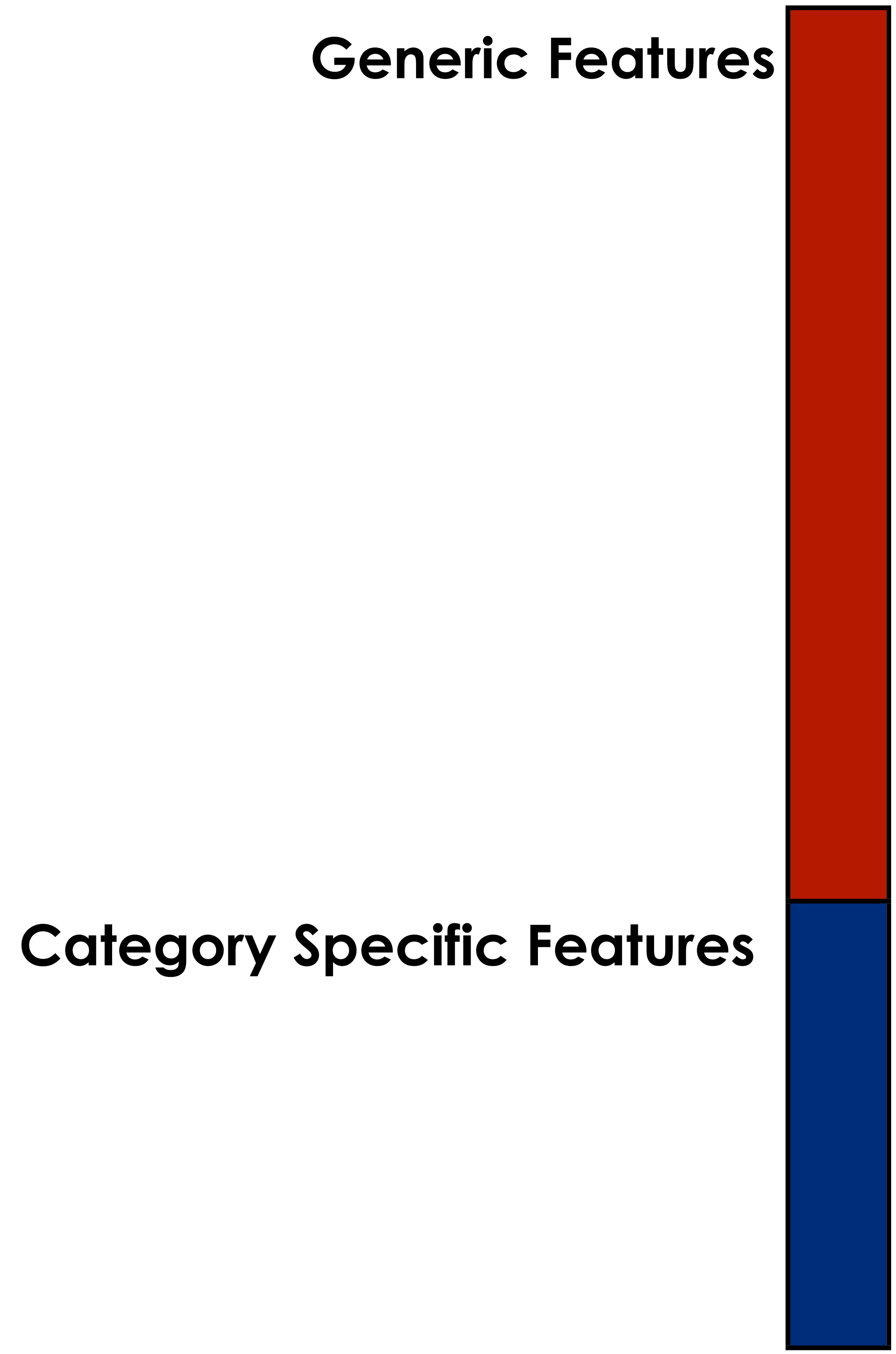
Features

Generic Features



Semantic Segmentation

Features



Semantic Segmentation

Features

Generic Features

- Geocentric Pose
  - Orientation Features
  - Height above ground
- Size Features
  - Spatial extent
  - Surface Area
  - Is clipped/occluded
- Shape Features
  - Planarity
  - Strength of local geometric gradients

Category Specific Features

Semantic Segmentation

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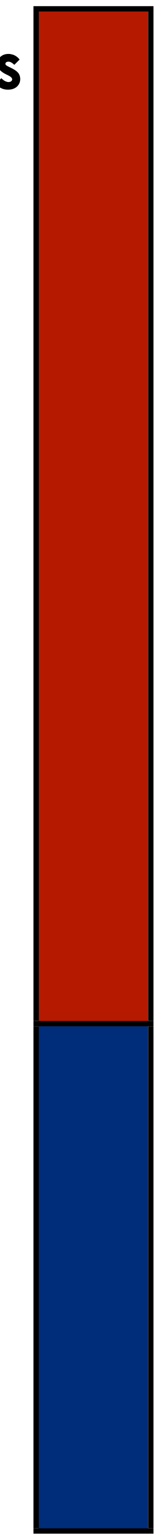

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Category Specific Features

VQ SIFT

Geocentric Textons

Semantic Segmentation

Features

Generic Features

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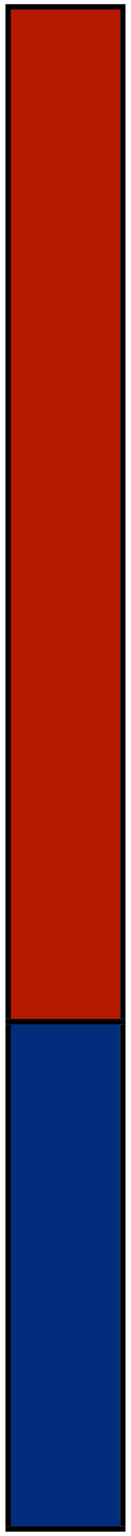
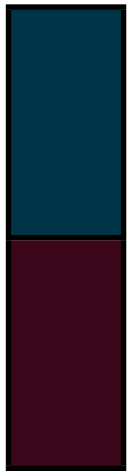


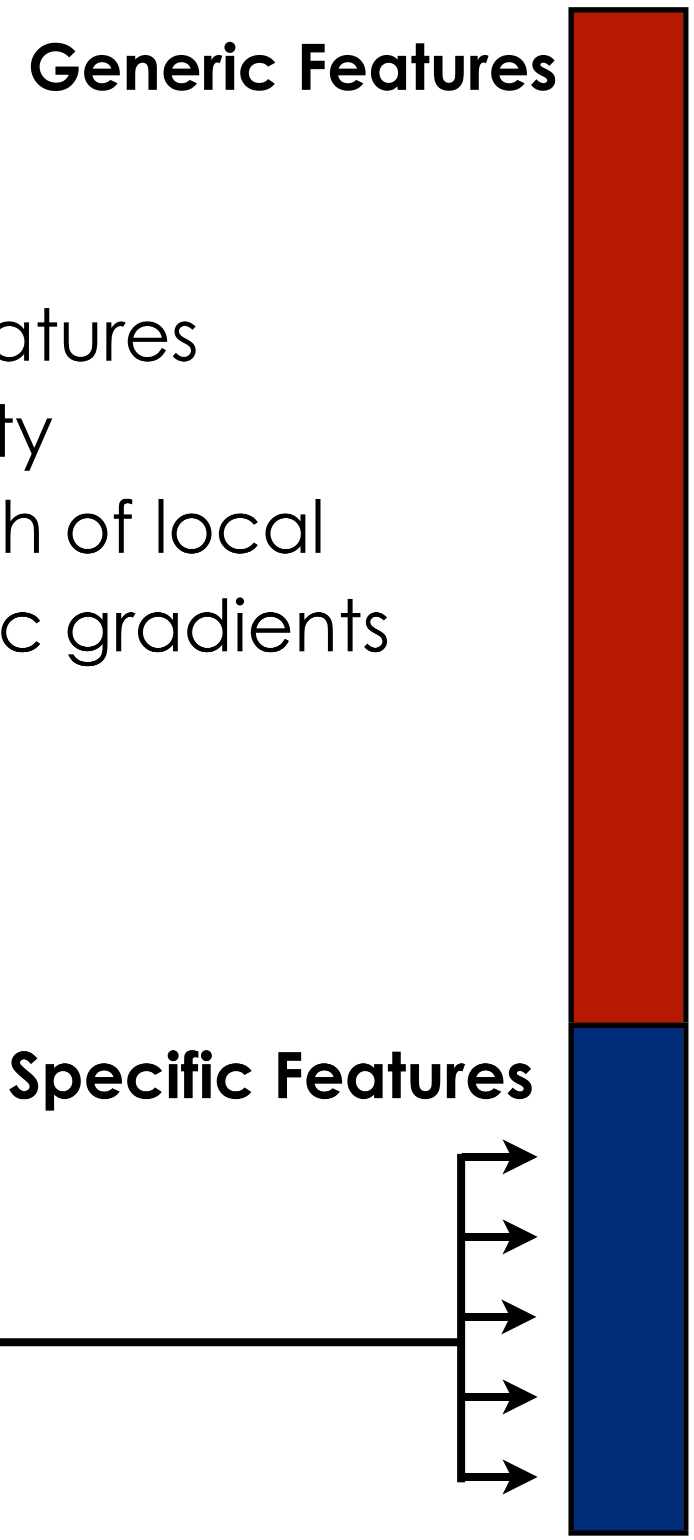
VQ SIFT

Geocentric Textons



Semantic Segmentation

Features



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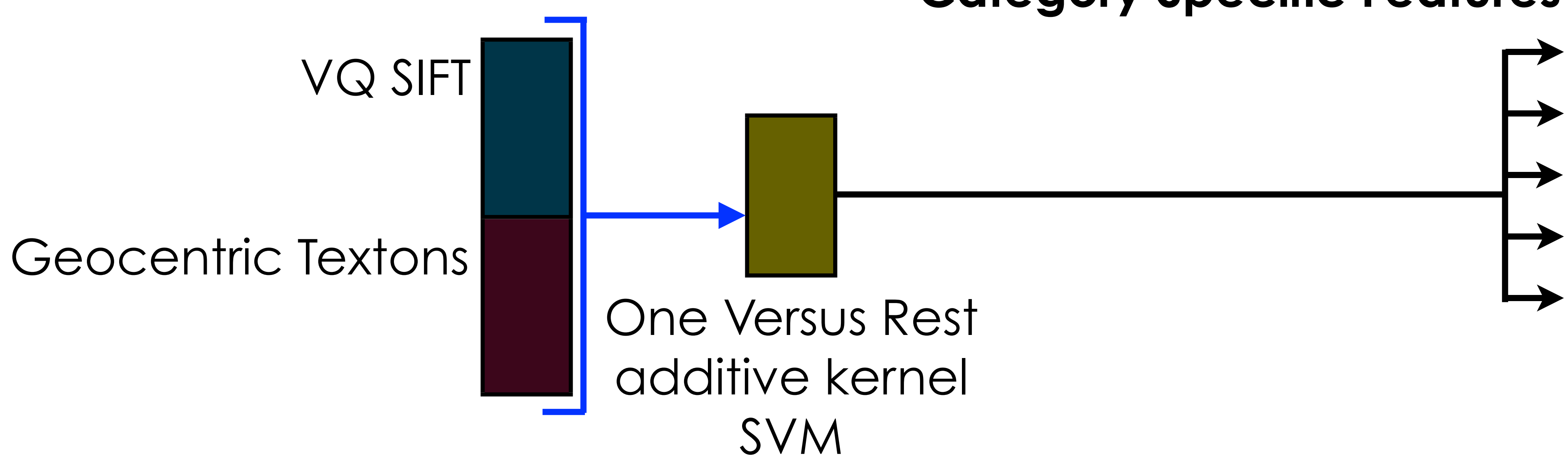

Semantic Segmentation

Finding Gravity Direction

Semantic Segmentation

Finding Gravity Direction

Original point cloud may not be in a geocentric frame

Semantic Segmentation

Finding Gravity Direction

Original point cloud may not be in a geocentric frame

Current Gravity
Direction
Estimate

Semantic Segmentation

Finding Gravity Direction

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Current Gravity
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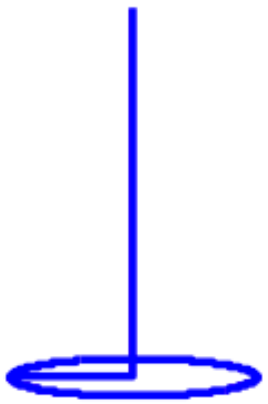
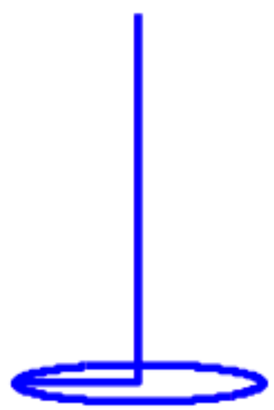


Semantic Segmentation

Finding Gravity Direction

Original point cloud may not be in a geocentric frame

Current Gravity Direction Estimate



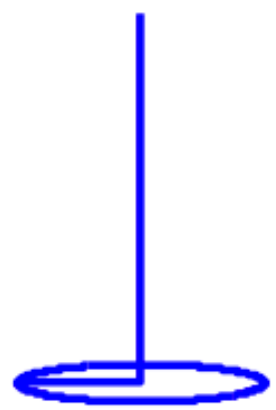
Current Estimate of horizontal and vertical surfaces

Semantic Segmentation

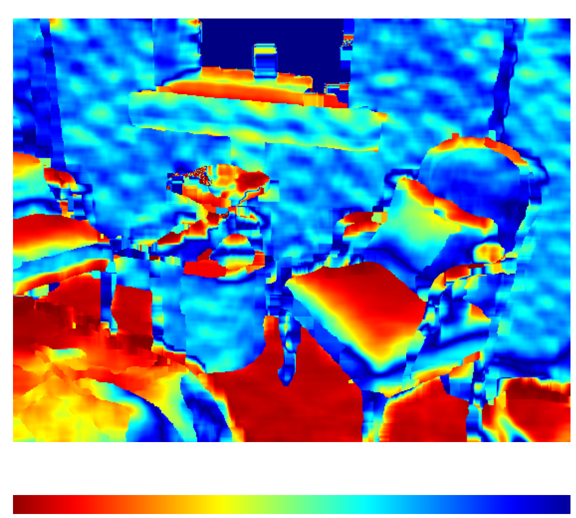
Finding Gravity Direction

Original point cloud may not be in a geocentric frame

Current Gravity Direction Estimate



Current Estimate of horizontal and vertical surfaces



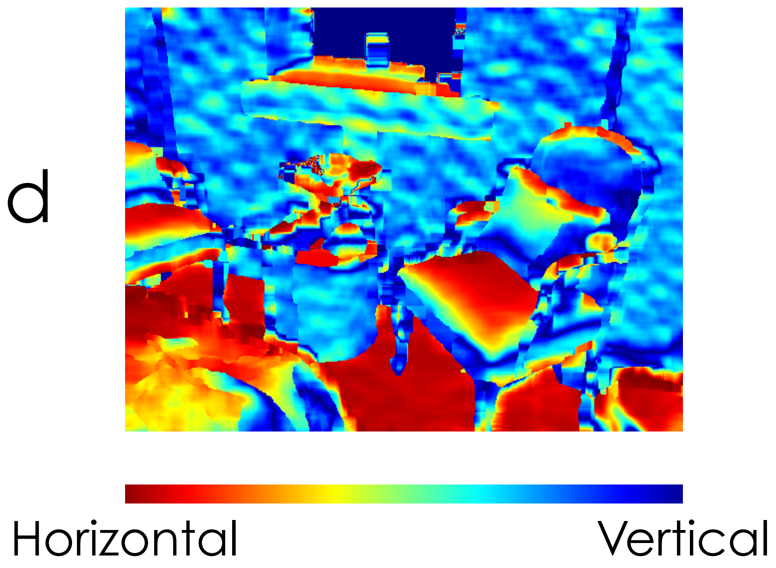
Semantic Segmentation

Finding Gravity Direction

Original point cloud may not be in a geocentric frame

Current Gravity Direction Estimate

Current Estimate of horizontal and vertical surfaces



Semantic Segmentation

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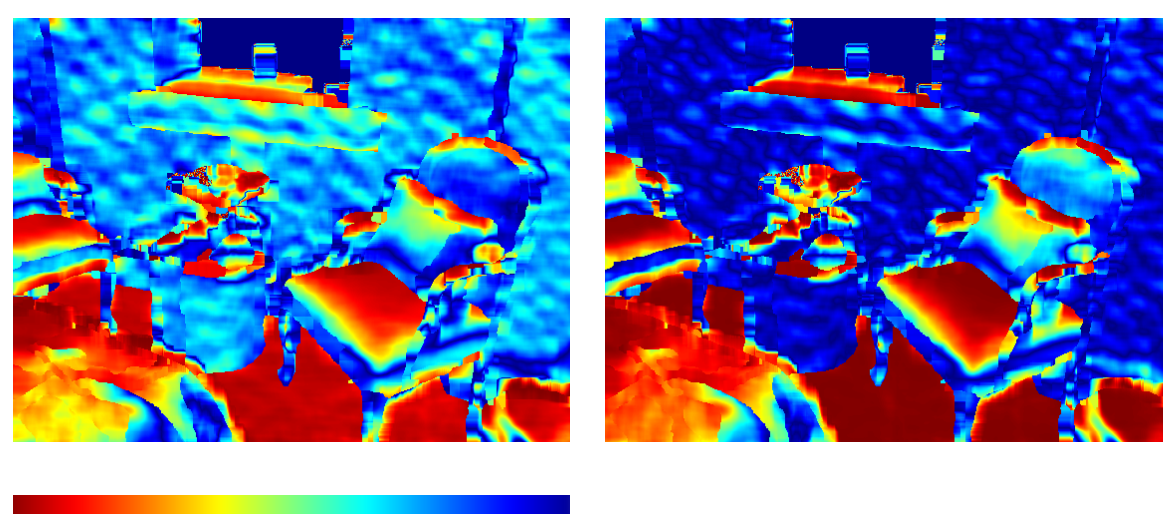

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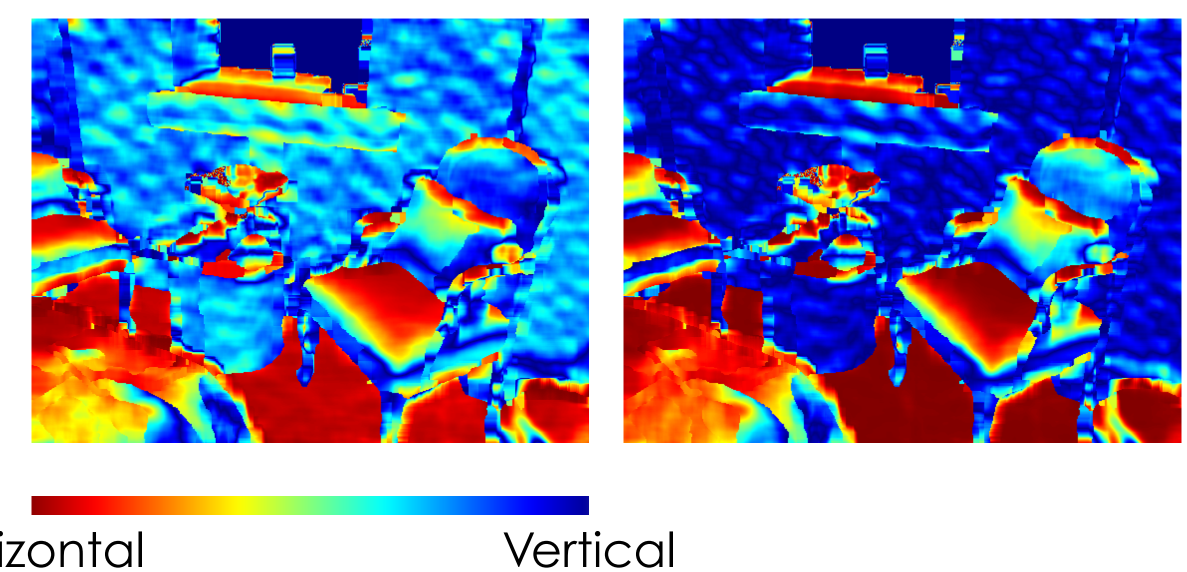

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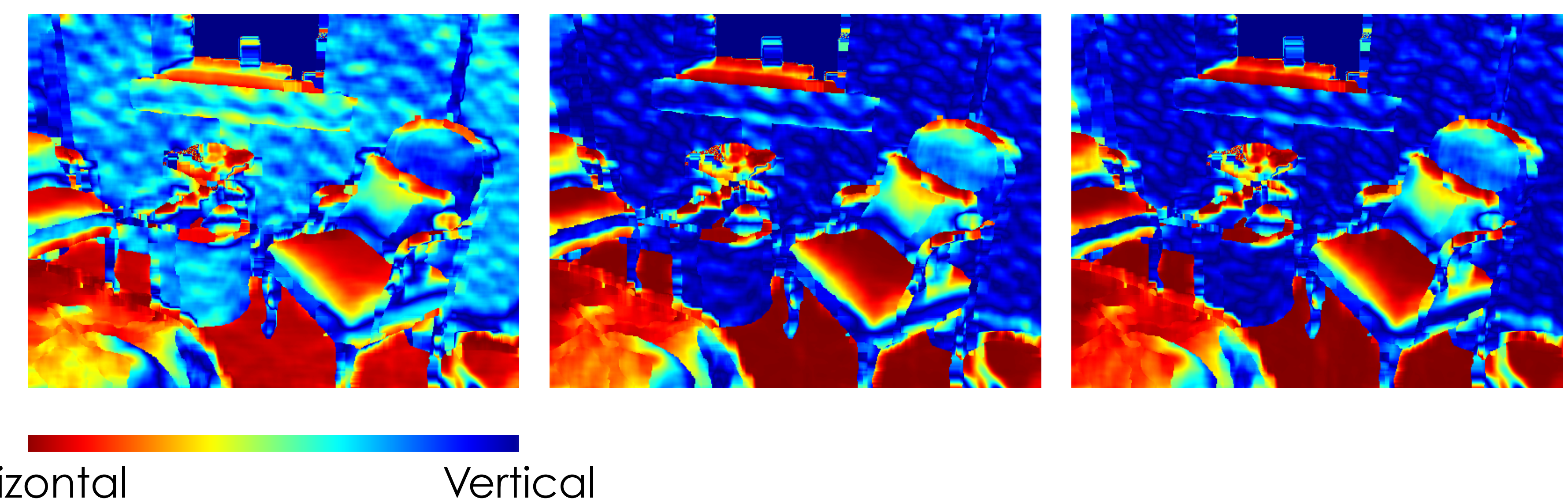
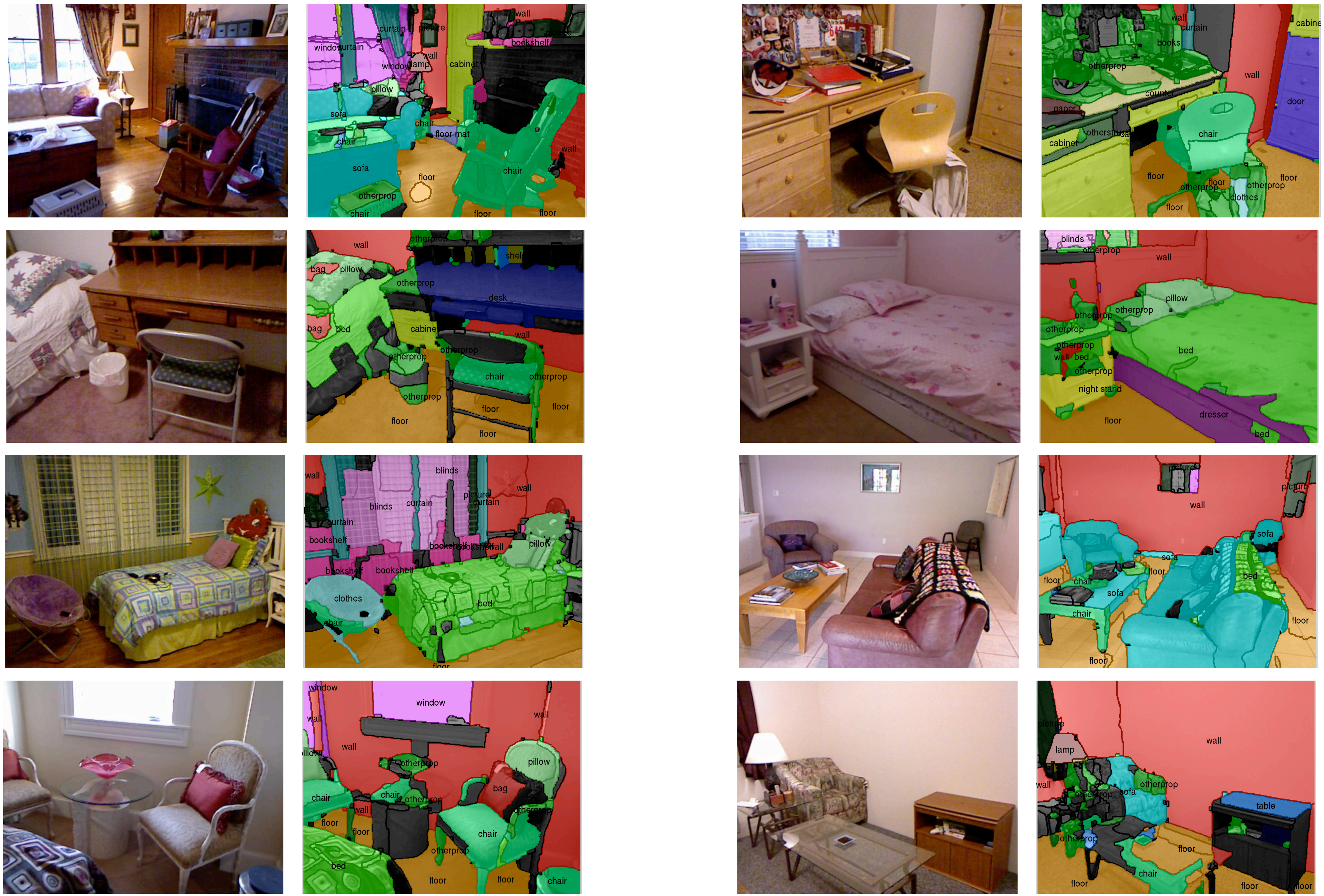


Results

Image | Output | Image | Output



Semantic Segmentation

Performance (I/U = Pascal Segmentation Metric)

	Silberman ECCV 12	Ren et al. CVPR 12	Our
wall	61	60	**68**
floor	78	75	**81**
cabinet	33	37	**48**
bed	40	42	**55**
chair	32	33	**40**
sofa	25	28	**44**
table	21	17	**30**
door	5.9	**13**	8.3
window	30	28	**33**
bookshelf	**23**	17	20

	Silberman ECCV 12	Ren et al. CVPR 12	Our
picture	36	32	**40**
counter	33	39	**47**
blinds	40	27	**44**
desk	4.6	**10**	**10**
shelves	3.3	**6.1**	5.1
curtain	27	28	**34**
dresser	13	7	**22**
pillow	19	20	**28**
mirror	4.4	18	**19**
floor mat	7.2	20	**22**

Silberman et al., ECCV12, Indoor segmentation and support inference from RGBD images.
Ren et al., CVPR12, RGB-(D) scene labeling: Features and algorithms

Semantic Segmentation

Aggregate Performance (Frequency weighted I/U)

	Silberman et al. ECCV 12	**Ren et al. CVPR 12**	**Our**
4 class task (Floor, Structure, Furniture, Props)	56.31	59.19	**64.9**
40 class task (Walls, Floor, Cabinet, Bed, Chair, Sofa, Table, ...)	38.23	37.64	**45.29**

Silberman et al., ECCV12, Indoor segmentation and support inference from RGBD images.
Ren et al., CVPR12, RGB-(D) scene labeling: Features and algorithms

Scene Classification

Scene Classification

Task

Classify the given scene into -
bedroom, living room, kitchen, ...

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Approach

Use the inferred semantic class
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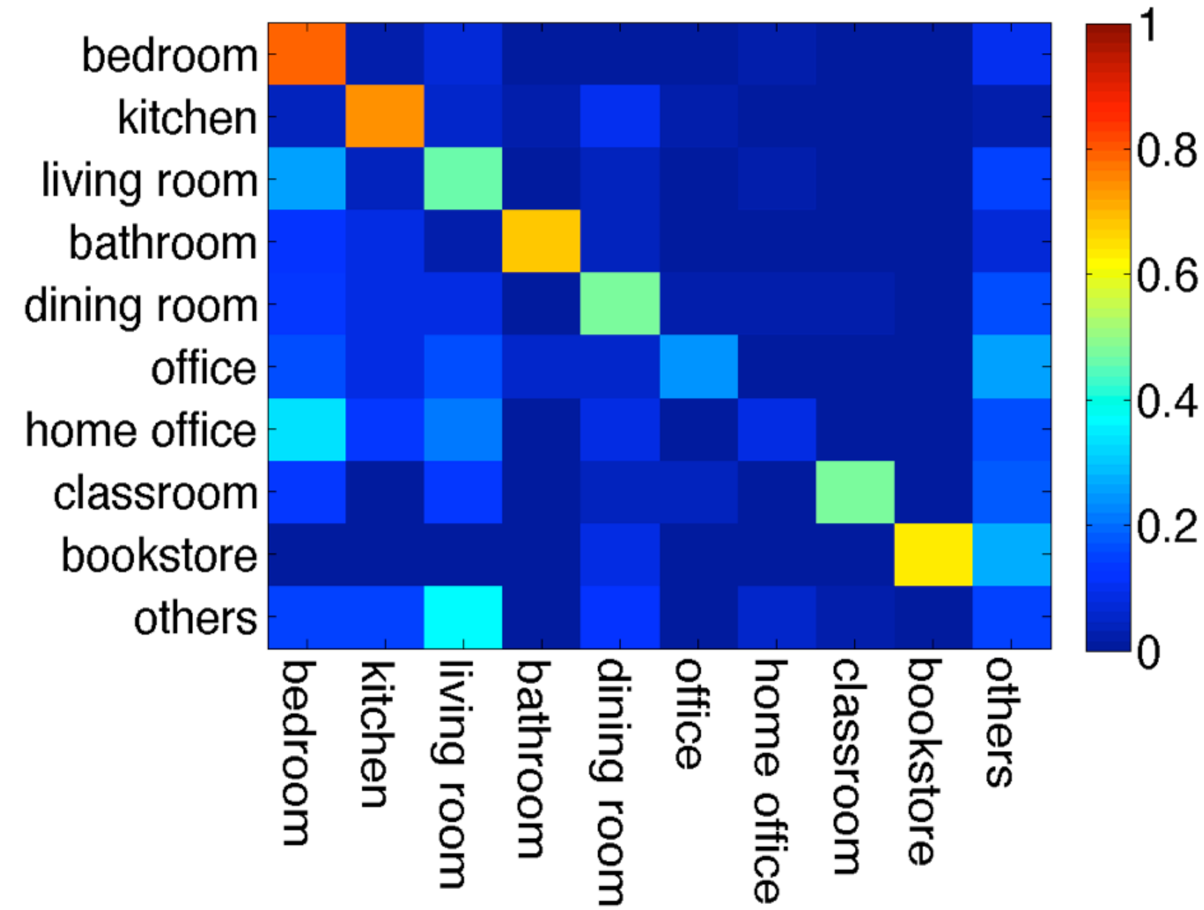

Mean Diagonal = .47

Scene Classification

Task

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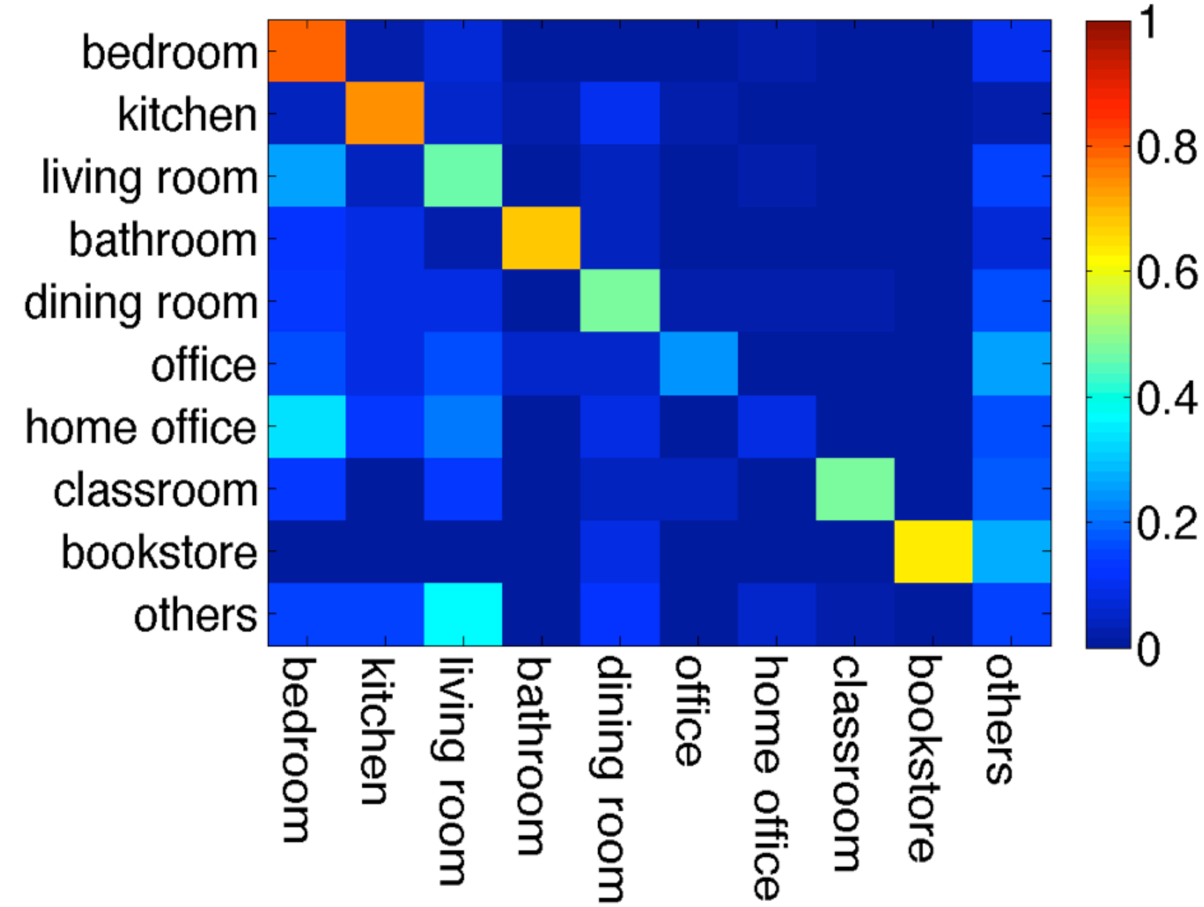
Performance



Mean Diagonal = .47

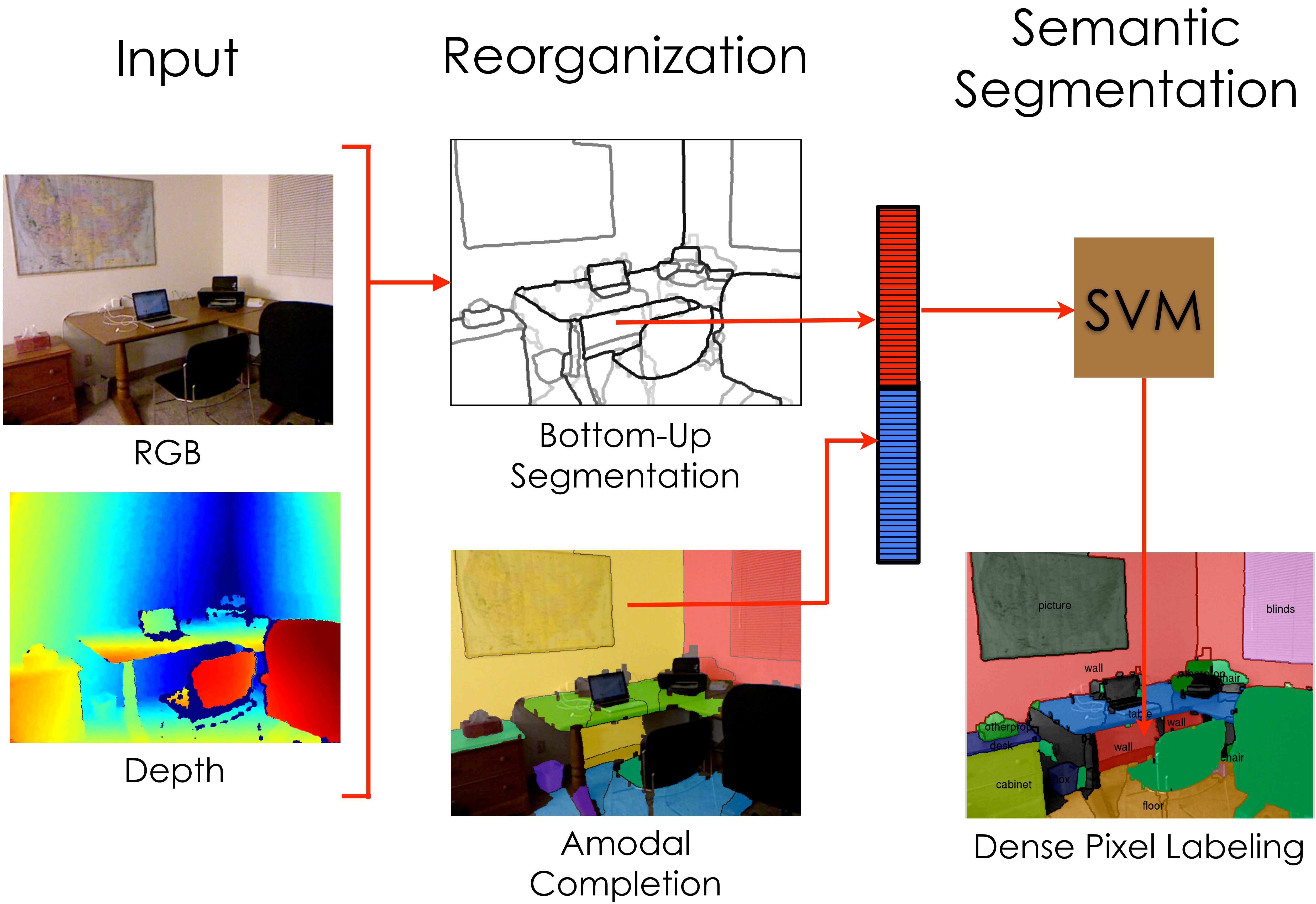
Approach

Use the inferred semantic class labels to predict the scene class

Scene Context

Using this inferred scene as additional features improves semantic segmentation accuracy by ~1%

Semantic Segmentation with RGB-D



Thank You

Code, benchmarks and results will be available on our group's website soon

http://www.eecs.berkeley.edu/Research/Projects/CS/vision/