PatchMatch Stereo – Stereo Matching with Slanted Support Windows

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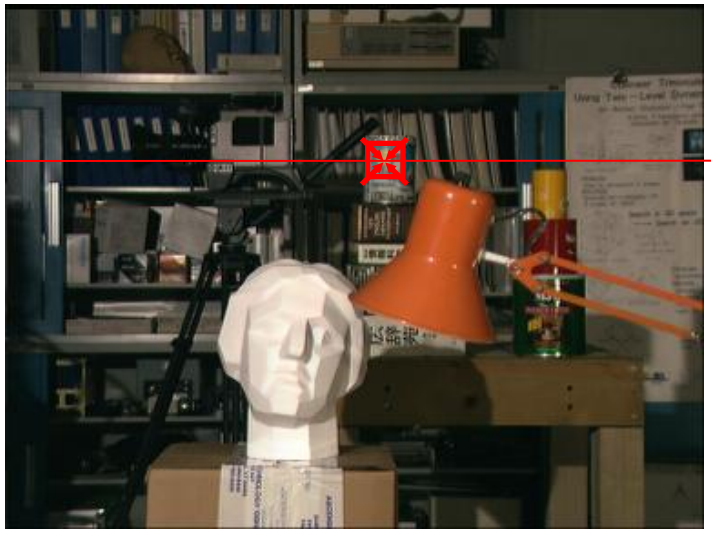
Local Stereo Algorithms



Left image

Right image

Local Stereo Algorithms

Implicit smoothness assumption:

- All pixels within support window have the **same integer-valued** disparity

Problems:

- Sub-pixel disparities
- Slanted surfaces
- Disparity discontinuities

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- All pixels within support window have the **same integer-valued** disparity

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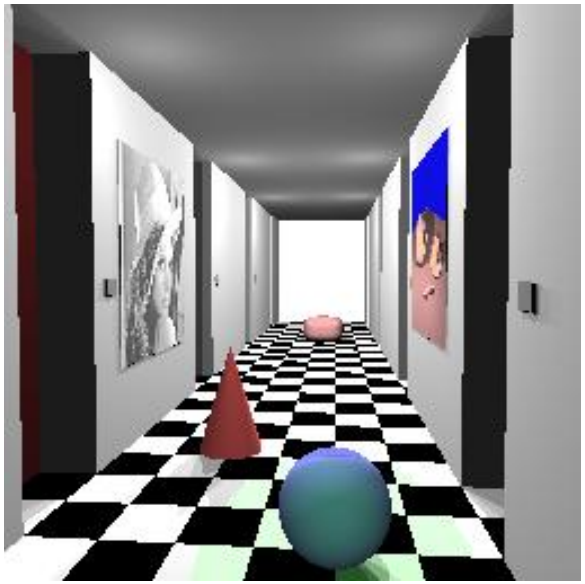
- Disparity discontinuities

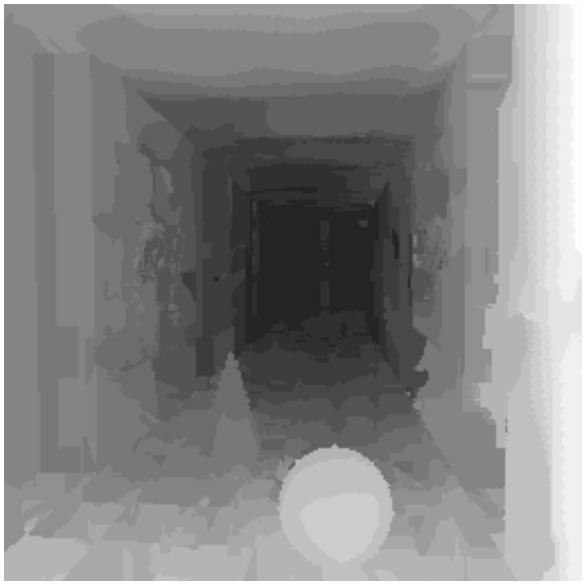
Focus of our work

We use adaptive Support Weights [Yoon, CVPR05]

Fronto-Par. Windows Matched at Integer Disparities



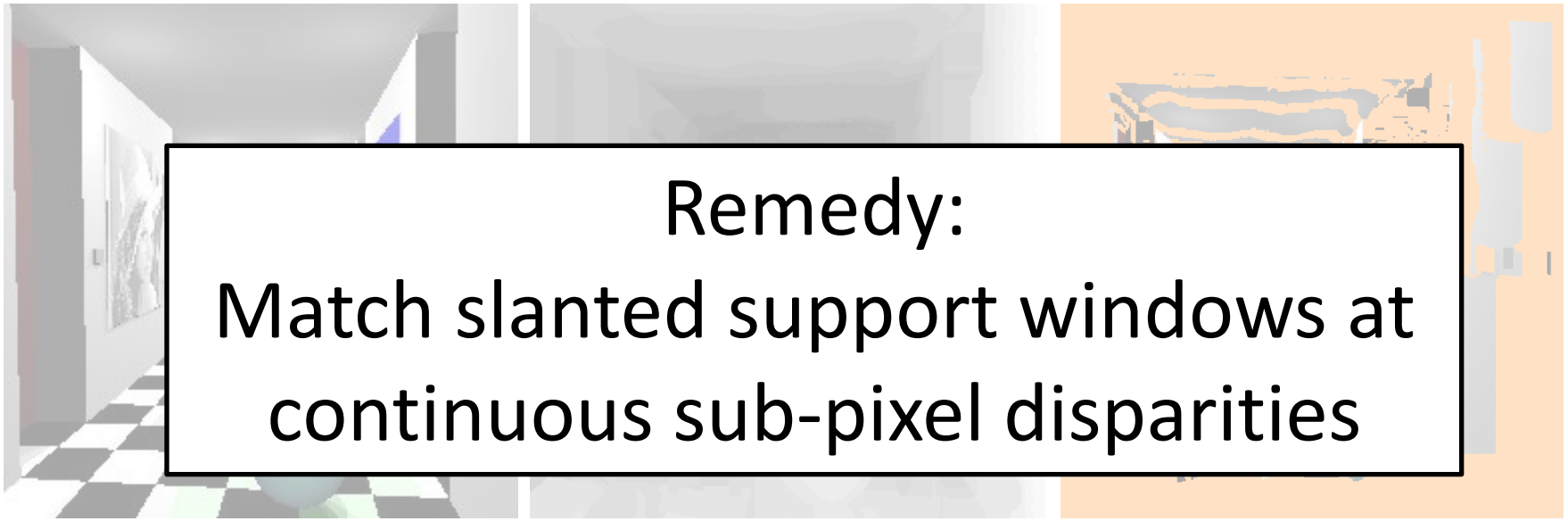
Left image



Disparity map

3D reconstruction

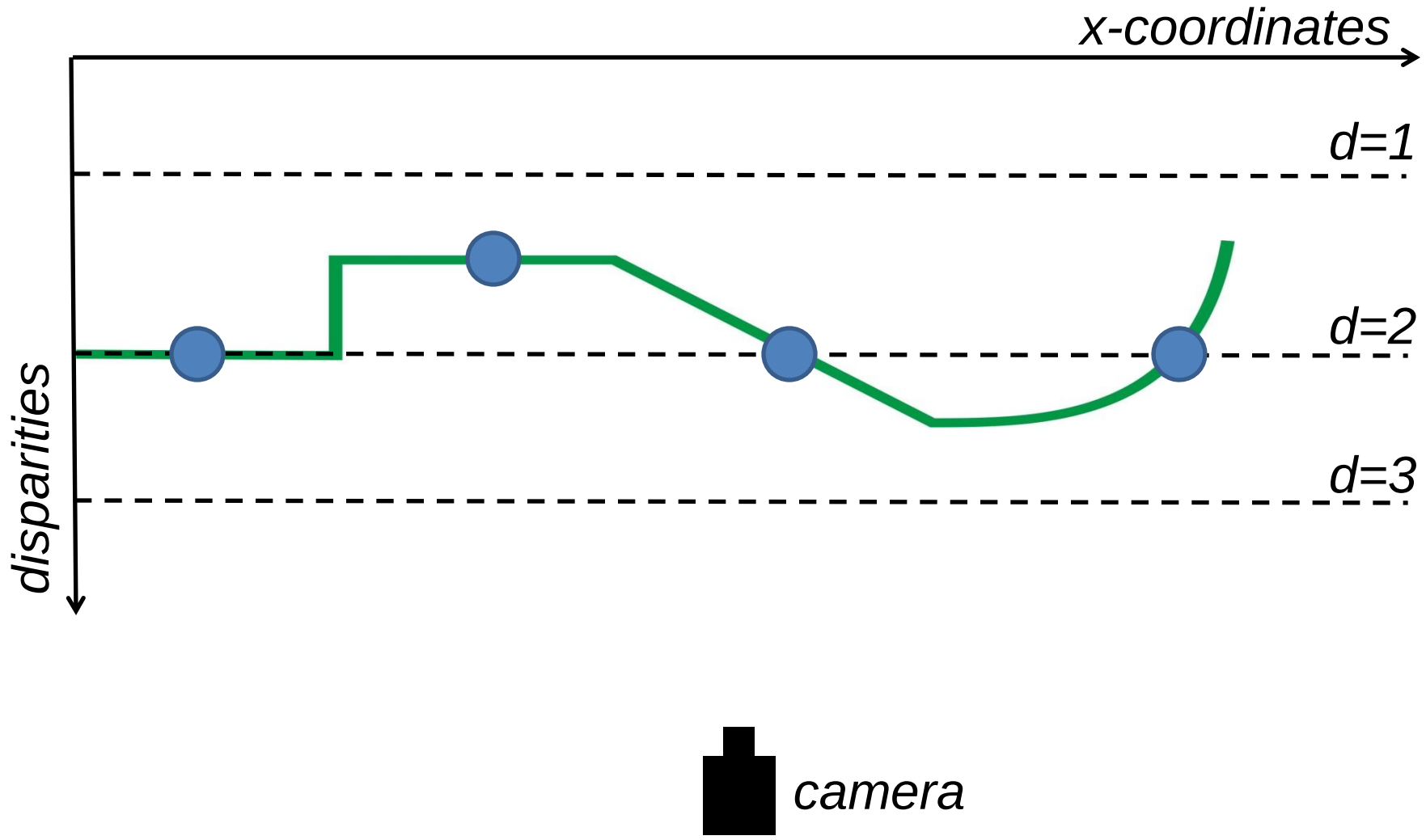
Fronto-Par. Windows Matched at Integer Disparities



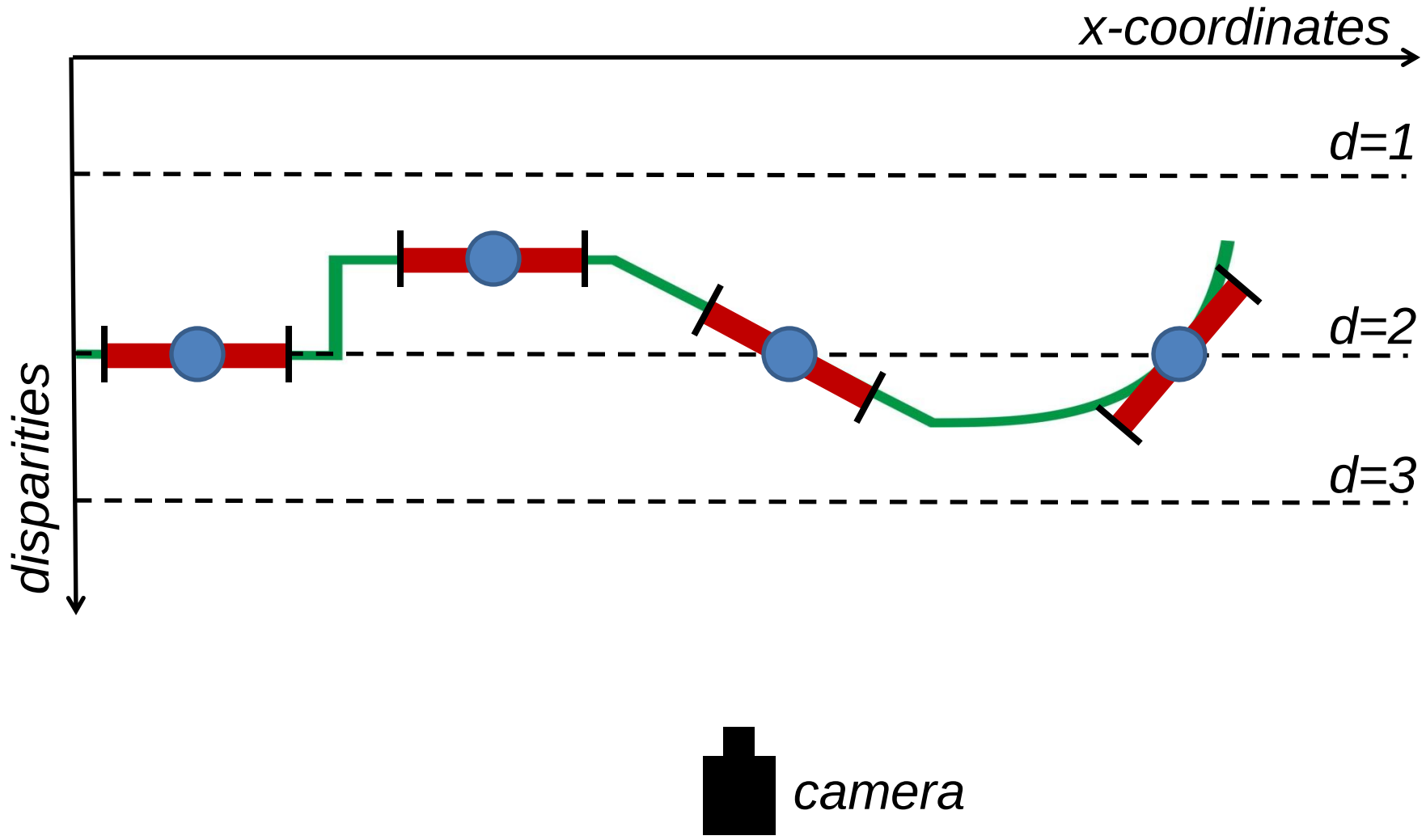
Remedy:
Match slanted support windows at continuous sub-pixel disparities

Left image | Disparity map | 3D reconstruction

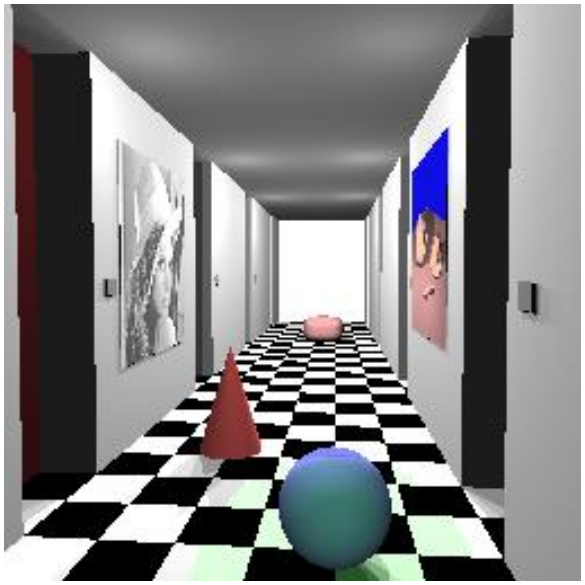
Slanted Support Windows



Slanted Support Windows

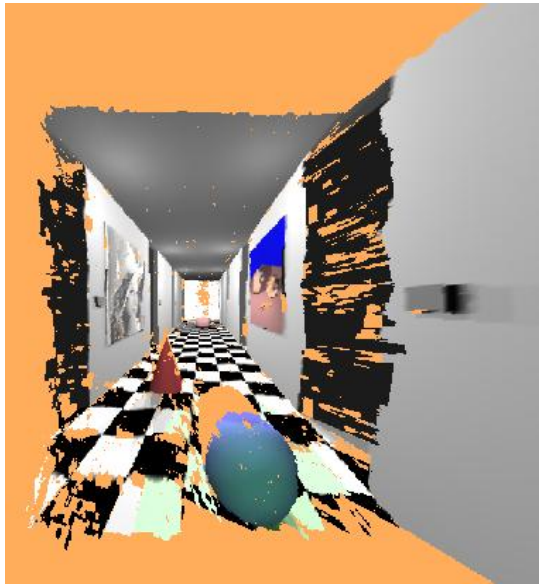


Our Slanted Windows



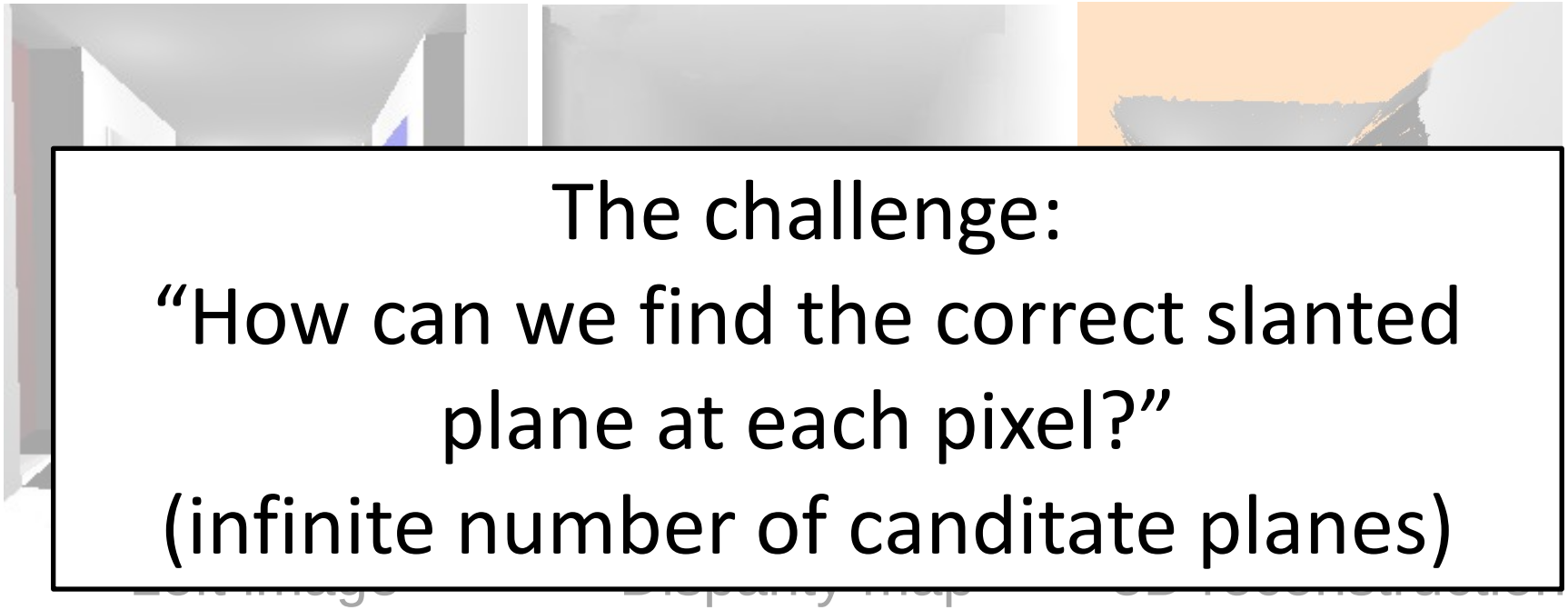
Left image

Disparity map



3D reconstruction

Our Slanted Windows



The challenge:
"How can we find the correct slanted plane at each pixel?"
(infinite number of canditate planes)

Previous Work

- Sub-pixel precision and slanted windows via extending label space:
  - Include fronto-parallel planes at sub-pixel disparities
  - Include slanted planes (plane sweeping)
- Problems
  - Each additional label adds extra computational complexity
  - Algorithm fails if correct plane not part of label space

Previous Work

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  - ex
  - P
    - Algorithm fails if correct plane not part of label space

Our algorithm:

- Continuous optimization over the set of all planes
- No quantization needed
- Based on PatchMatch [Barnes et al., SIGGRAPH09]

Our Algorithm

Basic Idea

- Relatively large regions of pixels can be modeled by approximately the same plane.
- Initialize each pixel with a random plane
- At least one pixel of a region should carry a plane close to correct one:
  - Many guesses (one per pixel)
- A single good guess is enough - it will be propagated to neighboring pixels

Left image – Sawtooth (Middlebury)

Ground truth disparities

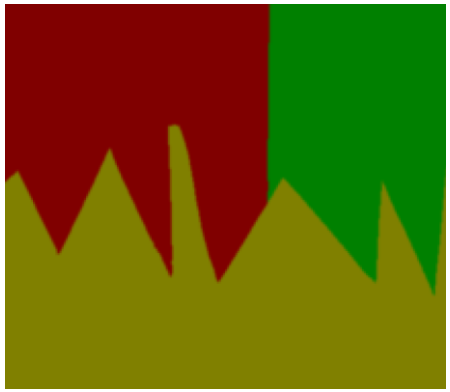
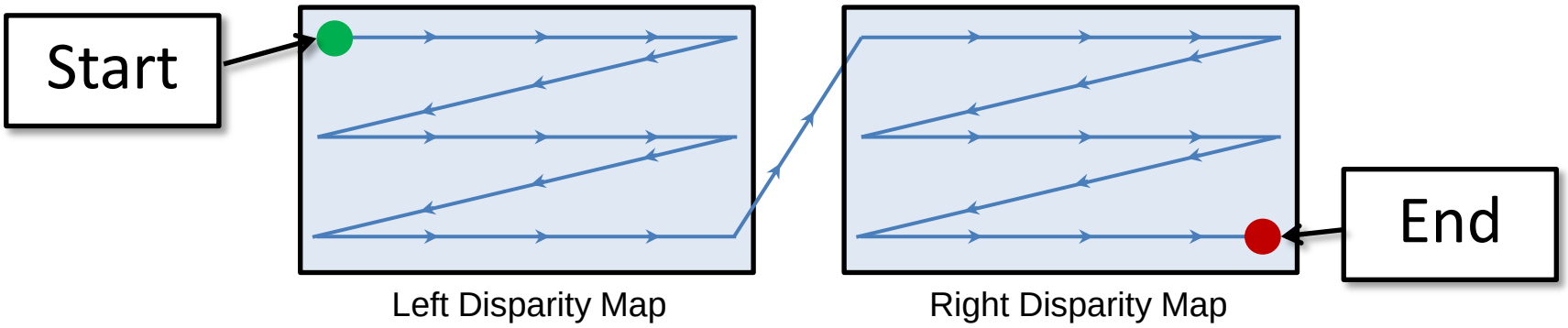


Image consists of 3 planes - ~80.000 guesses for yellow plane

Algorithm

- After random initialization process pixels in the following order:
  - Even iterations:



  - Odd iterations:
    - Reverse order
- We run 3 iterations

Algorithm

- After random initialization process pixels in the following order:

Run the following pipeline for each pixel *p*:

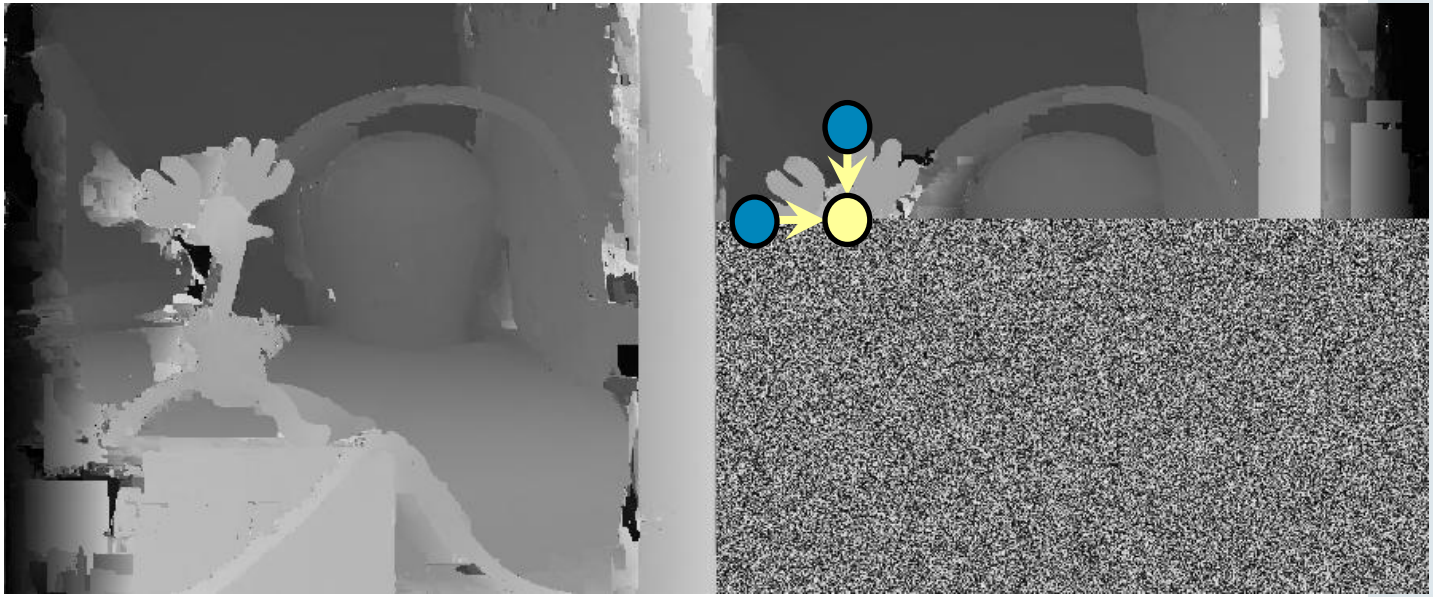
1. Spatial propagation
2. View propagation
3. Temporal propagation
4. Plane refinement

  - Odd iterations:
    - Reverse order
- We run 3 iterations

Spatial Propagation

- Look at the current pixel *p*'s spatial neighbors.
- Check if assigning *p* to a spatial neighbor's plane leads to lower aggregated costs.

Left image – Reindeer (Middlebury)

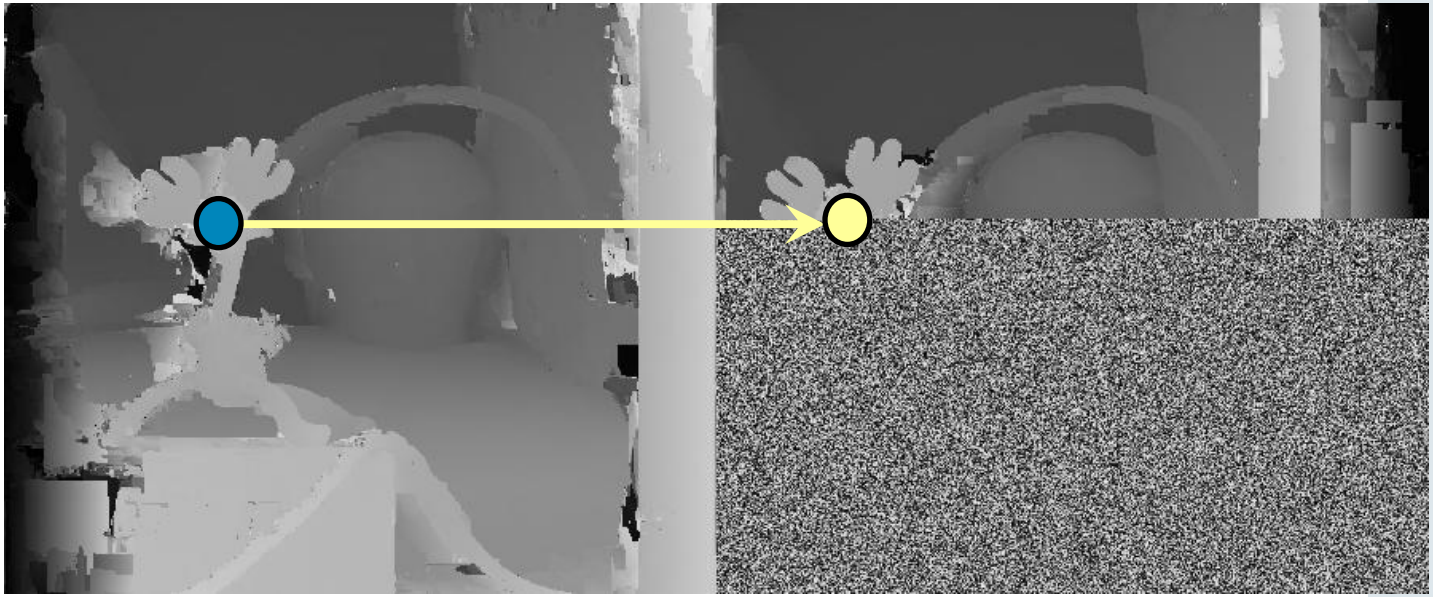


Left and right disparity maps (intermediate step of iteration 1)

View Propagation

- Find all pixels that have *p* as their matching point according to their current disparity.
- Check if plane of a matching point improves costs.

Left image – Reindeer (Middlebury)



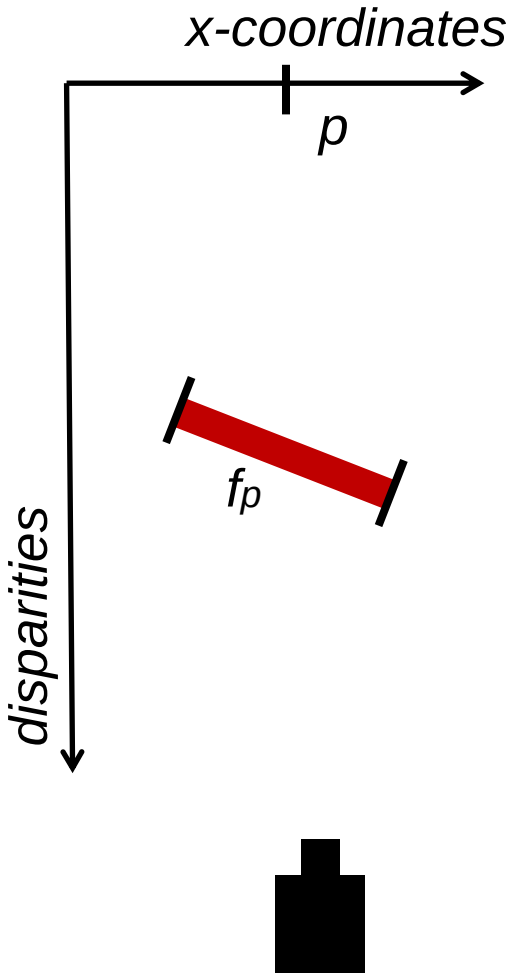
Left and right disparity maps (intermediate step of iteration 1)

Temporal Propagation

- Applicable if operating on video sequences
- Find planes at *p's* coordinates in the previous and consecutive frames.
- Check if planes improve current costs.

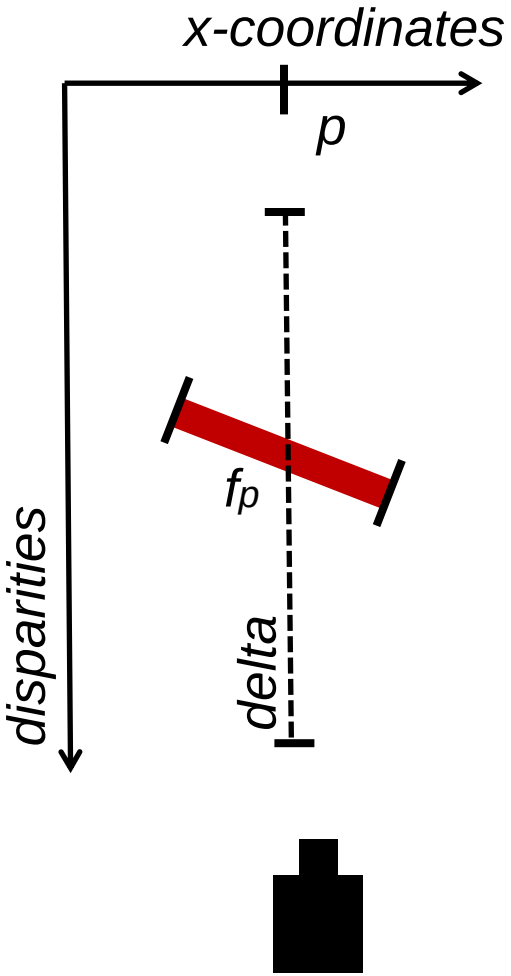
Plane Refinement

- Take *p*'s current plane f_p.



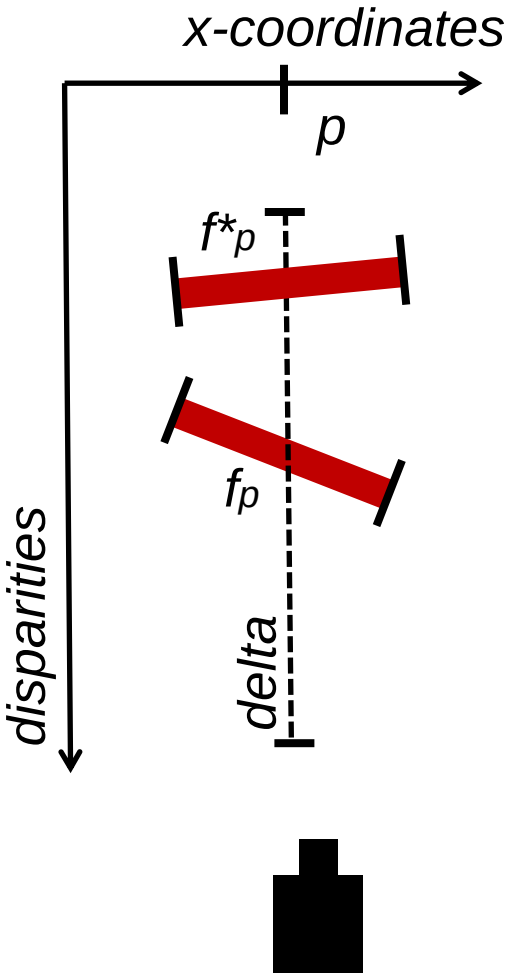
Plane Refinement

- Take *p*‘s current plane f_p.
- Distance *delta* defines the maximum allowed change of f_p.



Plane Refinement

- Take *p*‘s current plane f_p.
- Distance *delta* defines the maximum allowed change of f_p.
- Loop
  - Compute a random plane f^*_p within *delta*



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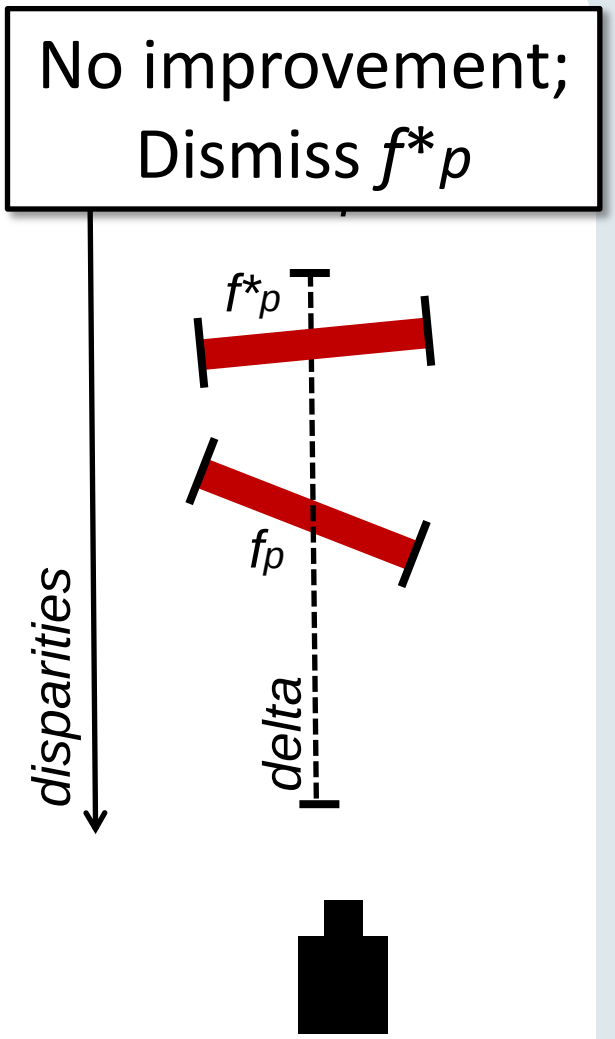
    $f_p := f^*_p$



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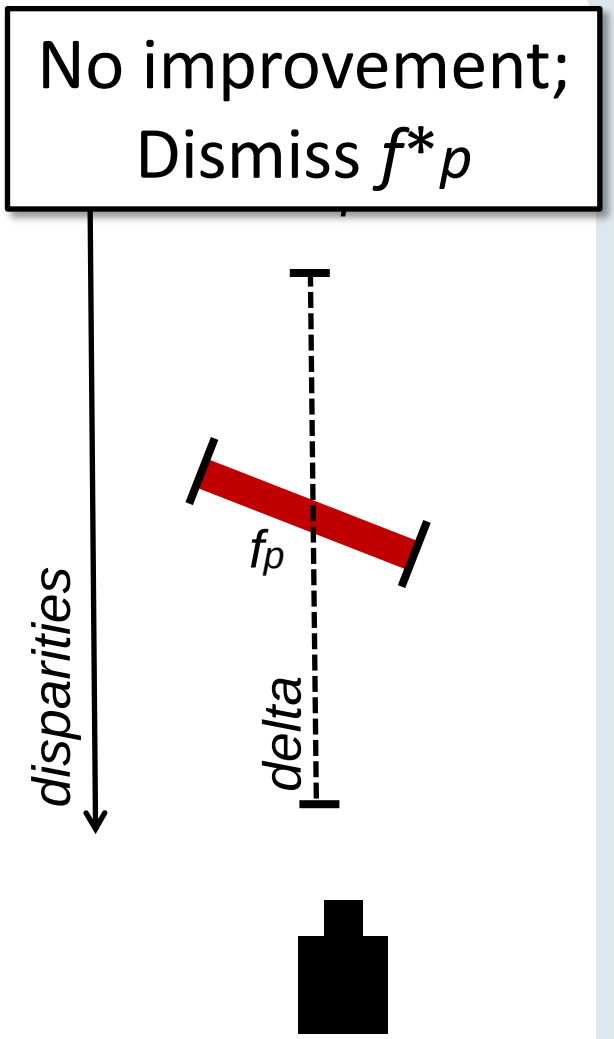

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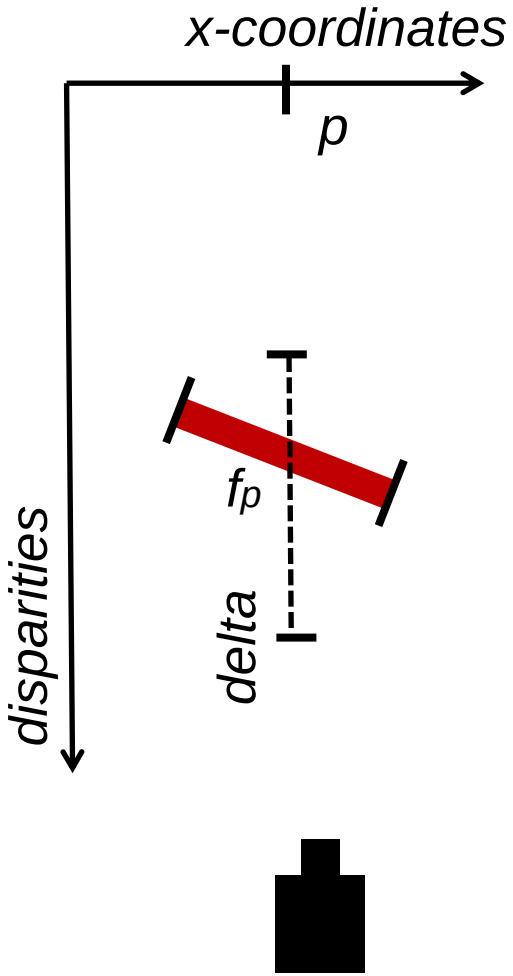
  - *delta* := *delta* / 2 (exponential reduction)
  - Break if *delta* < *eps*



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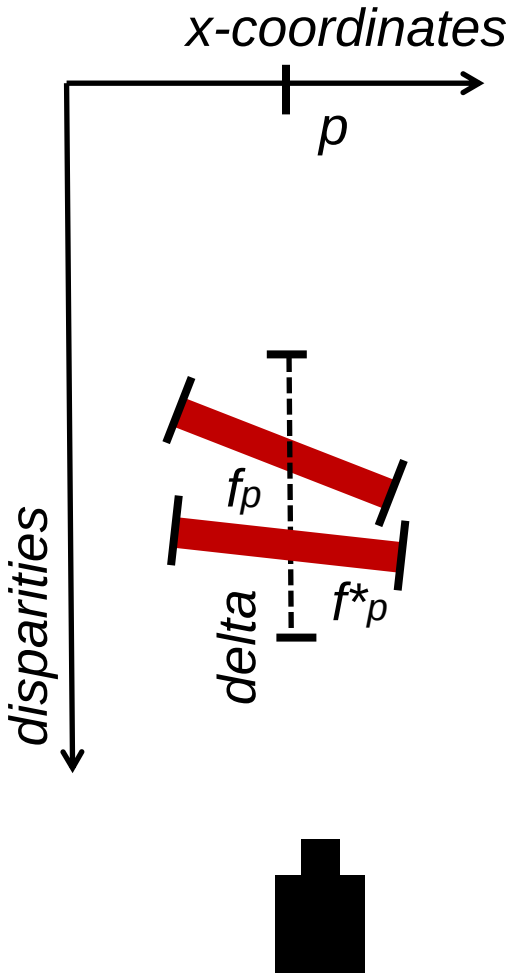

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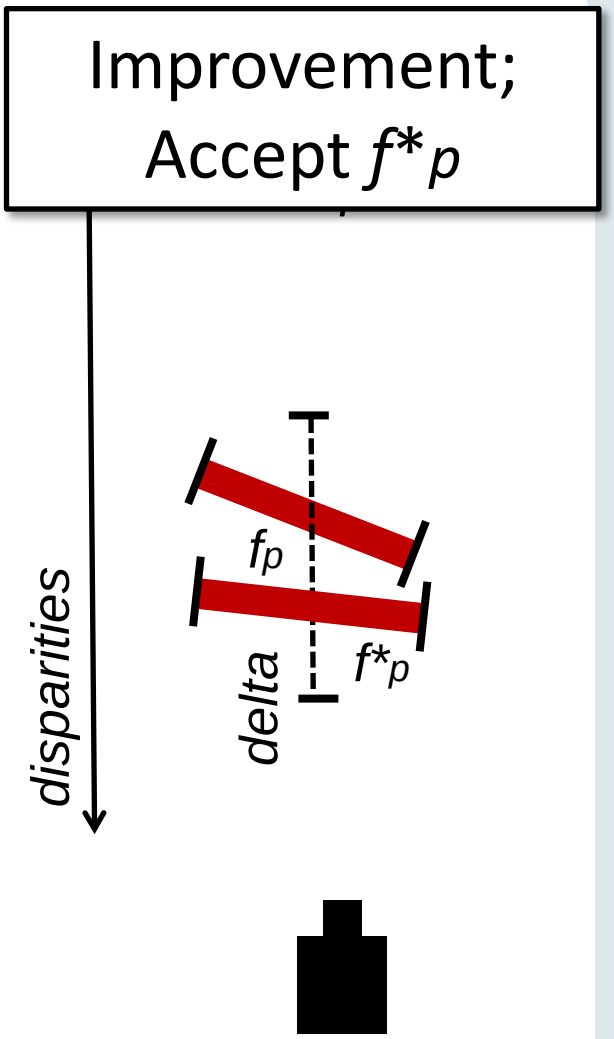

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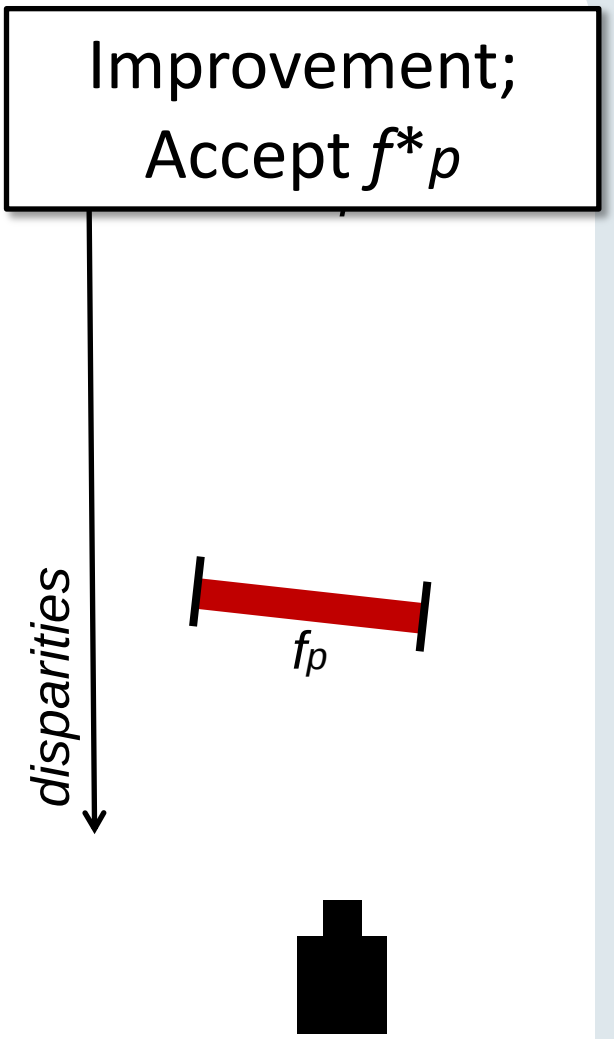

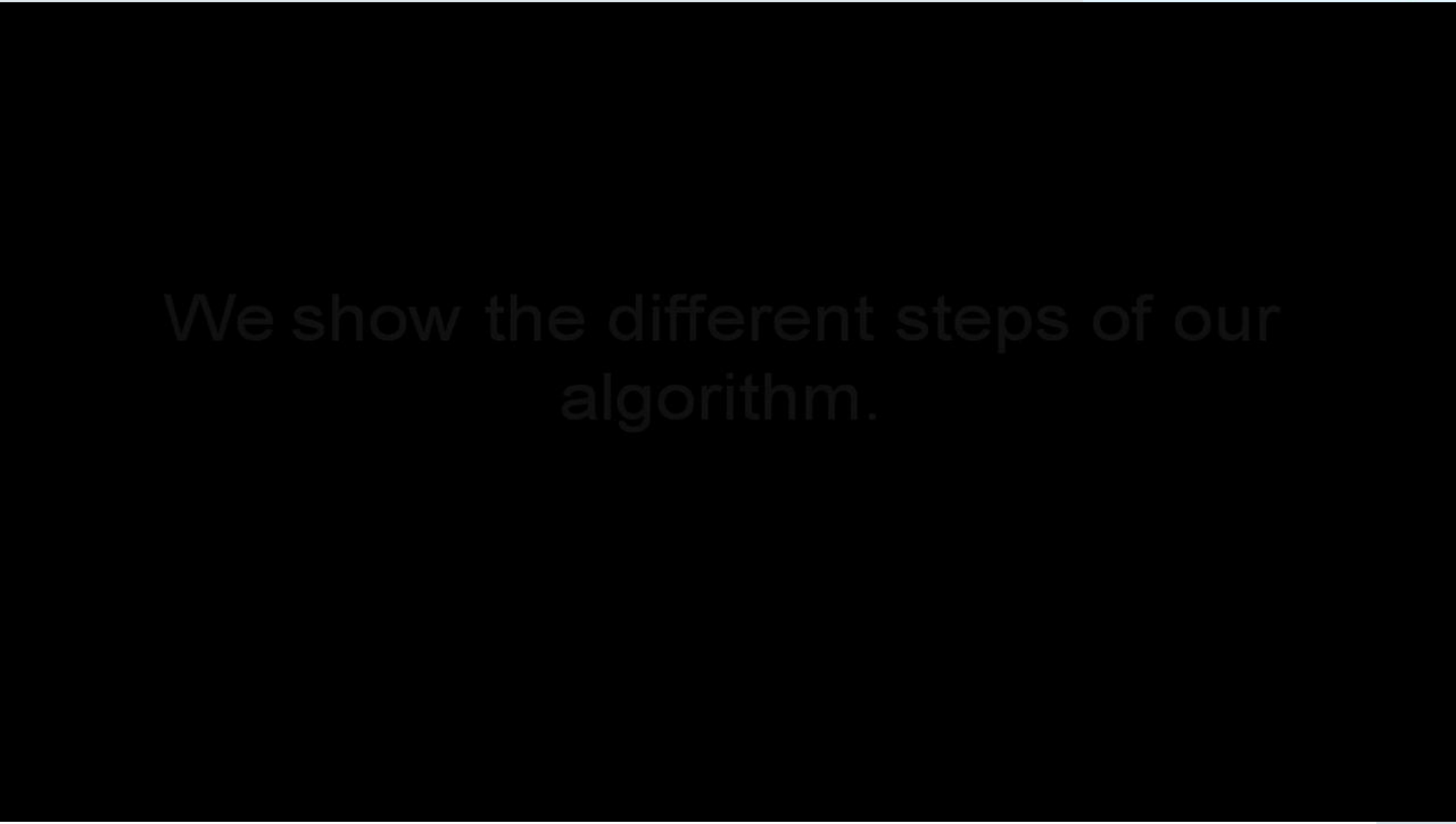
We show the different steps of our algorithm.

Global Methods

- Our slanted windows can be used as a data term for global methods (see paper).

Results

Evaluation

- We implement two competitors in our PatchMatch framework.
  - Competitor 1:
    - **Fronto-parallel** windows matched at **integer** disparities
  - Competitor 2:
    - **Fronto-parallel** windows matched at **sub-pixel** disparities
- Testbed:
  - Middlebury

Error threshold 1 (Middlebury default)

Algorithm	thresh.	Rank	Tsukuba			Venus			Teddy			Cones		
			nocc	all	disc	nocc	all	disc	nocc	all	disc	nocc	all	disc
Slanted Support	1.0	11	2.09_{57}	2.33_{43}	9.31_{54}	0.21_{20}	0.39_{15}	2.62_{26}	$\mathbf{2.99}_{1}$	8.16_{8}	9.62_{2}	2.47_{4}	7.80_{8}	7.11_{6}
Fronto-Par. Sub-Pixel	1.0	22	2.13_{57}	2.32_{43}	9.92_{60}	0.25_{27}	0.42_{16}	2.76_{27}	5.52_{17}	10.5_{17}	14.2_{15}	3.23_{27}	8.33_{17}	8.20_{18}
Fronto-Par. Integer	1.0	32	2.23_{58}	2.44_{44}	9.18_{53}	0.25_{25}	0.41_{16}	2.21_{16}	6.73_{34}	12.2_{34}	16.9_{38}	3.71_{35}	8.90_{27}	9.31_{35}

Ranking in the Middlebury online table

Error threshold 1 (Middlebury default)

- Fronto-parallel windows at integer disparities (Comp. 1)
- Rank **32** of **110** Middlebury submissions

Algorithm	thresh.	Rank												
Slanted Support	1.0	11												
Fronto-Par. Sub-Pixel	1.0	2[illegible]	2.13_{57}	2.32_{43}	9.92_{60}	0.25_{27}	0.42_{16}	2.76_{27}	5.52_{17}	10.5_{17}	14.2_{15}	3.23_{27}	8.33_{17}	8.20_{18}
Fronto-Par. Integer	1.0	32	2.23_{58}	2.44_{44}	9.18_{53}	0.25_{25}	0.41_{16}	2.21_{16}	6.73_{34}	12.2_{34}	16.9_{38}	3.71_{35}	8.90_{27}	9.31_{35}

Ranking in the Middlebury online table

Left image – Teddy set (Middlebury)

Disparity map

Error map (black = wrong)

Error threshold 1 (Middlebury default)

- Fronto-parallel windows at sub-pixel disp. (Comp. 2)
- Rank **22** of **110** Middlebury submissions

Algorithm	thresh.	Rank												
Slanted Support	1.0	1	2.09_{57}	2.33_{43}	9.31_{54}	0.21_{20}	0.39_{15}	2.62_{26}	**2.99_{1}**	8.16_{8}	9.62_{2}	2.47_{4}	7.80_{8}	7.11_{6}
Fronto-Par. Sub-Pixel	1.0	22	2.13_{57}	2.32_{43}	9.92_{60}	0.25_{27}	0.42_{16}	2.76_{27}	5.52_{17}	10.5_{17}	14.2_{15}	3.23_{27}	8.33_{17}	8.20_{18}
Fronto-Par. Integer	1.0	32	2.23_{58}	2.44_{44}	9.18_{53}	0.25_{25}	0.41_{16}	2.21_{16}	6.73_{34}	12.2_{34}	16.9_{38}	3.71_{35}	8.90_{27}	9.31_{35}

Ranking in the Middlebury online table

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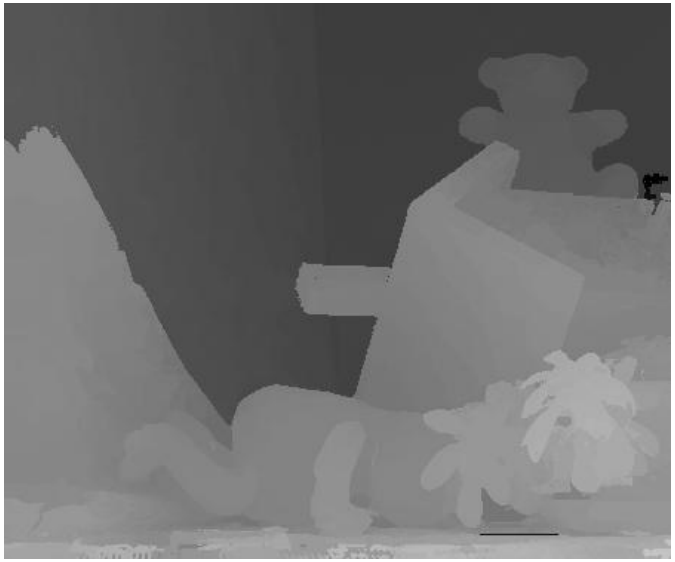


Disparity map

Error map (black = wrong)

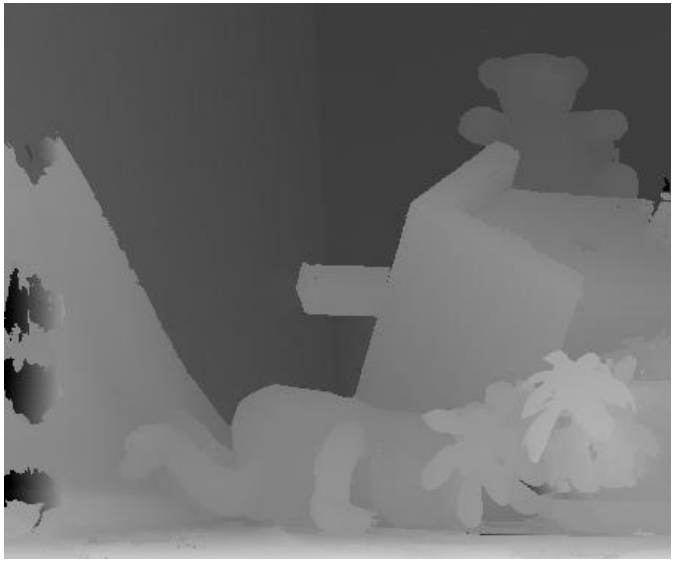
Error thresh

- Our slanted windows
- Rank **11** of **110** Middlebury submissions
- Best-performing local method

Algorithm	thresh.	Rank	nocc	all	disc	nocc	all	disc	nocc	all	disc	nocc	all	disc
Slanted Support	1.0	11	2.09_{57}	2.33_{43}	9.31_{54}	0.21_{20}	0.39_{15}	2.62_{26}	$\mathbf{2.99}_{1}$	8.16_{8}	9.62_{2}	2.47_{4}	7.80_{8}	7.11_{6}
Fronto-Par. Sub-Pixel	1.0	22	2.13_{57}	2.32_{43}	9.92_{60}	0.25_{27}	0.42_{16}	2.76_{27}	5.52_{17}	10.5_{17}	14.2_{15}	3.23_{27}	8.33_{17}	8.20_{18}
Fronto-Par. Integer	1.0	32	2.23_{58}	2.44_{44}	9.18_{53}	0.25_{25}	0.41_{16}	2.21_{16}	6.73_{34}	12.2_{34}	16.9_{38}	3.71_{35}	8.90_{27}	9.31_{35}

Ranking in the Middlebury online table

Left image – Teddy set (Middlebury)



Disparity map

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Error thresh

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Algorithm	thresh.	Rank	nocc	all	disc	nocc	all	disc	nocc	all	disc	nocc	all	disc
Slanted Support	1.0	11	2.09_{57}	2.33_{43}	9.31_{54}	0.21_{20}	0.39_{15}	2.62_{26}	**2.99_{1}**	8.16_{8}	9.62_{2}	2.47_{4}	7.80_{8}	7.11_{6}
Fronto-Par. Sub-Pixel	1.0	22	2.13_{57}	2.32_{43}	9.92_{60}	0.25_{27}	0.42_{16}	2.76_{27}	5.52_{17}	10.5_{17}	14.2_{15}	3.23_{27}	8.33_{17}	8.20_{18}
Fronto-Par. Integ									34	12.2_{34}	16.9_{38}	3.71_{35}	8.90_{27}	9.31_{35}

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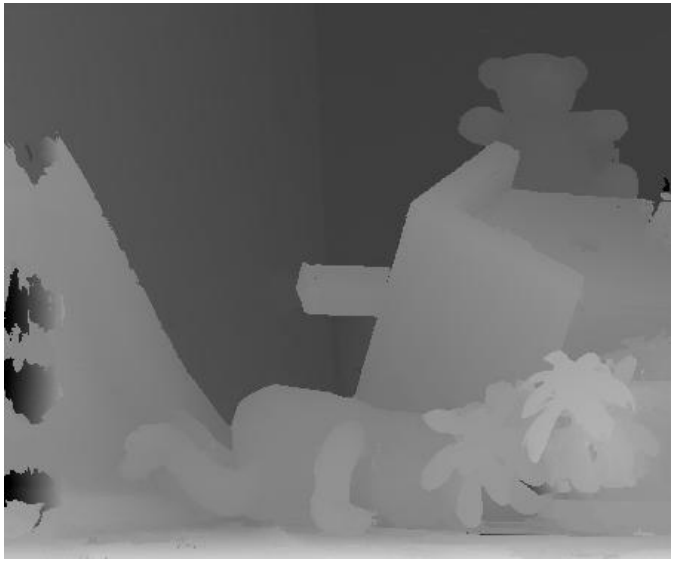
- Rank #1 on Teddy in non-occluded regions

Left image – Teddy set (Middlebury)



Disparity map

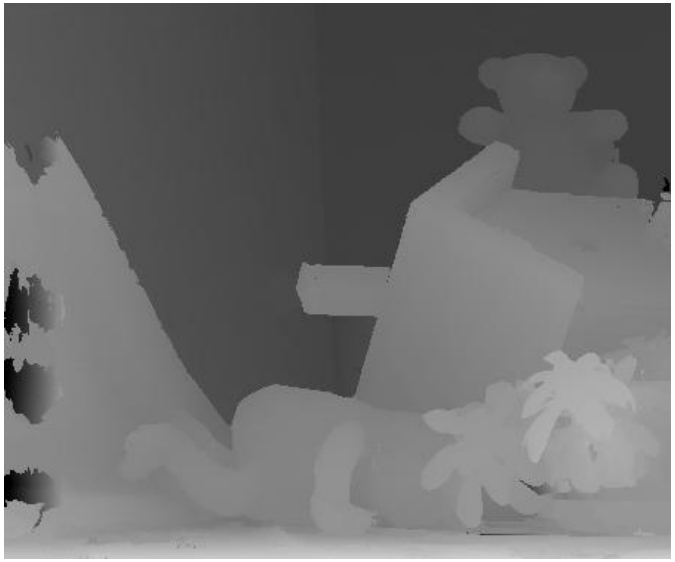
Error map (black = wrong)

Error threshold 0.5 (Sub-Pixel Evaluation)

Algorithm	thresh.	Rank	Tsukuba			Venus			Teddy			Cones		
			nocc	all	disc	nocc	all	disc	nocc	all	disc	nocc	all	disc
Slanted Support	0.5	2	15.0_{37}	15.4_{36}	20.3_{45}	1.00_{4}	1.34_{4}	7.75_{7}	$\mathbf{5.66}_{1}$	11.8_{2}	$\mathbf{16.5}_{1}$	$\mathbf{3.80}_{1}$	$\mathbf{10.2}_{1}$	$\mathbf{10.2}_{1}$
Fronto-Par. Sub-Pixel	0.5		14.1_{36}	14.4_{32}	19.2_{35}	1.73_{7}	2.15_{7}	7.84_{7}	9.63_{6}	16.2_{8}	22.6_{8}	7.08_{24}	12.6_{16}	13.2_{11}
Fronto-Par. Integer	0.5	41												

- Our slanted windows
- Rank **2** of **110** Middlebury submissions

Left image – Teddy set (Middlebury)



Disparity map

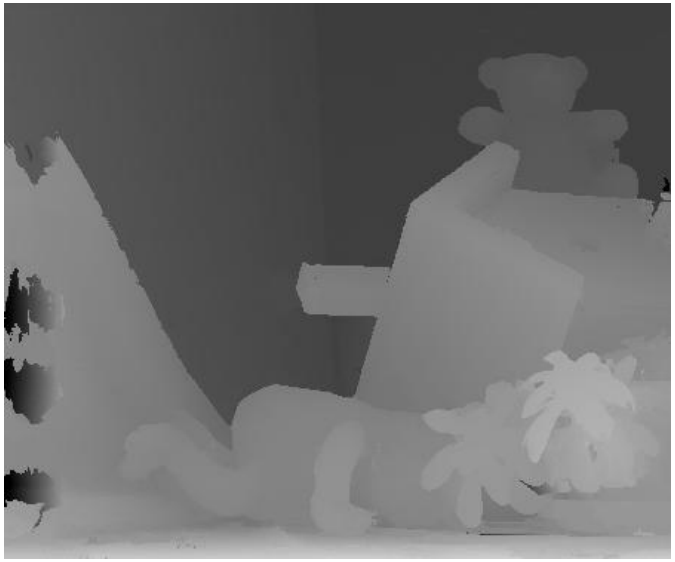
Error map (black = wrong)

Error threshold 0.5 (Sub-Pixel Evaluation)

Algorithm	thresh.	Rank	Tsukuba			Venus			Teddy			Cones		
			nocc	all	disc	nocc	all	disc	nocc	all	disc	nocc	all	disc
Slanted Support	0.5	2	15.0_{37}	15.4_{36}	20.3_{45}	1.00_{4}	1.34_{4}	7.75_{7}	**5.66_{1}**	11.8_{2}	**16.5_{1}**	**3.80_{1}**	**10.2_{1}**	**10.2_{1}**
Fronto-Par. Sub-Pixel	0.5	4	14.1_{36}	14.4_{32}	19.2_{35}	1.73_{7}	2.15_{7}	7.84_{7}	9.63_{6}	16.2_{8}	22.6_{8}	7.08_{24}	12.6_{16}	13.2_{11}
Fron											29.1_{37}	11.6_{53}	16.9_{42}	18.3_{41}

- First rank on almost all error measurements on the complex Teddy and Cones sets

Left image – Teddy set (Middlebury)



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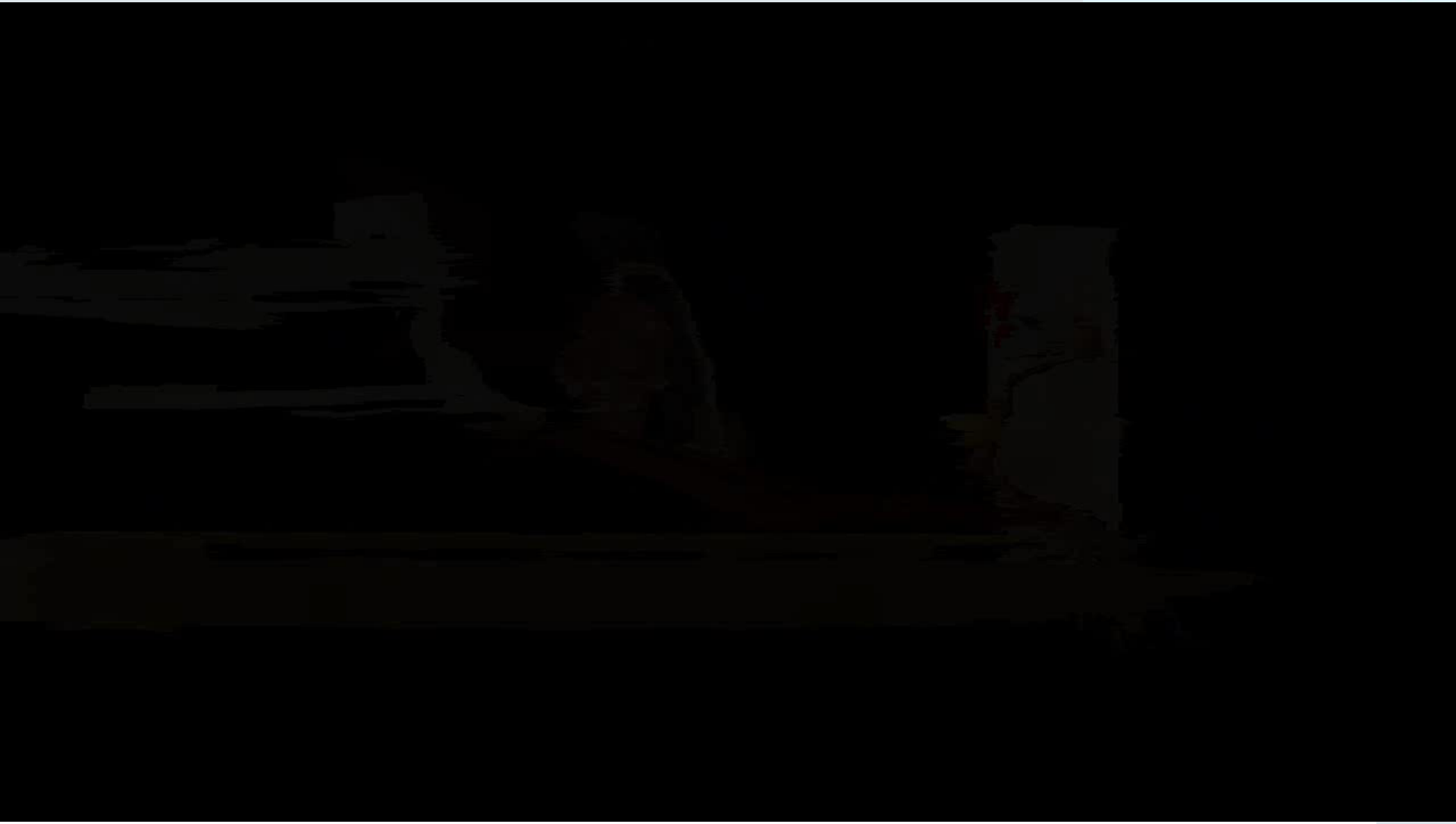


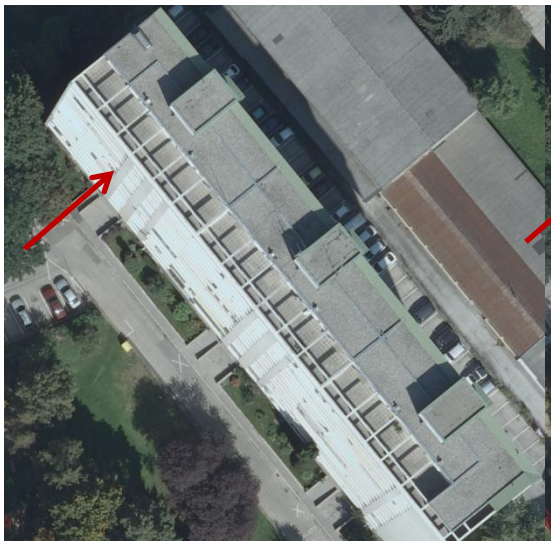
Computational Speed

- Approximately 1 minute per Middlebury pair (CPU)
- Runtime independent of the number of labels (disparities)
  - Well suited for optical flow computation (future work)
- Low memory requirements:
  - We only need to hold the current matching costs and a plane at each pixel in memory
  - => We can do high-resolution stereo

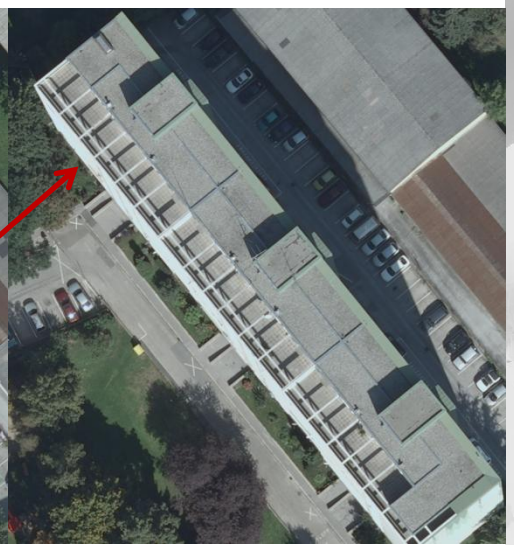
Image of Graz (2048x2048 pixels)

Image of Graz (2048x2048 pixels)

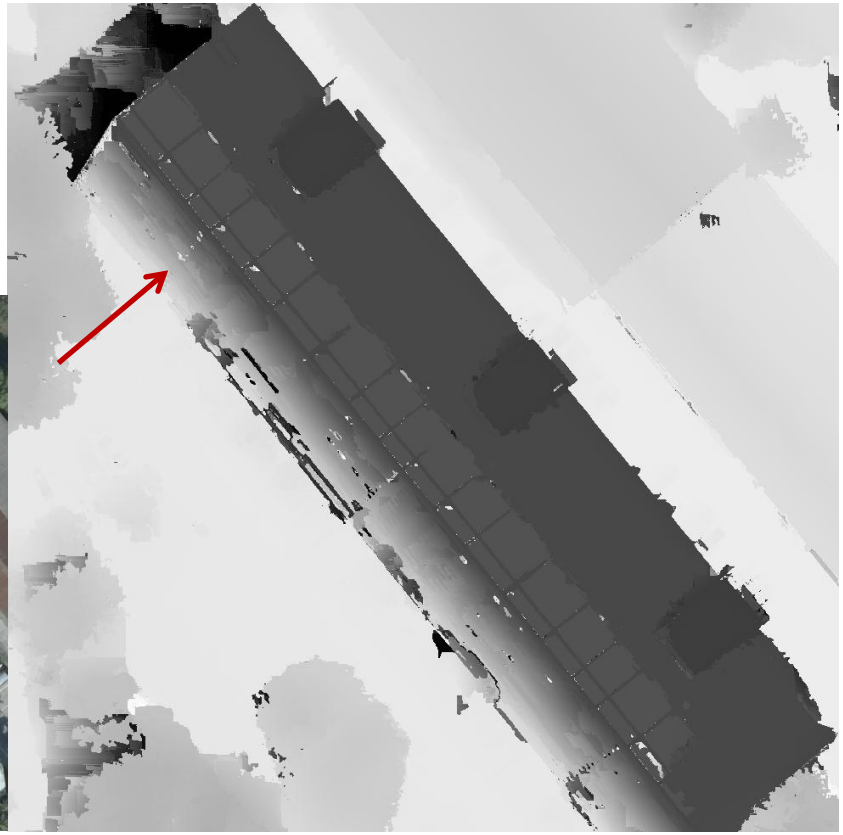
Image of Graz (2048x2048 pixels)



Crop of left image



Crop of right image



Left disparity map
(before left/right check)

Playroom Set (image courtesy Daniel Scharstein)

Playroom Set (image courtesy Daniel Scharstein)

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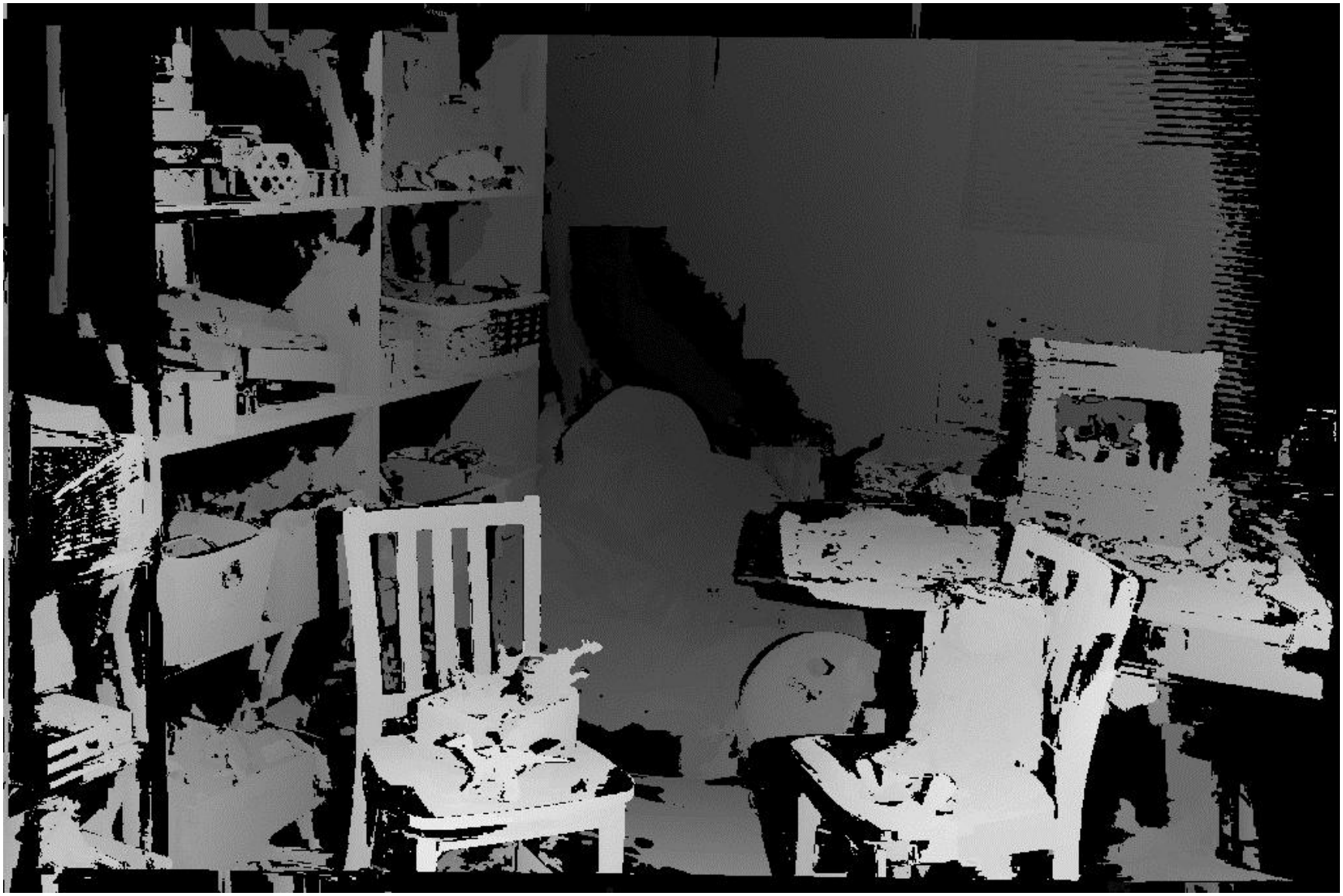

Conclusions

- Local stereo algorithm uses slanted support windows
- An ideal algorithm to find the slanted windows is PatchMatch
- High quality results on complex images and videos at reasonable runtimes

Future Work

- Optical flow
- Improve computational speed (GPU implementation – real time)