Imagining the Unseen: Stability-based Cuboid Arrangements for Scene Understanding

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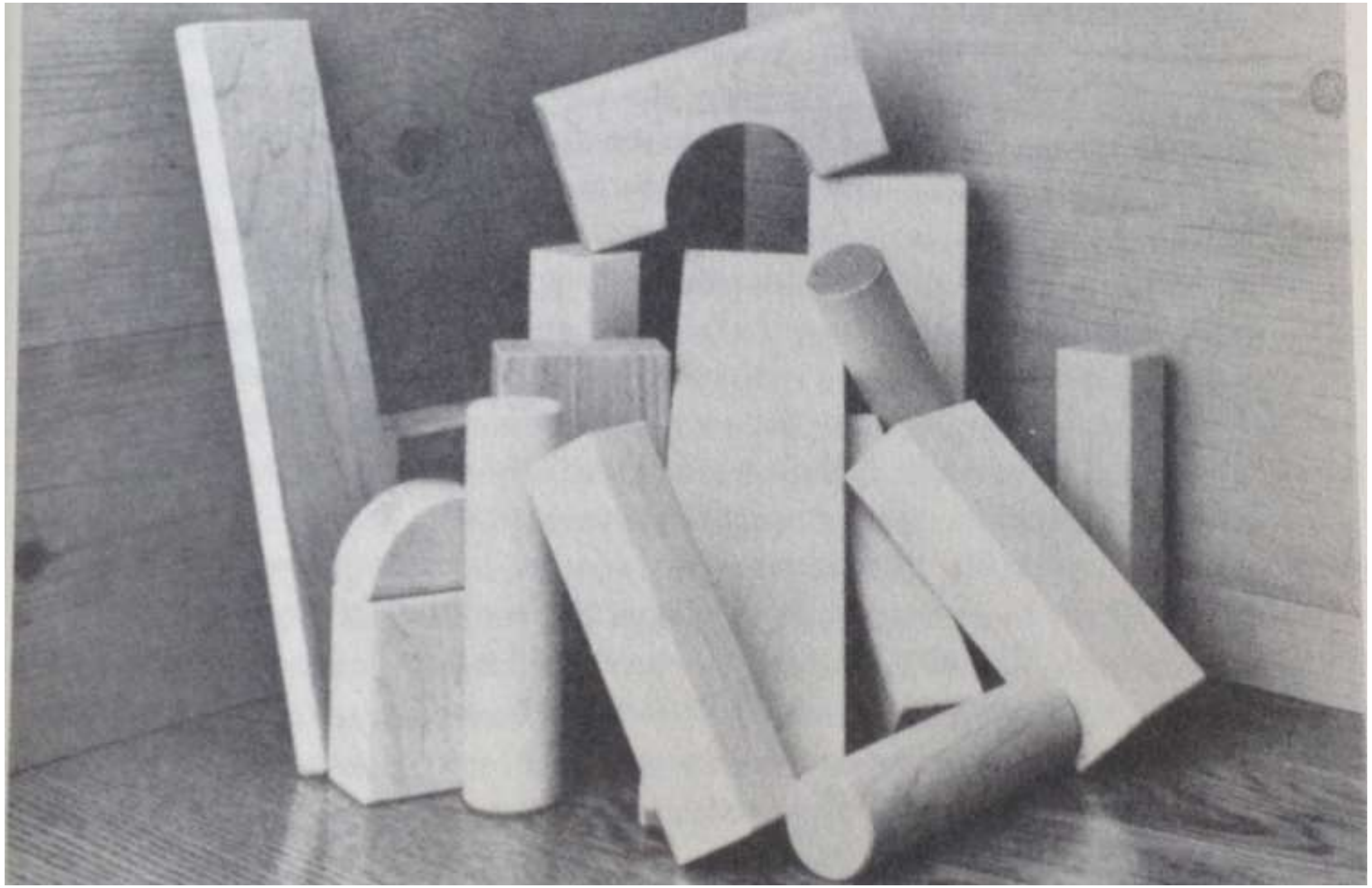
Background

- A fundamental problem for single view data acquisition
  - Missing observations due to scene occlusion
  - Limiting the understanding of indoor scenes

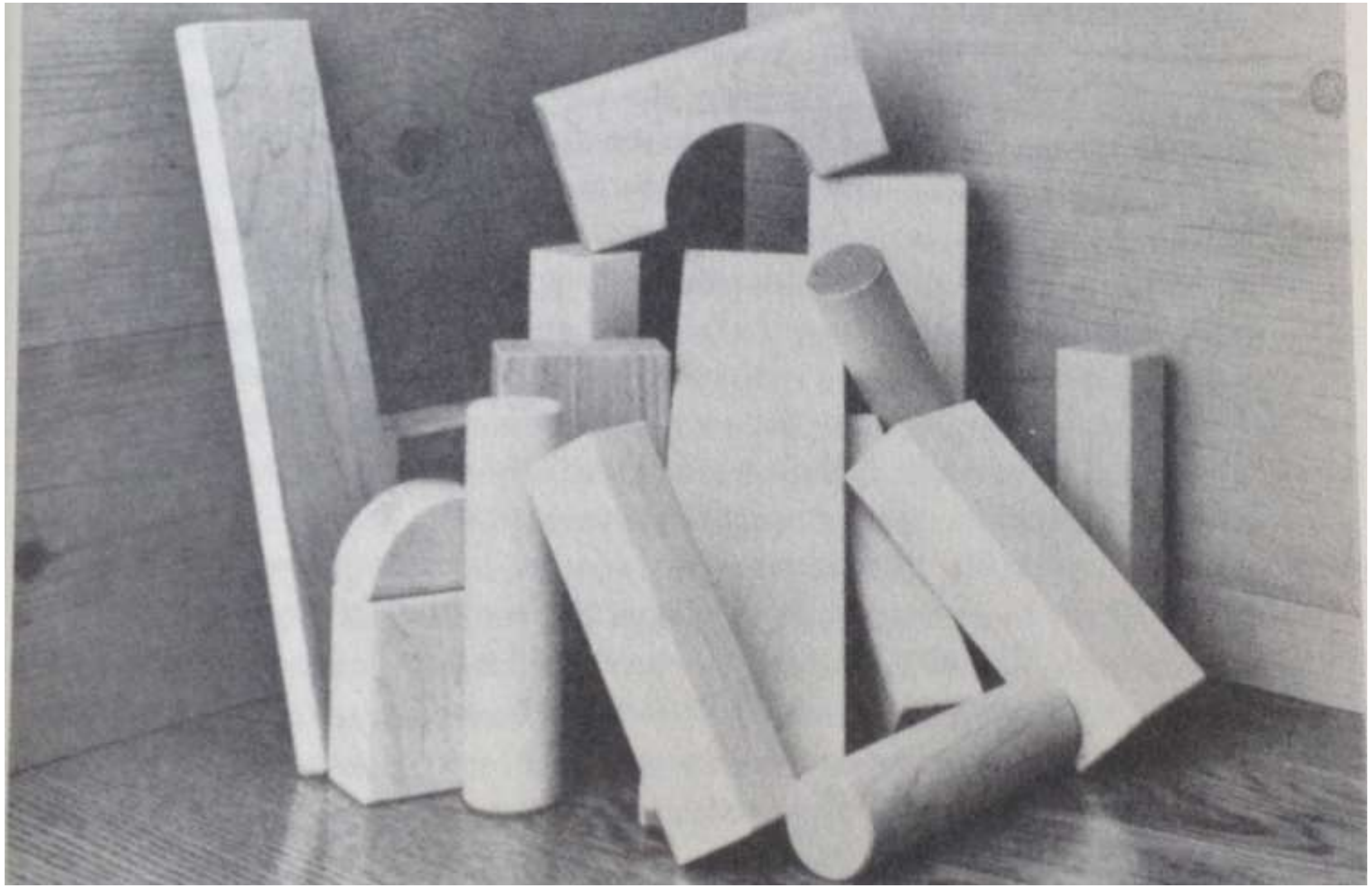
From the capture view

From another view

How do We Imagine Unseen Data?



How do We Imagine Unseen Data?



Our Motivation

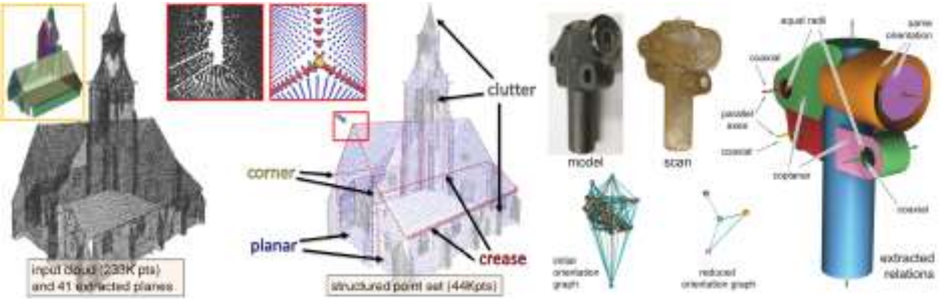
Mimic the process of human's imagination based on physical stability

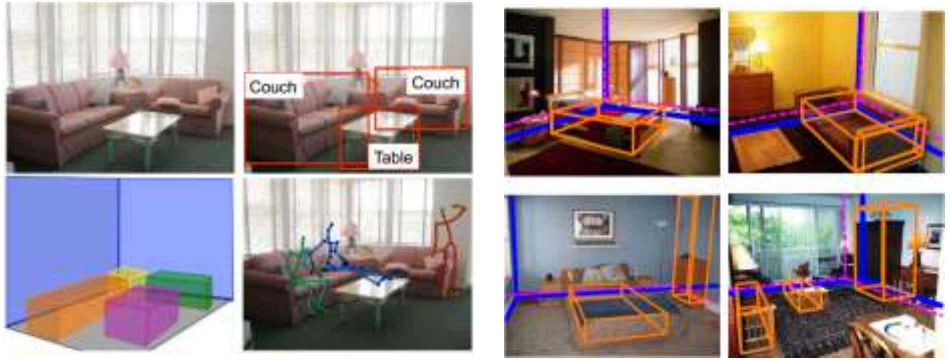
Our Motivation

- Physical stability can help to reason about the scene structure
  - Relationship among parts – touching or fixed

Related Works: Proxy-based Scene Understanding

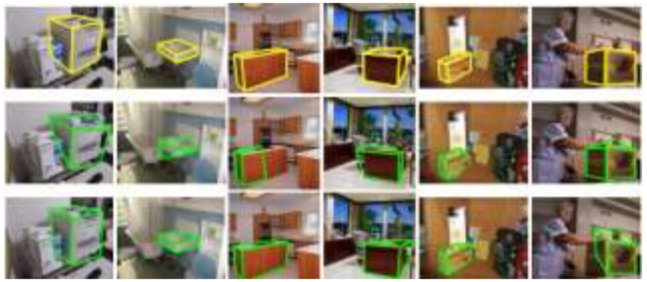
- Structured output of primitives
  - [Li et al. 2011]
  - [Lafarge et al. 2013]
- Creating abstracted geometry
  - [Arikan et al. 2013]
- Studying spatial layout
  - [Gupta et al. 2010]
  - [Lee et al. 2010]
  - [Hartley et al. 2012]
- Image manipulation
  - [Zheng et al. 2012]

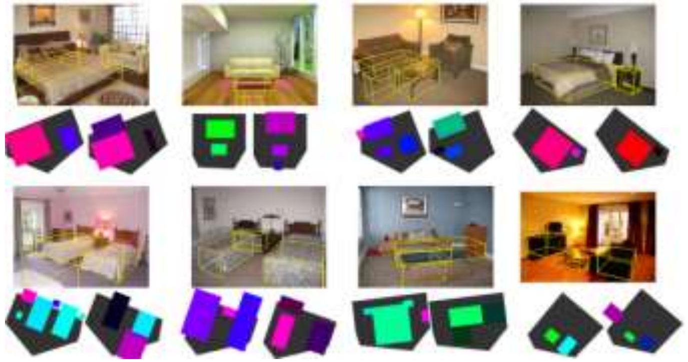




Related Works: Cuboid Detection

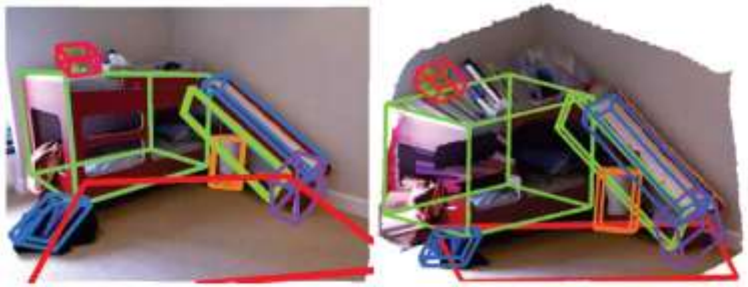
- Statistical deformable cuboid model
  - [Fidler et al. 2012]
- Cuboid corner point model
  - [Xiao et al. 2012]
- Image space contrast-based features
  - [Hedau et al. 2012]



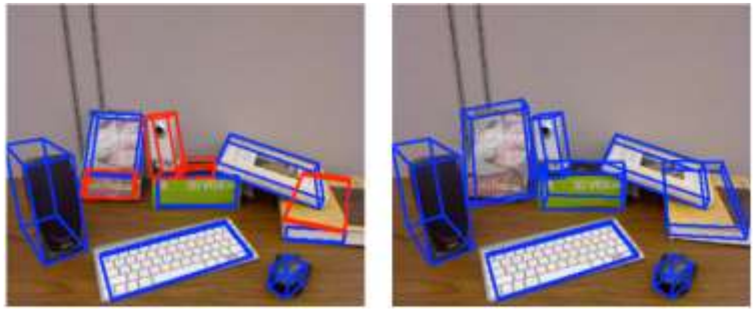


Related Works: Physical Validity Constraints

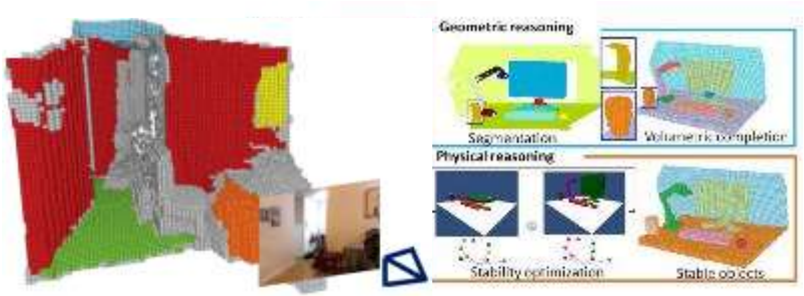
- Penetration free
  - [Hedau et al. 2010]
  - [Jiang and Xiao 2013]



- Improve segmentation
  - [Jia et al. 2013]



- Voxel-based scene parsing
  - [Zheng et al. 2013]
  - [Kim et al. 2013]

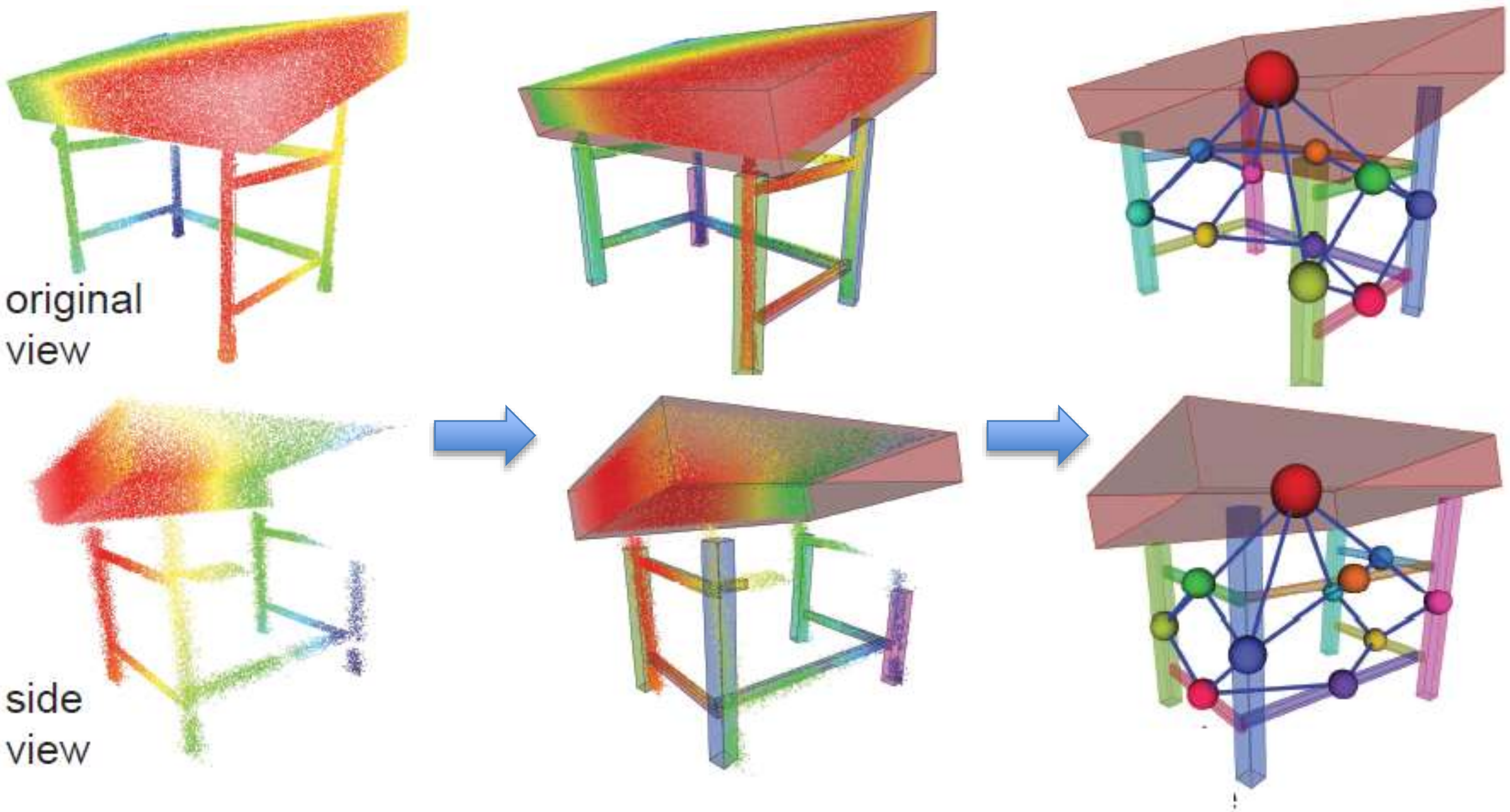


Our Goal

- Recover the underlying structure of indoor scenes
  - Abstracting indoor scenes as collections of cuboids
  - Hallucinate geometry in the occluded regions
  - Identifying part parameters (size and orientation)
  - Identifying part relations (touching or fixed)

Algorithm Overview

Algorithm Overview

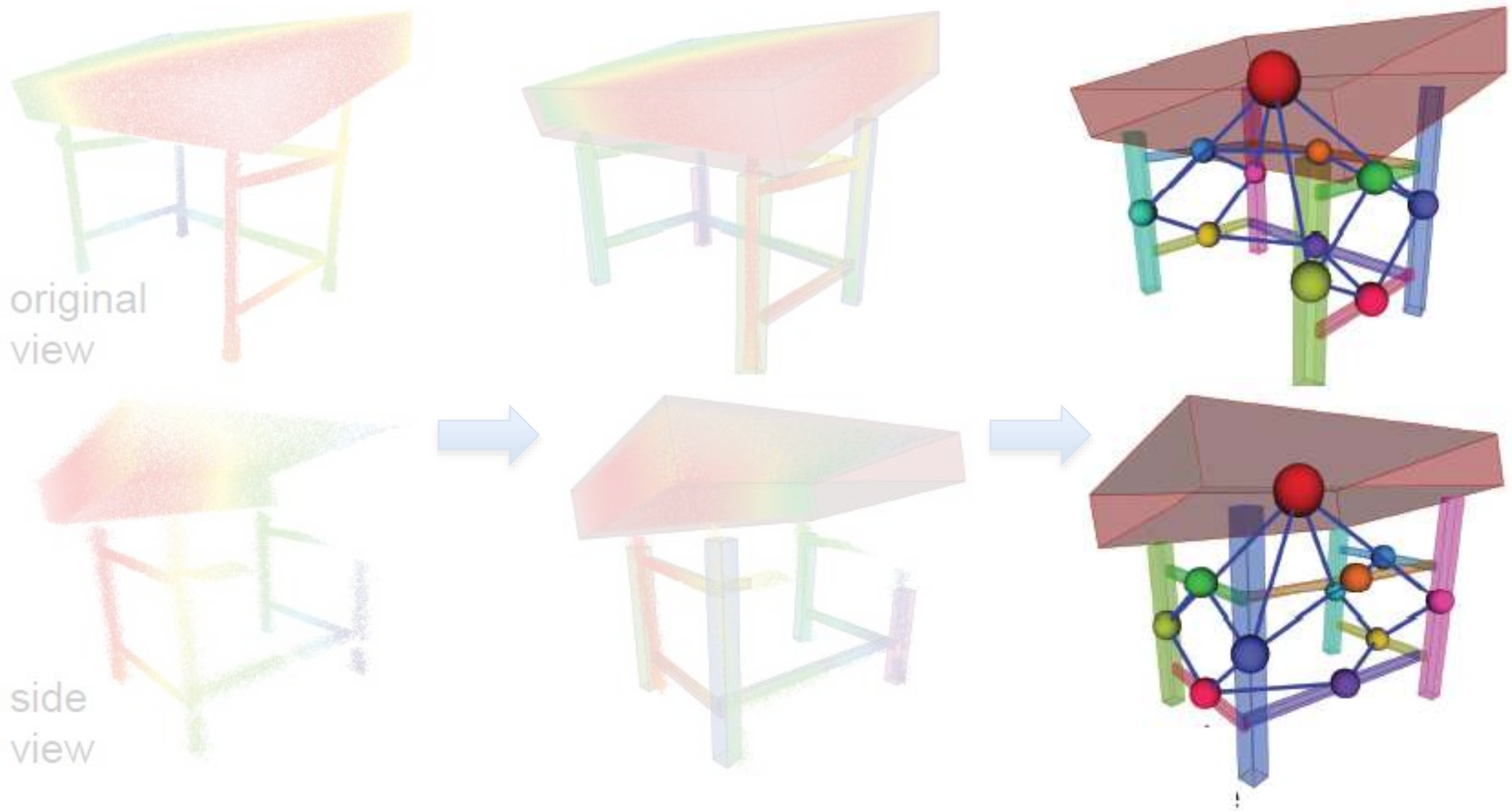


Input scan

Initial cuboids

Optimized cuboids +
recovered structure

Algorithm Overview



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Inferring Geometry and Relations

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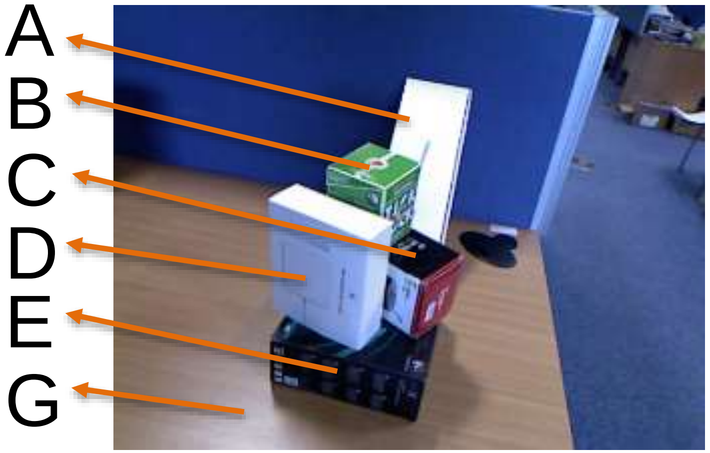
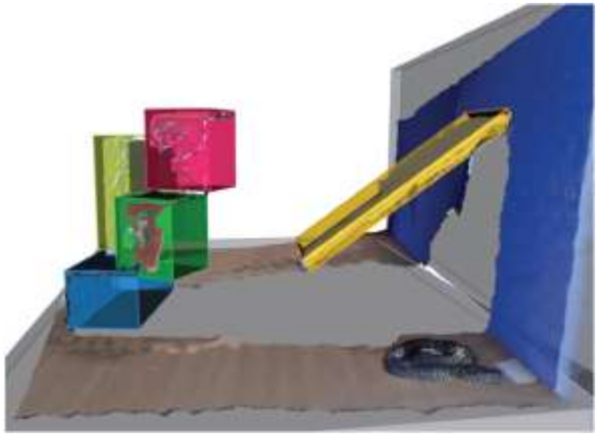
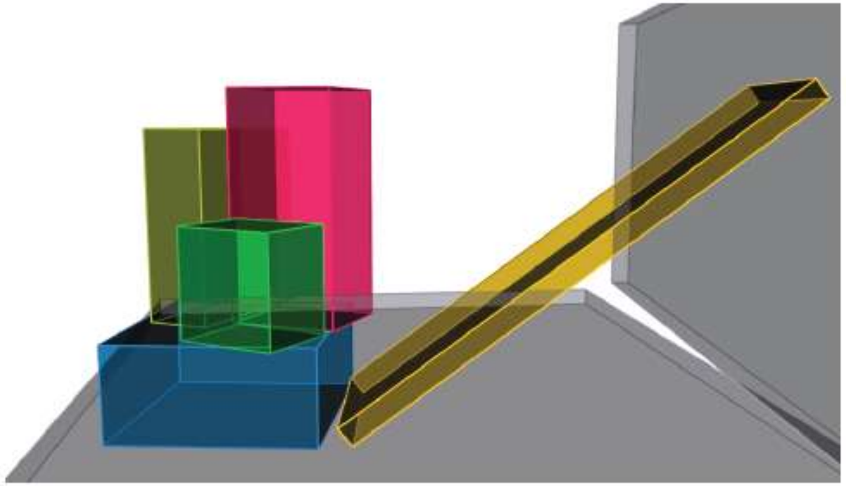
Key observation: relations are coupled with geometry



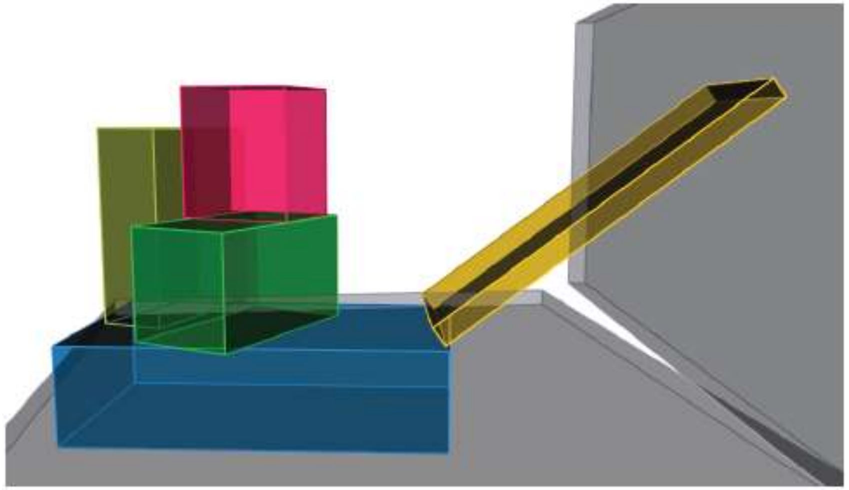


G supports A & E;
E supports B & C & D



Optimized geometry

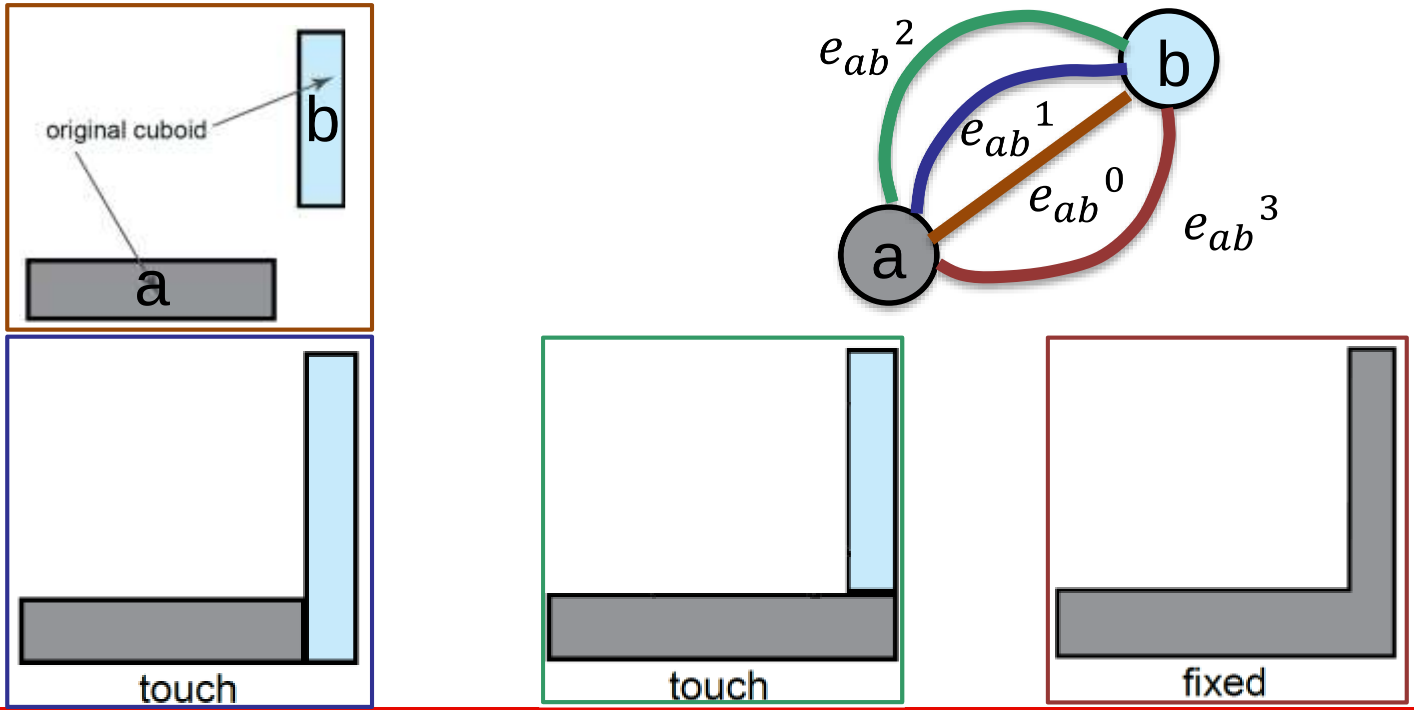
G supports E;
E supports A & C & D;
C supports B



Optimized geometry

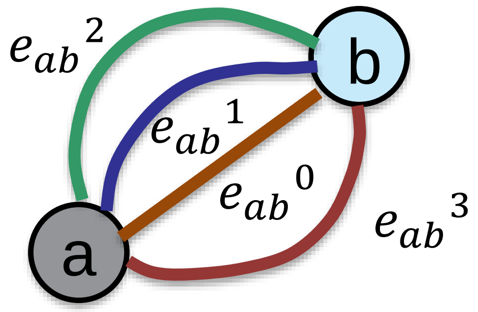
Inferring Geometry and Relations

- Encode the discrete interaction among the cuboids as a multi-connection graph $G \coloneqq (V, E)$
  - V: cuboids;
  - E: contact types (and corresponding cuboid extensions)



Inferring Geometry and Relations

- Optimization formulation
  - Edge selection problem
  - $x_{ij}{}^{k} = 1$: edge type $e_{ij}{}^{k}$ selected;
  - $x_{ij}{}^{k} = 0$: not selected.
  - Goal: Physically stable arrangement of cuboids with minimal number of fixed contacts
  - $\min_{\{x_{ij}{}^{k}\}} \#(e_{ij}{}^{k} = \text{fixed joint})$
  - Constraints: $\sum_k x_{ij}{}^{k} = 1$

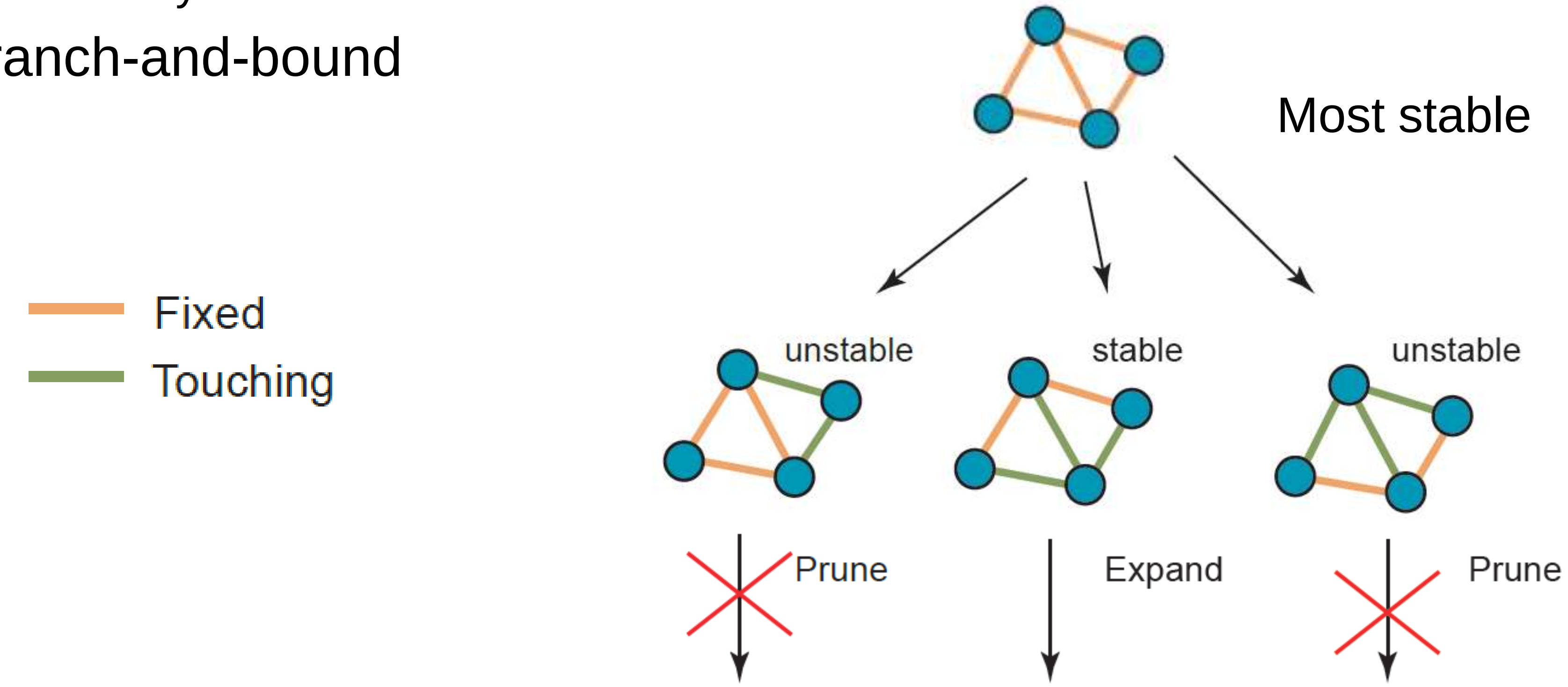


Inferring Geometry and Relations

- Pruning the solution space
  - Pre-pruning
    - Penetration check
    - Visibility check

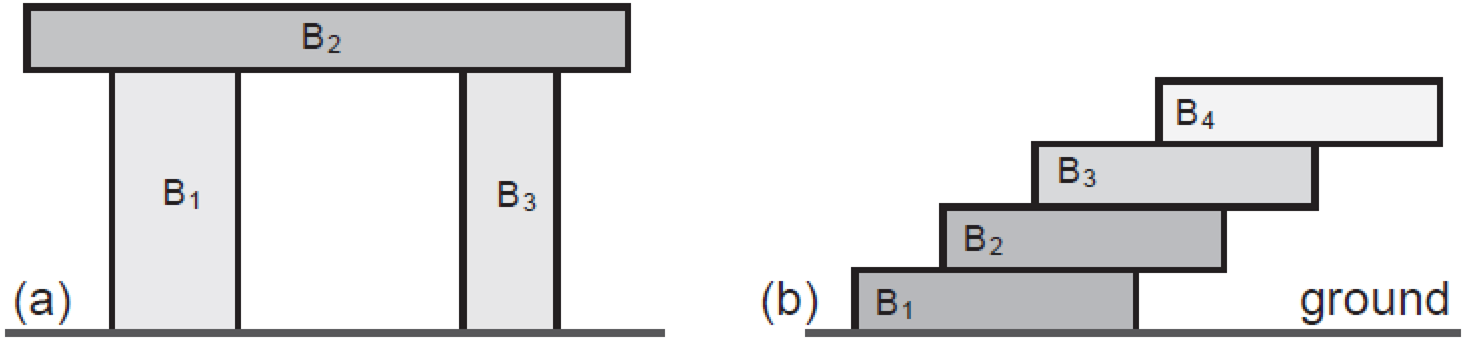
Inferring Geometry and Relations

- Pruning the solution space
  - Pre-pruning
    - Penetration check
    - Visibility check
  - Branch-and-bound



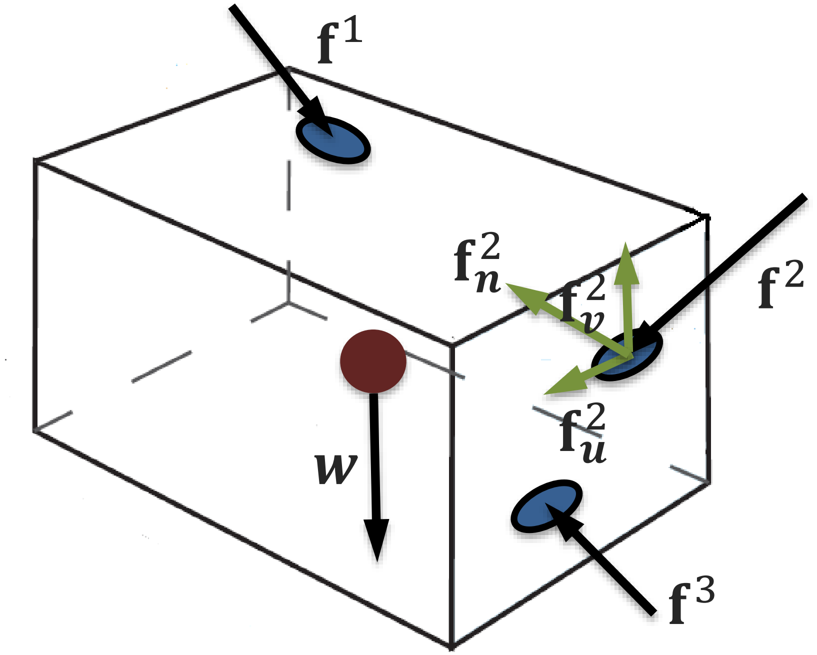
Inferring Geometry and Relations

- Assessing physical stability
  - Local reasoning is not enough



Inferring Geometry and Relations

- Measuring global stability through static equilibrium
  - The net force and torque should be zero
  - Decompose the contact forces to compression forces and friction forces
  - $\mathrm{E}_s(\mathrm{A}) := \min_{\mathbf{f}} \|\mathbf{Df} + \mathbf{w}\|^2 \ s.t. \ \mathbf{f}_n^i \geq 0$ and $|\mathbf{f}_u^i|, |\mathbf{f}_v^i| < \mu \mathbf{f}_n^i$



- Ground truth
- Metrics
- Robustness
- Validity
- Applications

Overview

- Ground truth
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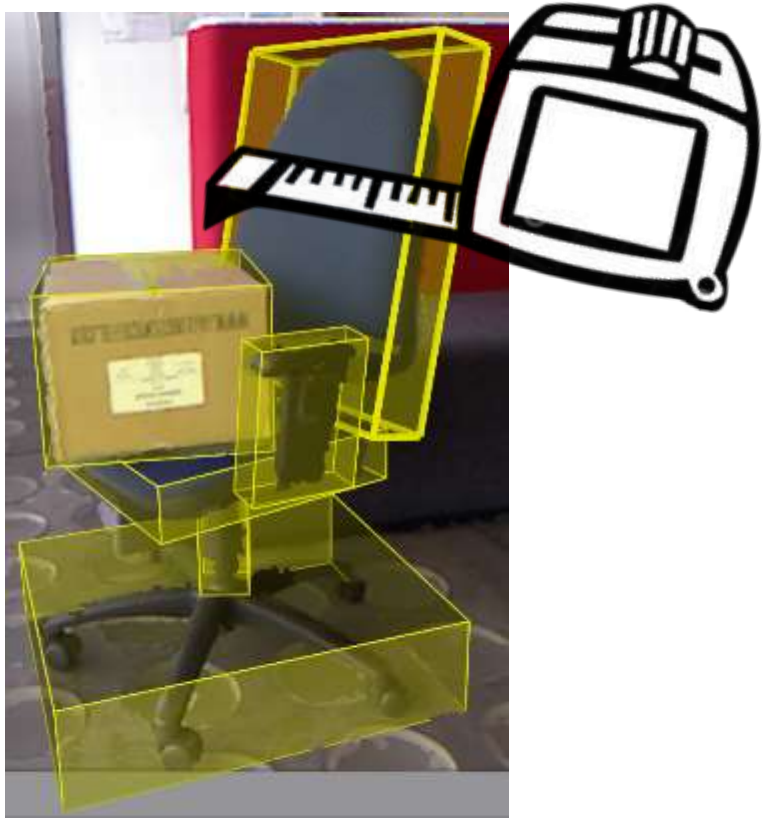
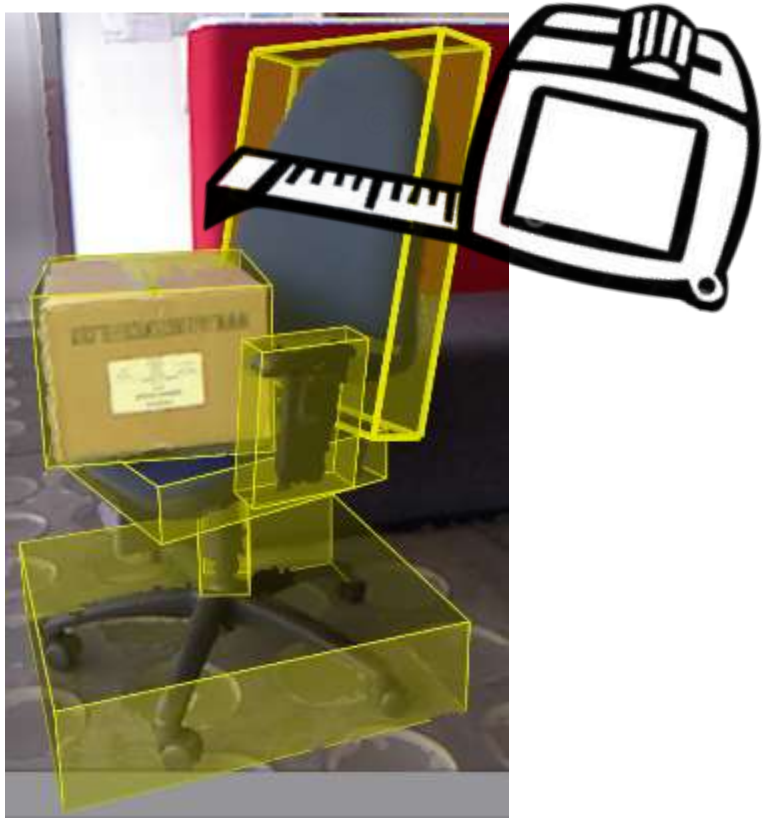
Evaluation – Ground Truth

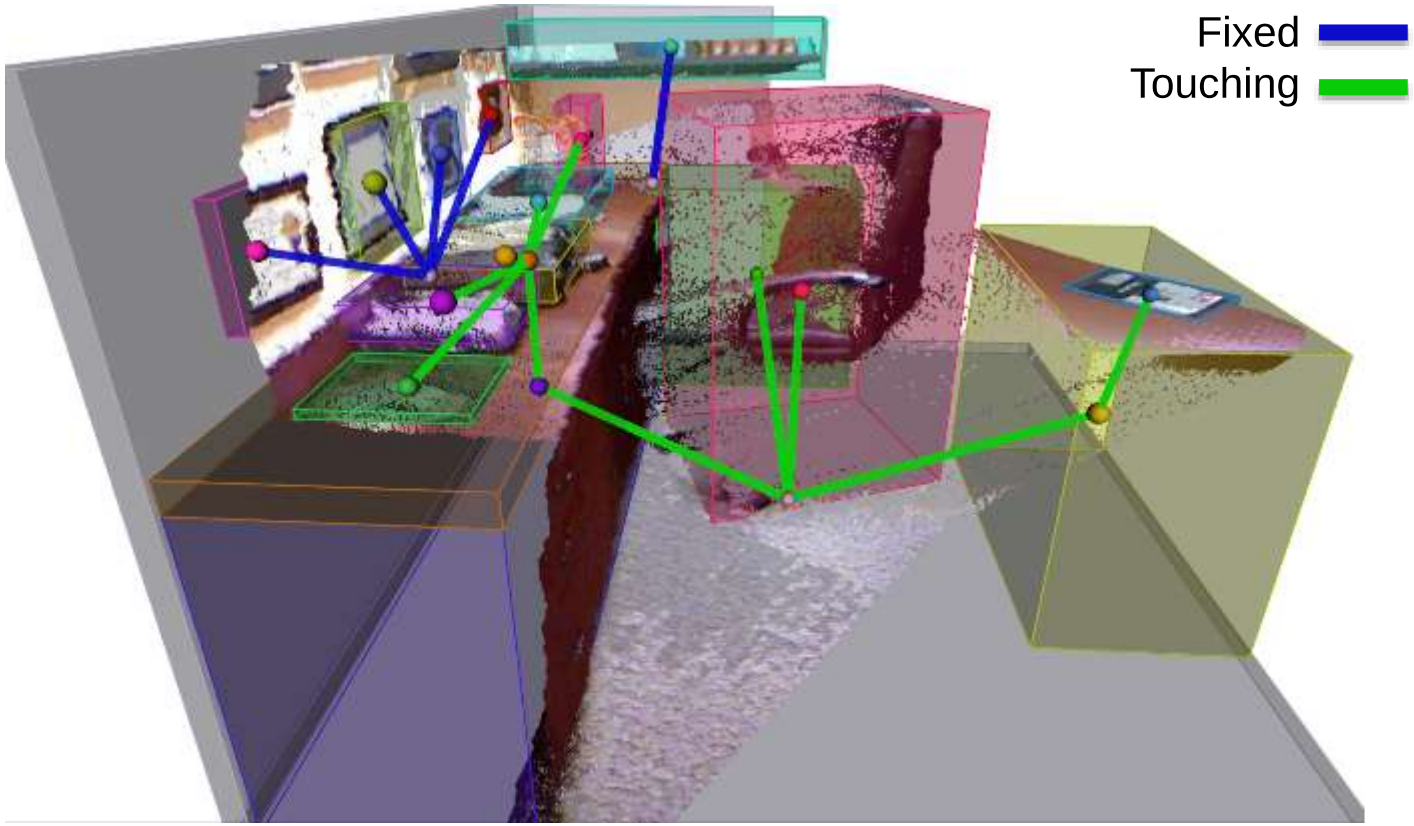
Evaluation – Ground Truth



- 20 scenes
- High occlusion
- 3 dimensions measured by hand

Evaluation – Ground Truth



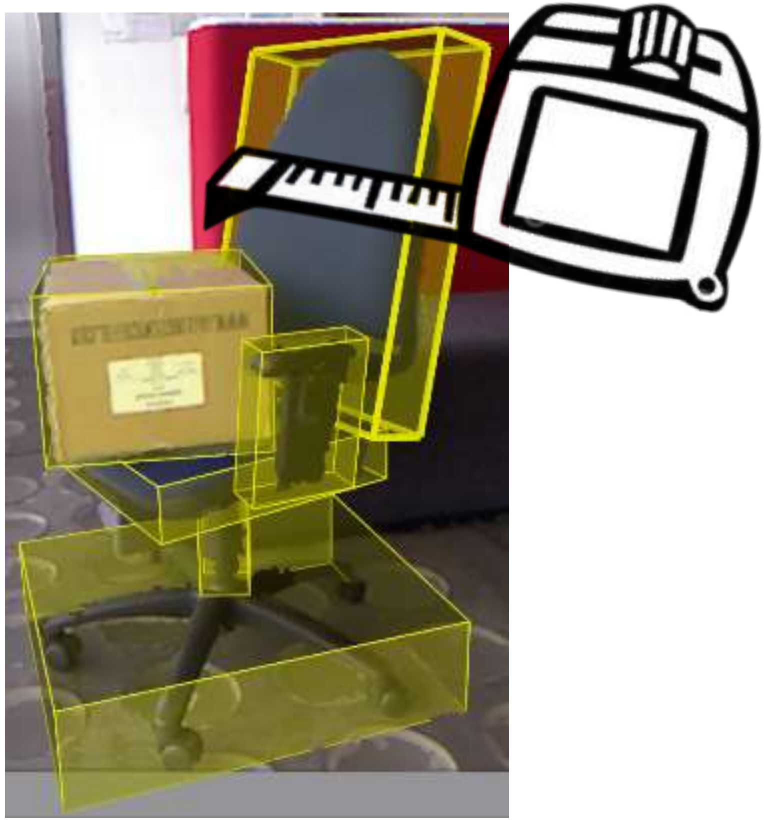


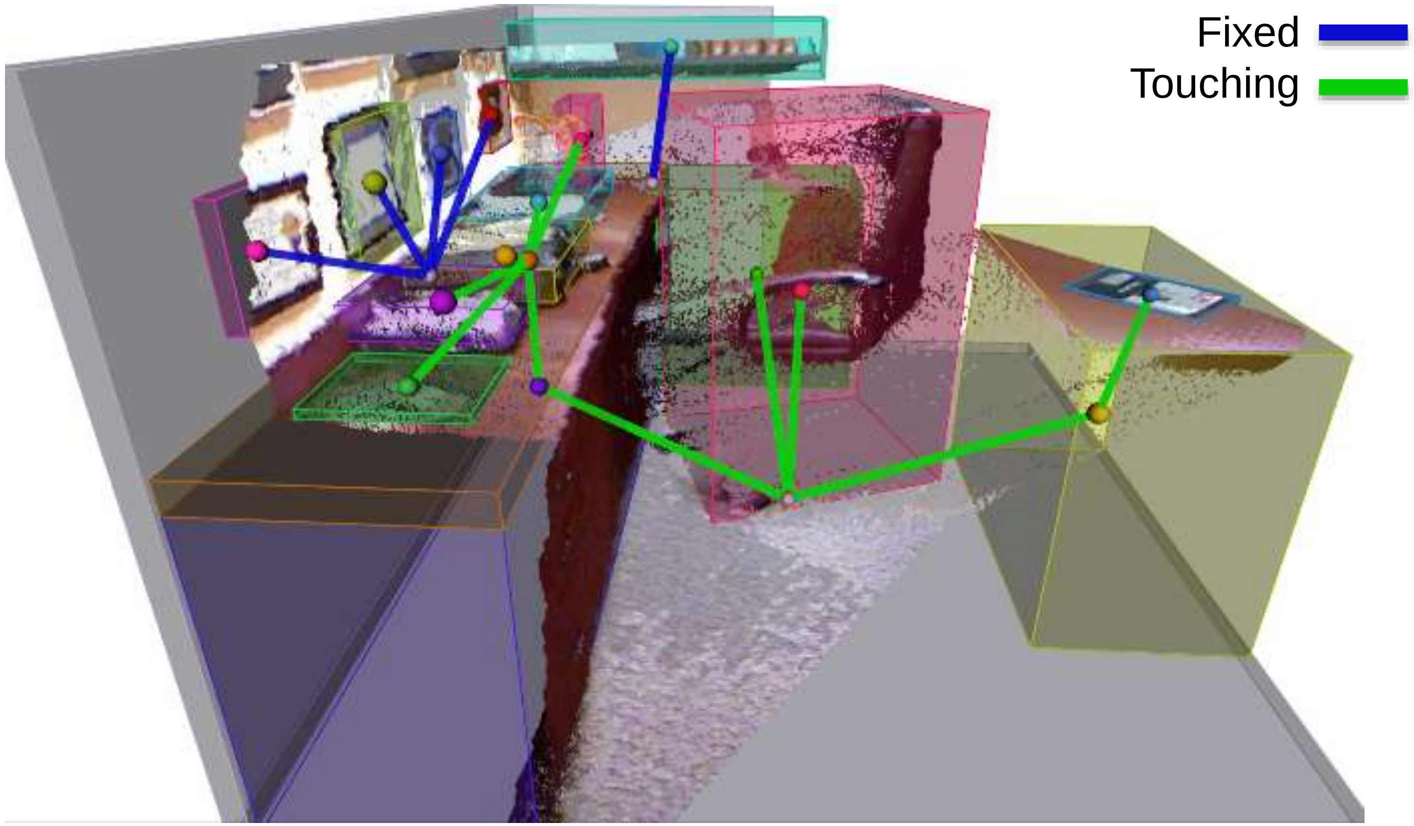
- 20 scenes
- High occlusion
- 3 dimensions measured by hand

- 700 scenes (NYU2)
- Medium occlusion

- Cuboids, floors, walls
- Support graph
- Initialization

Evaluation – Ground Truth





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Online: 720 scenes, annotator tool

- Ground truth
- Metrics
- Robustness
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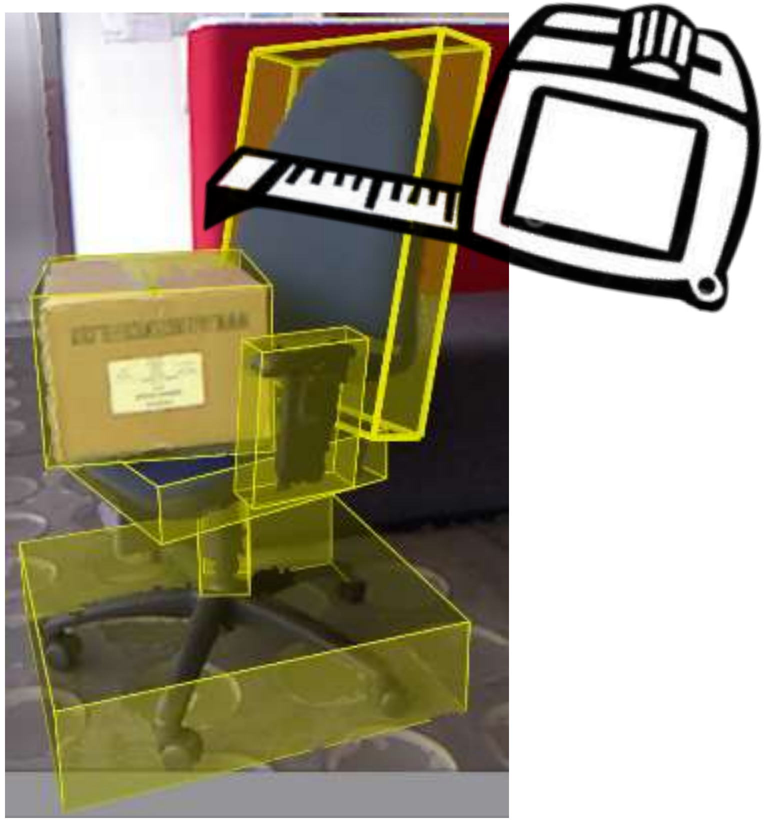
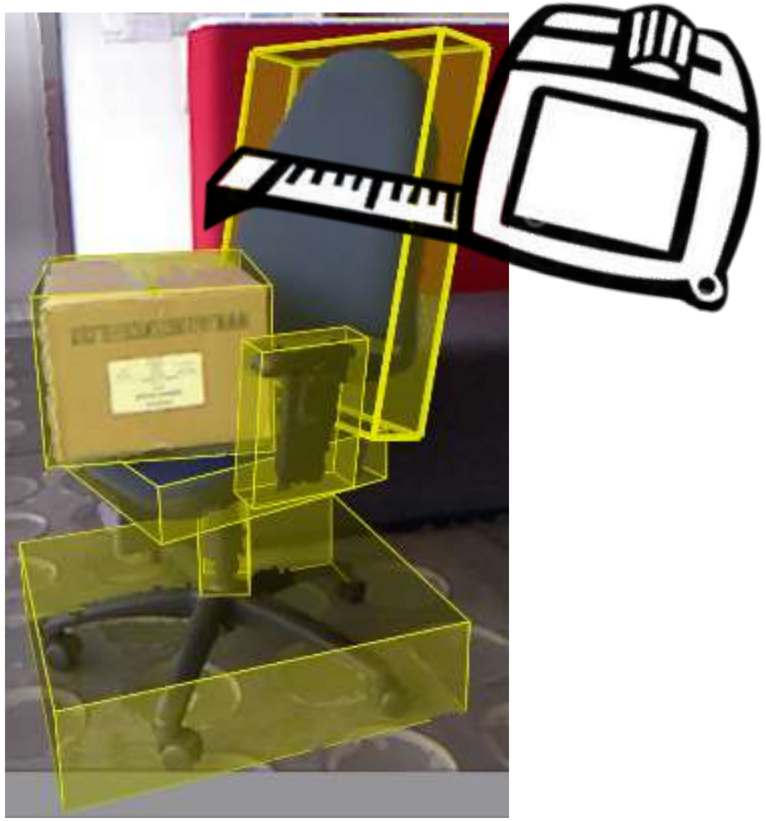
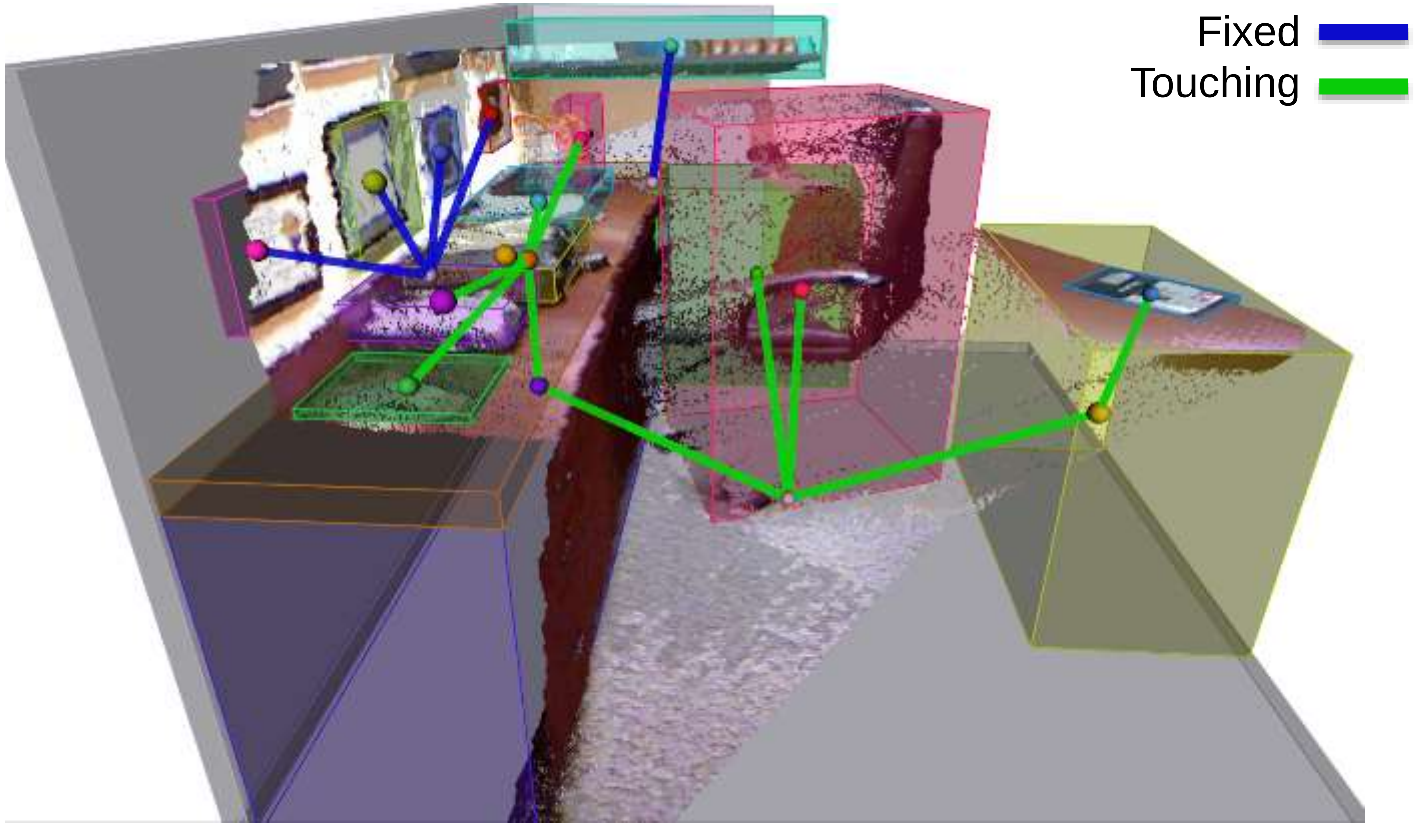
Evaluation – Metrics



- Approximation error
- L_1-norm

Evaluation – Metrics

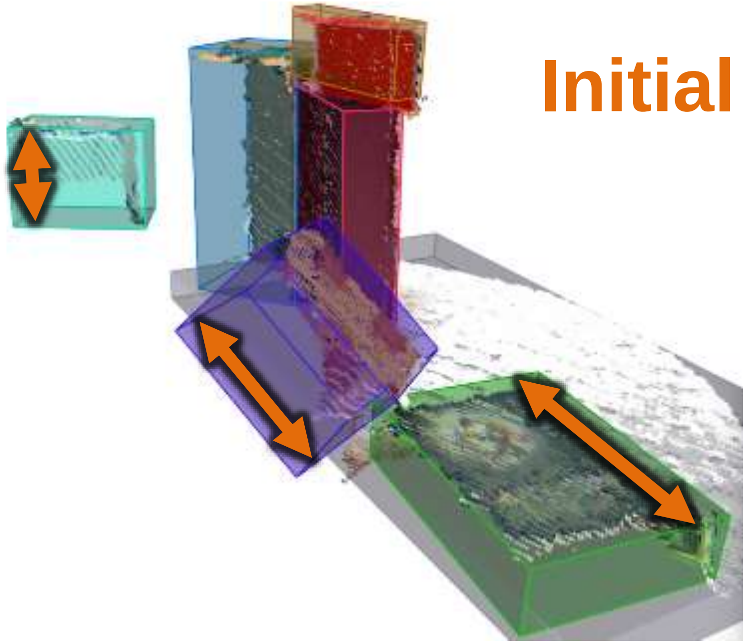




- Approximation error
- L_1-norm

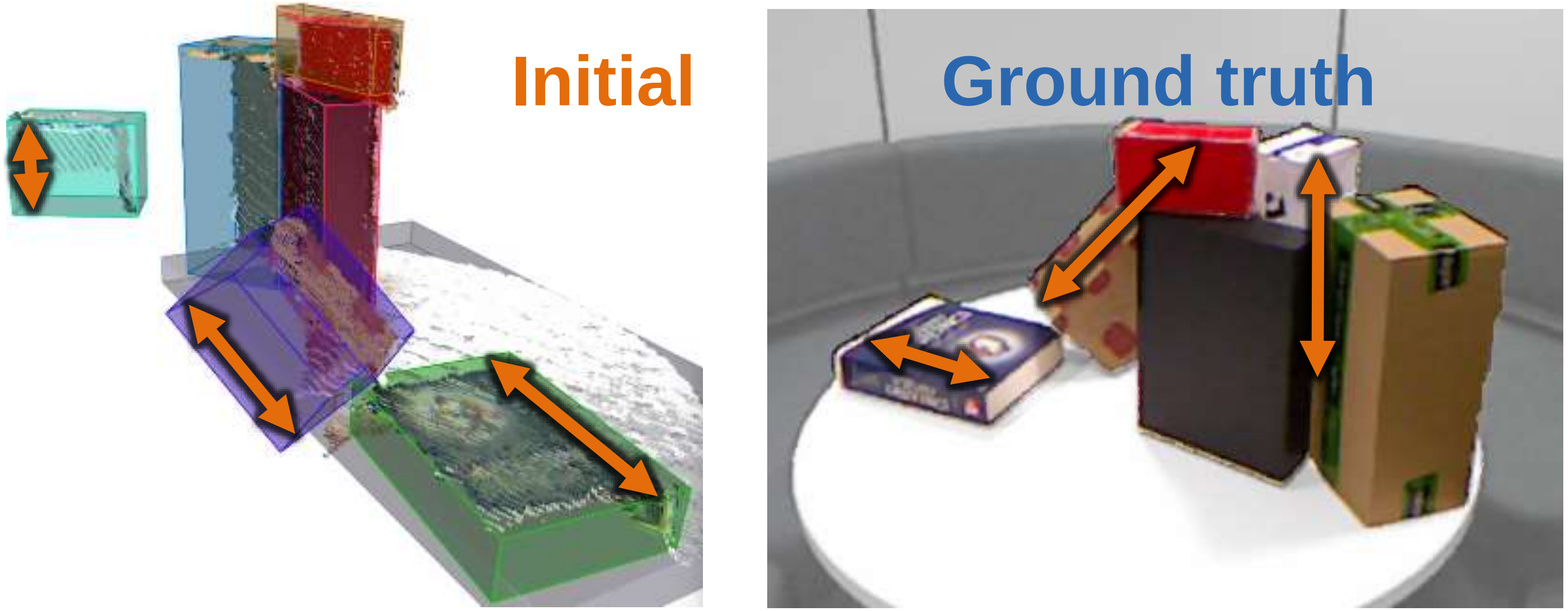
- Correctness of structure graph
- F_1 score

Evaluation – Approximation error



Initial

Evaluation – Approximation error



$$\{err_i^{init}\}$$

Evaluation – Approximation error

$\{err_i^{init}\}$ $\{err_i^{optimized}\}$

Evaluation – Approximation error

$$\{err_i^{init}\} \qquad \{err_i^{optimized}\}$$

$$err_i^{init} - err_i^{optimized} \overset{?}{>} 5\%$$

Evaluation – Approximation error

$\{err_i^{init}\}$ $\{err_i^{optimized}\}$

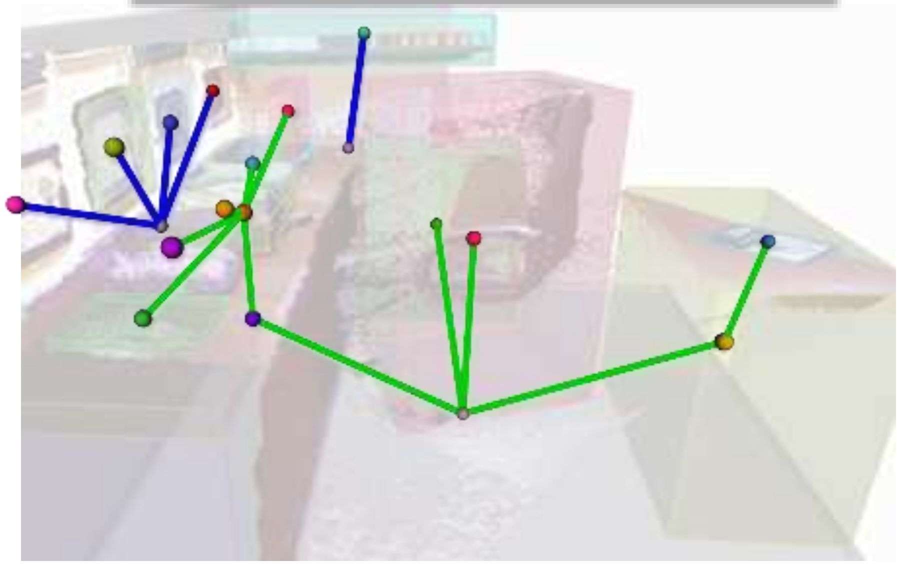
$$err_i^{init} - err_i^{optimized} \overset{?}{>} 5\%$$

35% 3%

Evaluation – F_1 score

RGB(-D)

Ground Truth



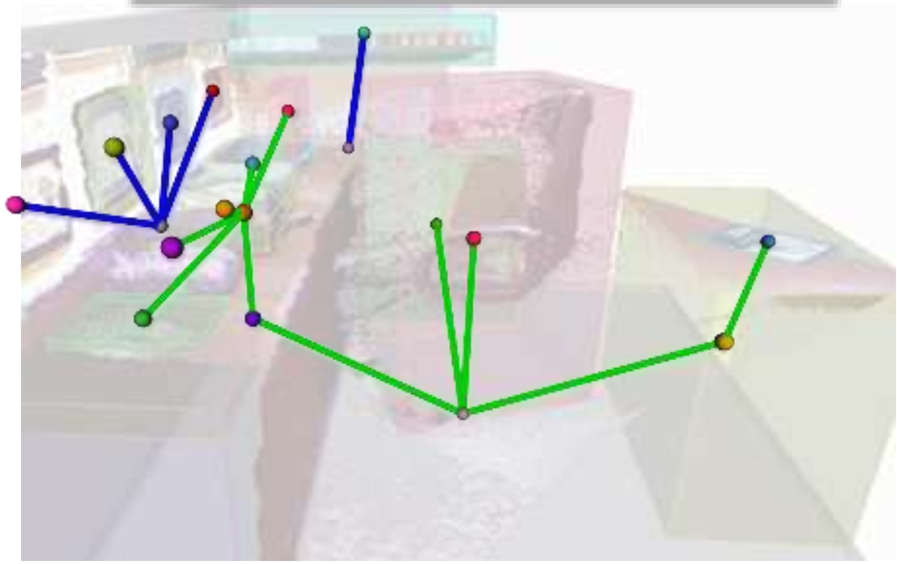
Fixed

Touching

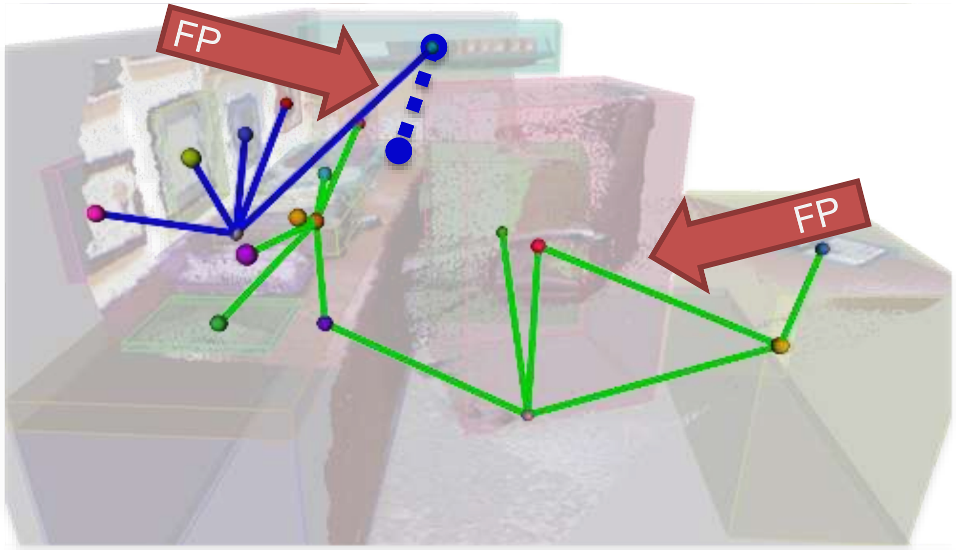
Evaluation – F_1 score

RGB(-D)

Ground Truth



Fixed
Touching

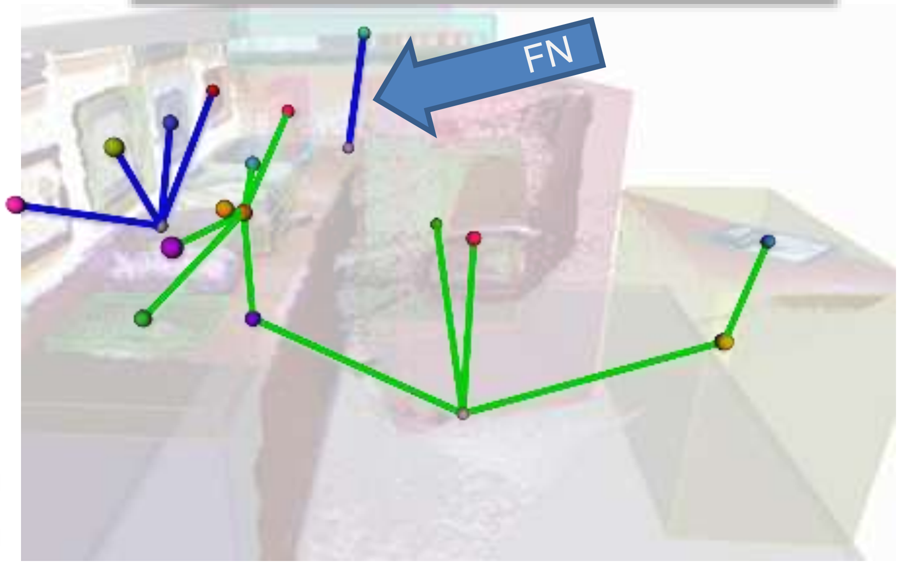


Output

Evaluation – F_1 score

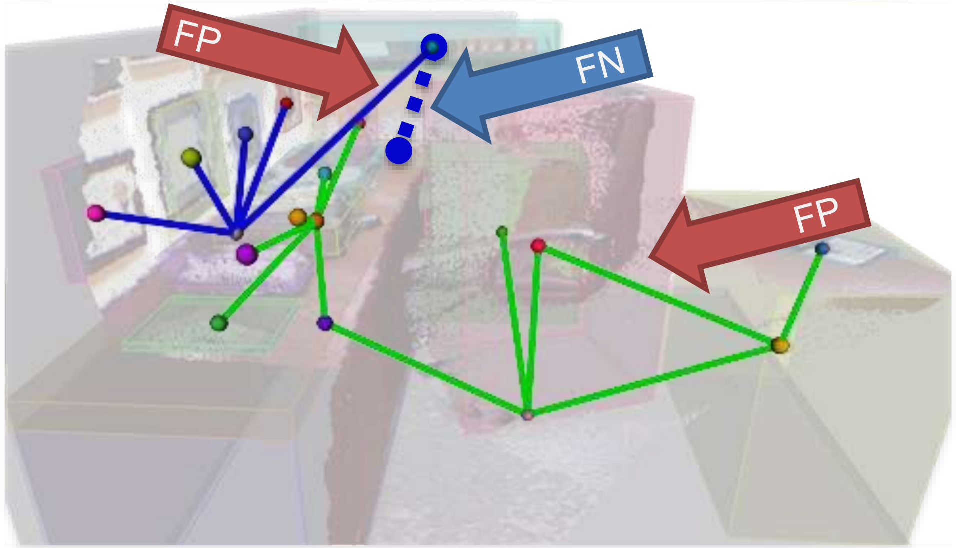
RGB(-D)

Ground Truth



Fixed

Touching



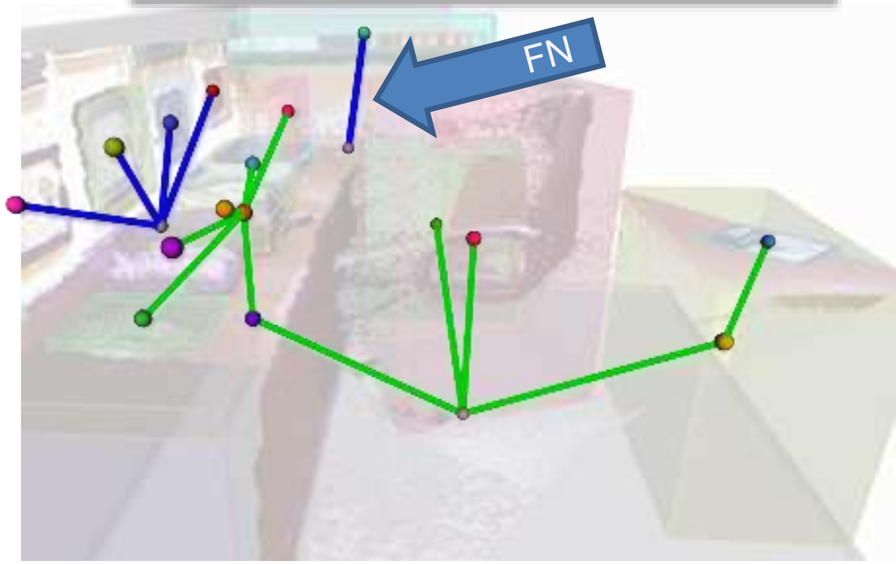
Output

Evaluation – F_1 score

RGB(-D)

Precision	$\frac{TP}{TP+FP}$
Recall	$\frac{TP}{TP+FN}$
$\mathbf{F_1}$	$200 \cdot \frac{Precision \cdot Recall}{Precision + Recall}$

Ground Truth



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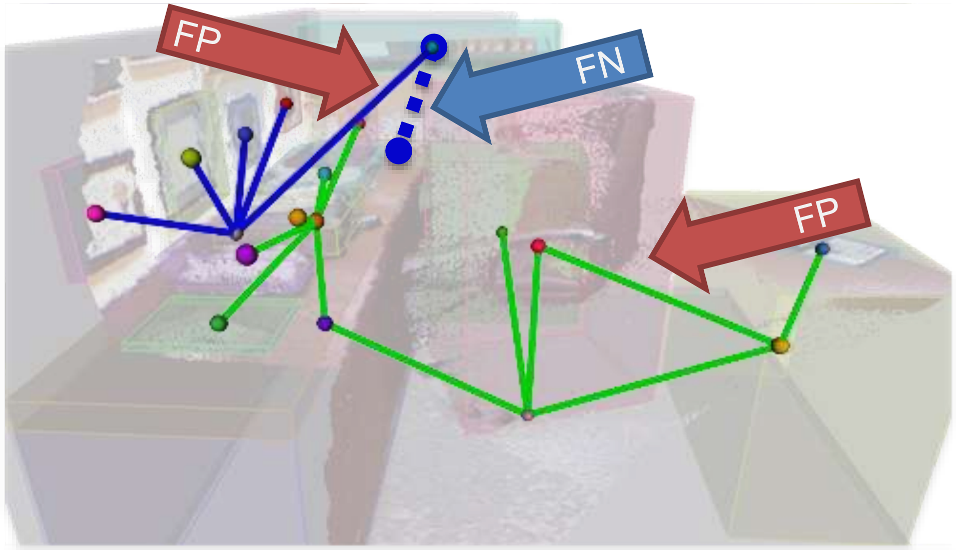


Fixed

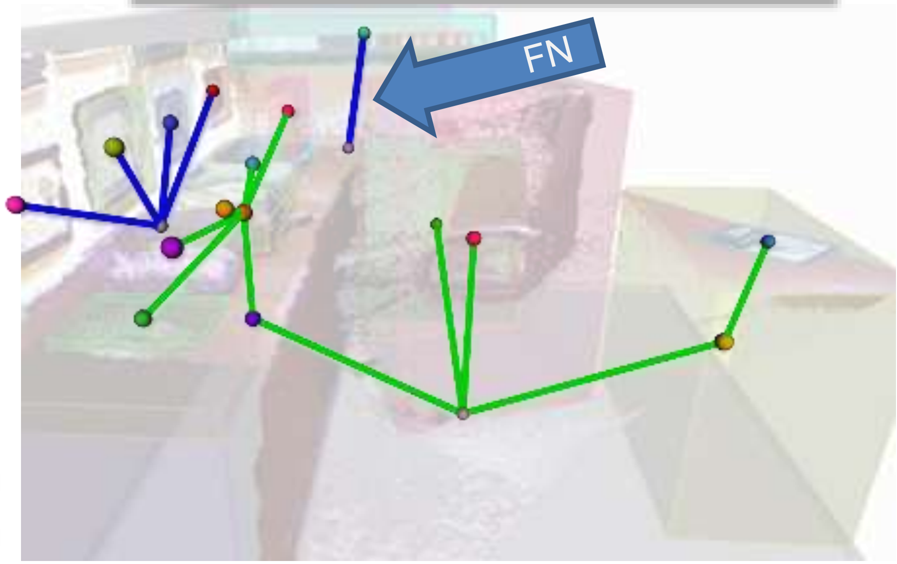
Touching

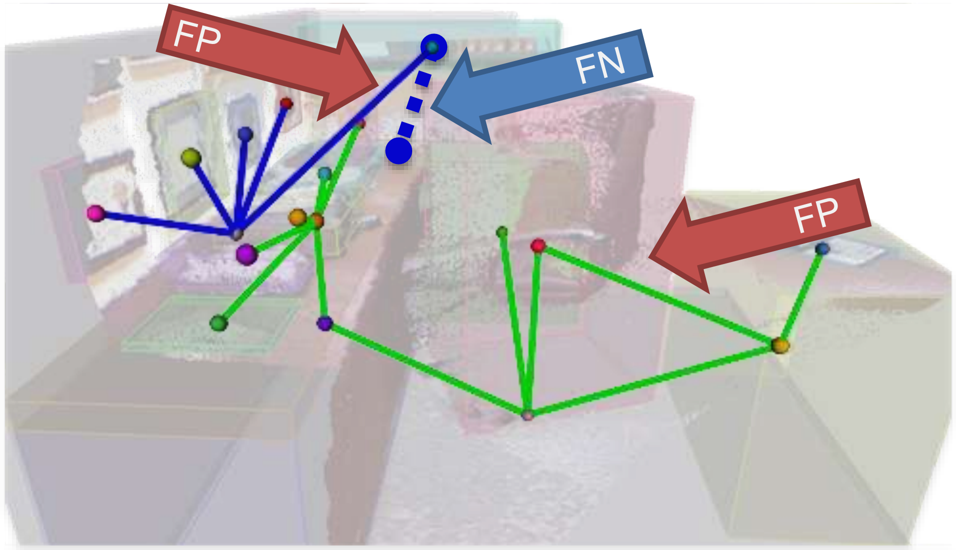
Evaluation – F_1 score

RGB(-D)

	#Scenes	Initial	Optimized
Synthetic	12	32.2	**87.2**
NYU2	700	40.0	**60.5**
Own	20	56.5	**95.9**
Kinfu	2	32.1	**89.7**

Ground Truth





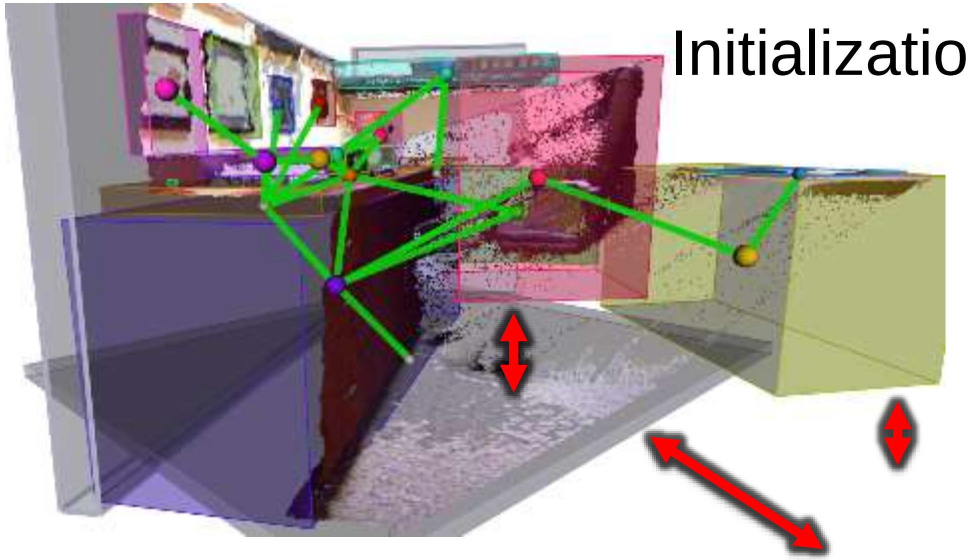
Output

Fixed
Touching

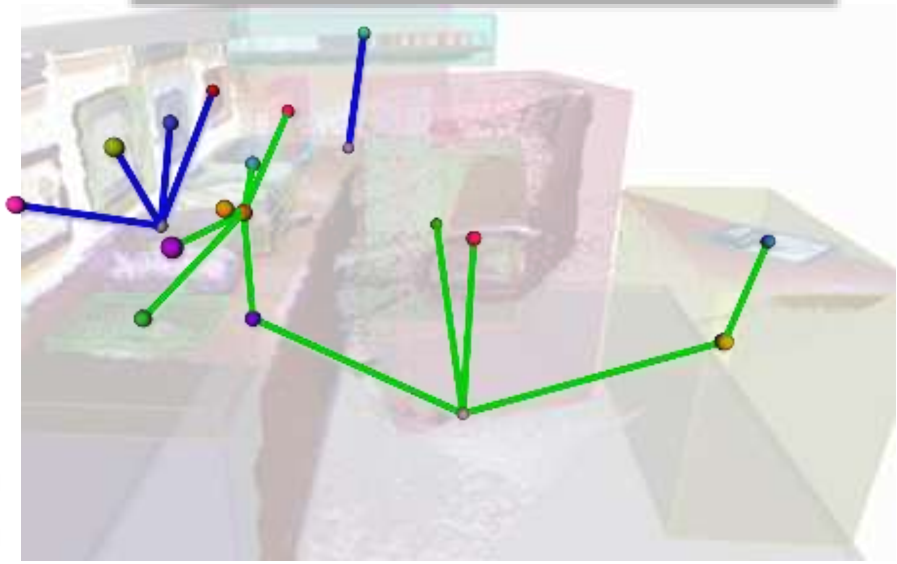
Evaluation – F_1 score

RGB(-D)

Initialization



Ground Truth



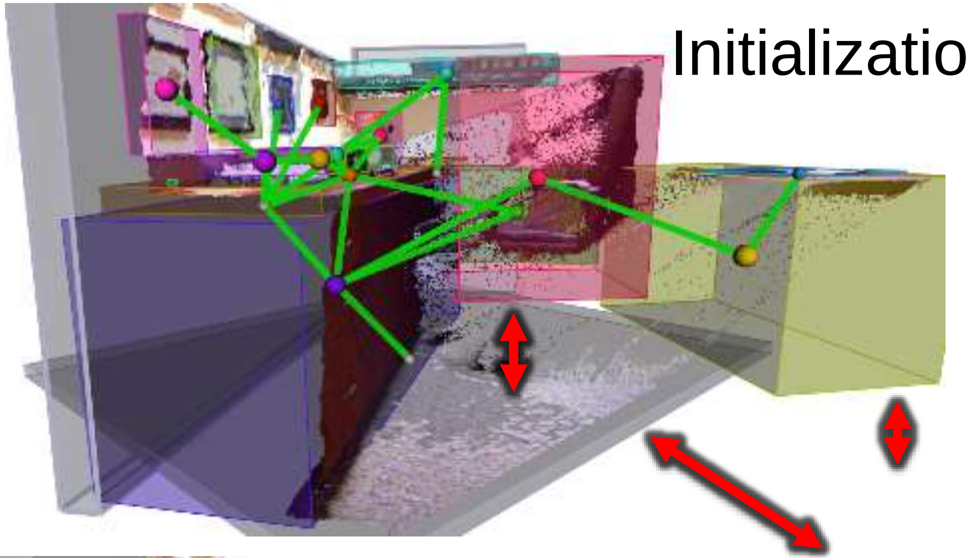
Fixed

Touching

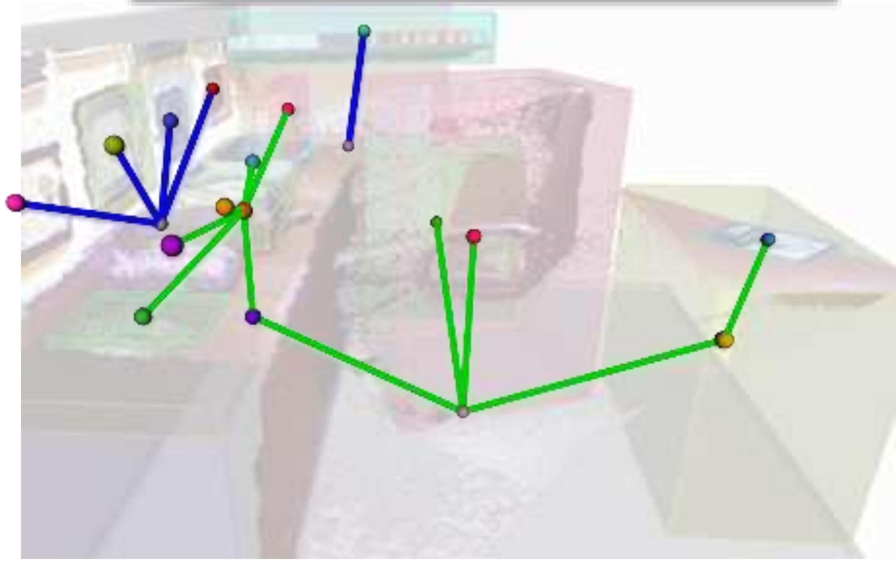
Evaluation – F_1 score

RGB(-D)

Initialization



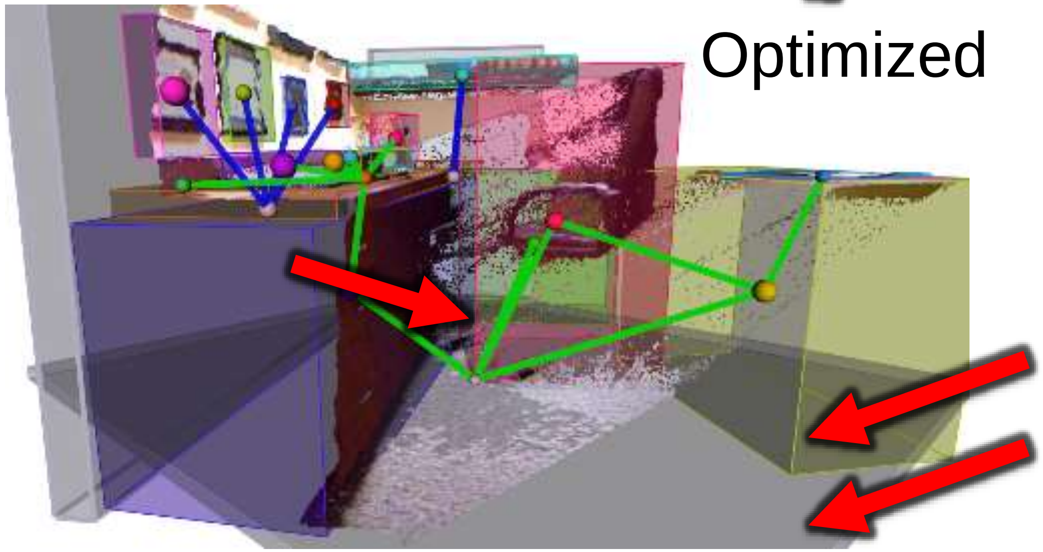
Ground Truth



Fixed

Touching

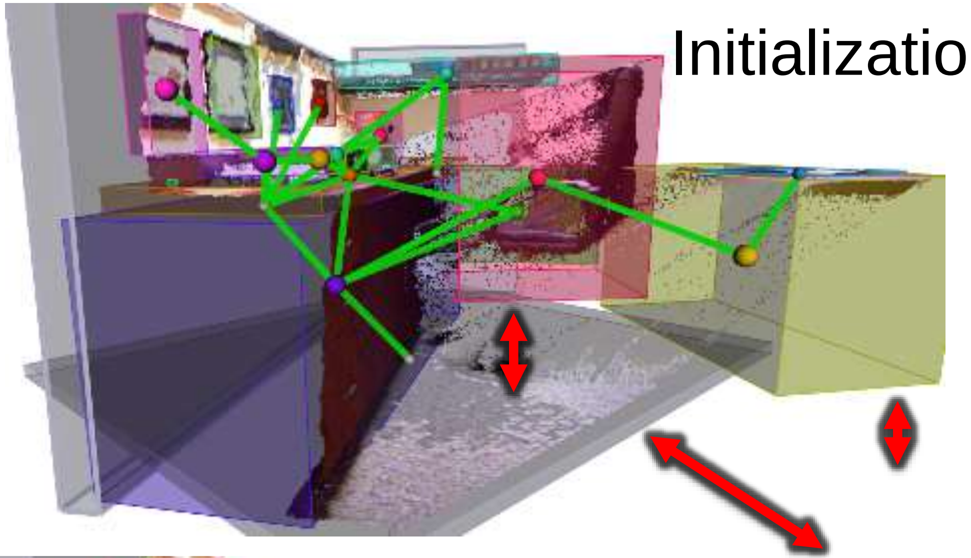
Optimized



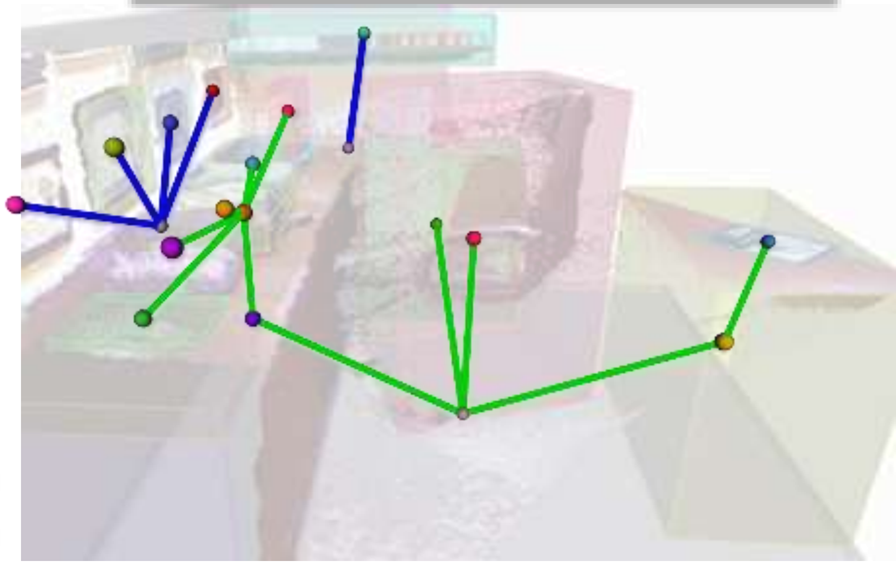
Evaluation – F_1 score

RGB(-D)

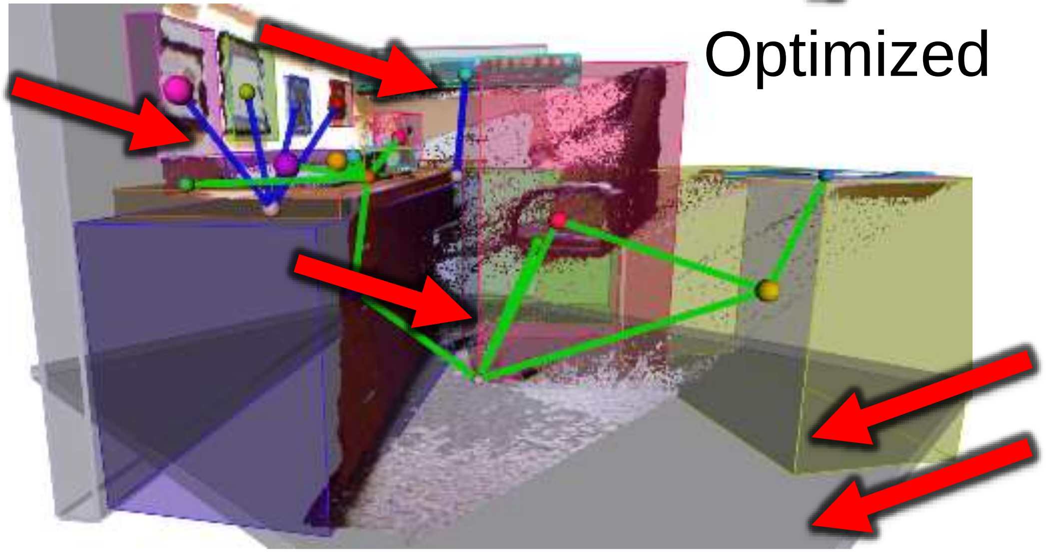
Initialization



Ground Truth



Optimized



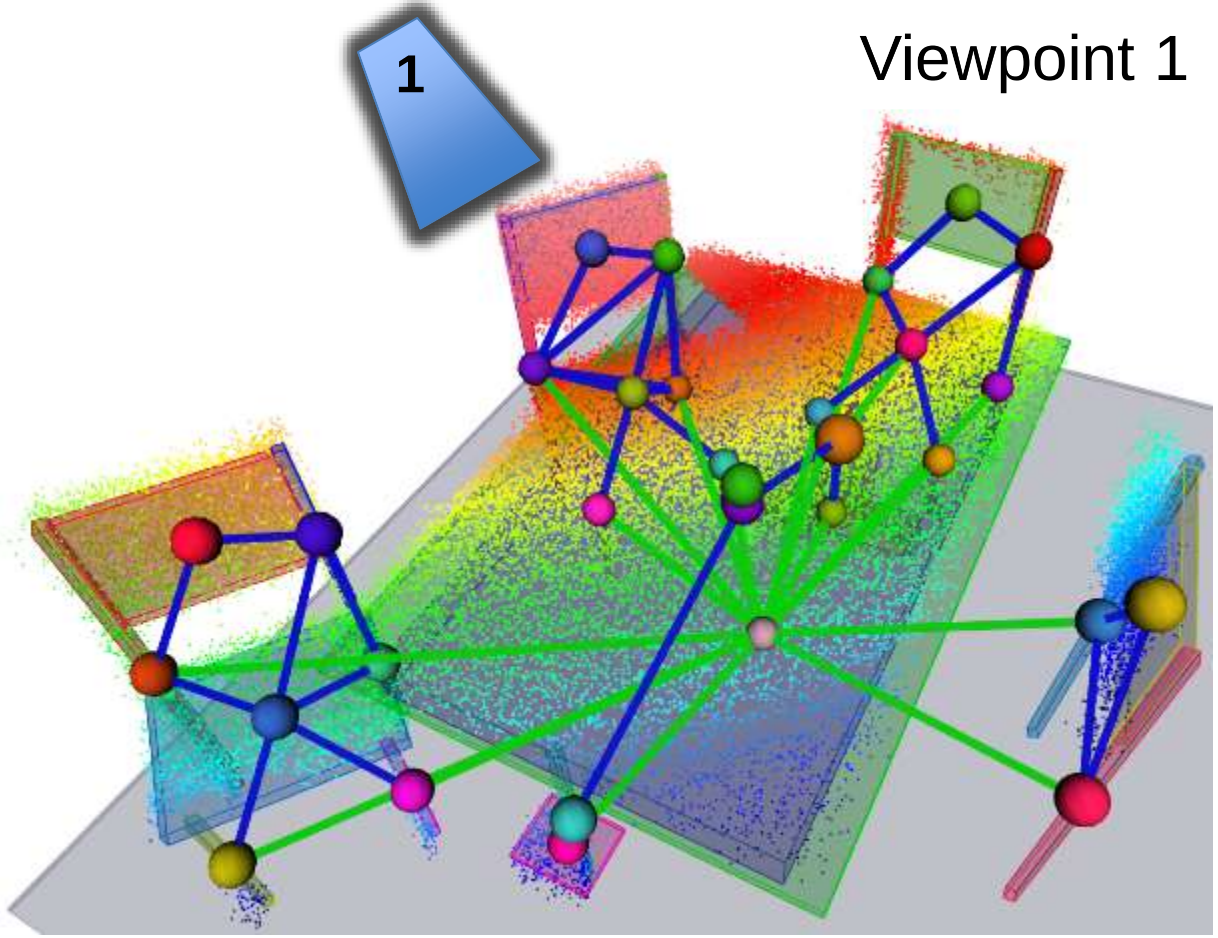
Fixed

Touching

Overview

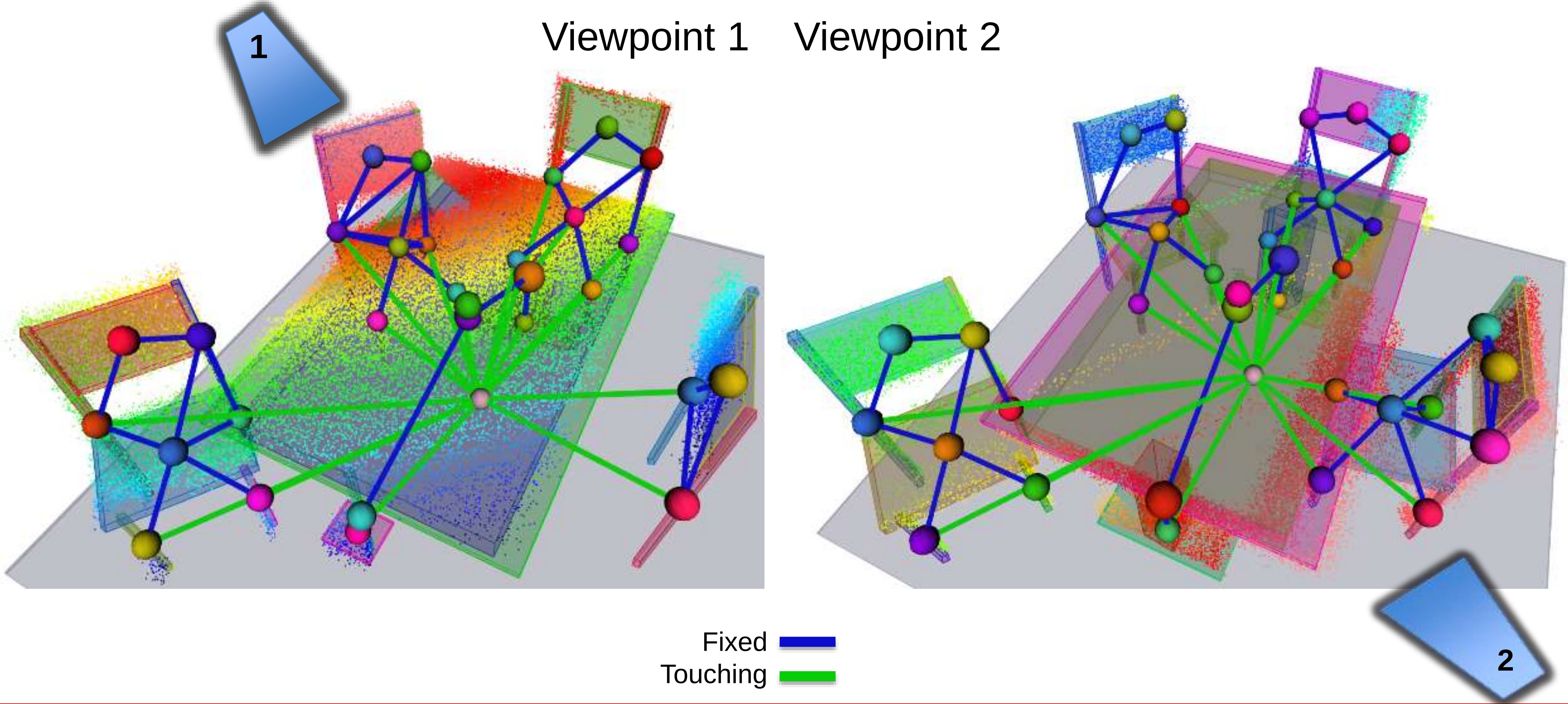
- Ground truth
- Metrics
- Robustness
- Validity
- Applications

Robustness to viewpoint

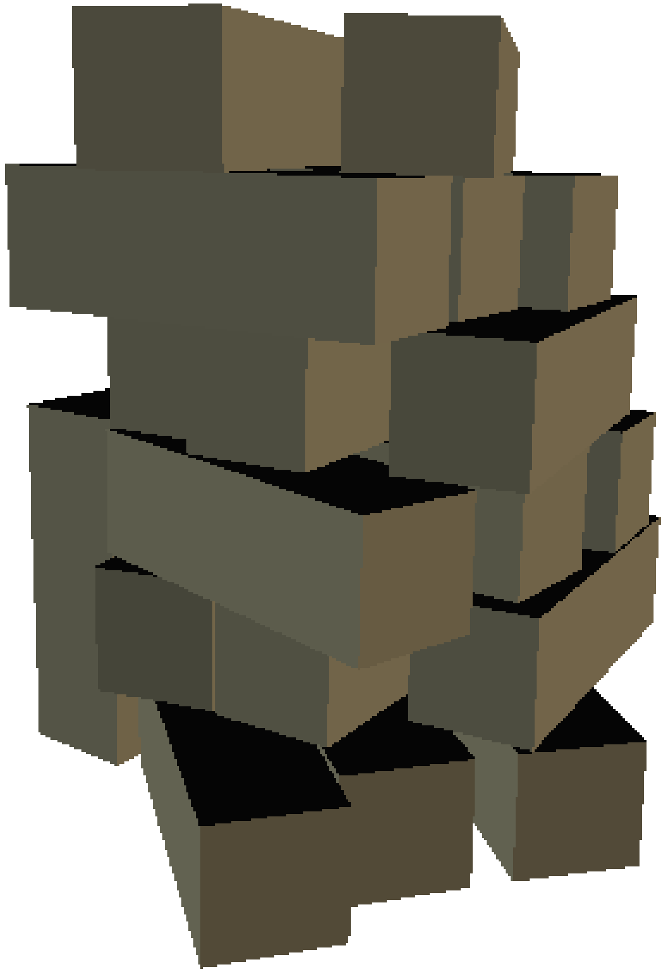


Fixed
Touching

Robustness to viewpoint

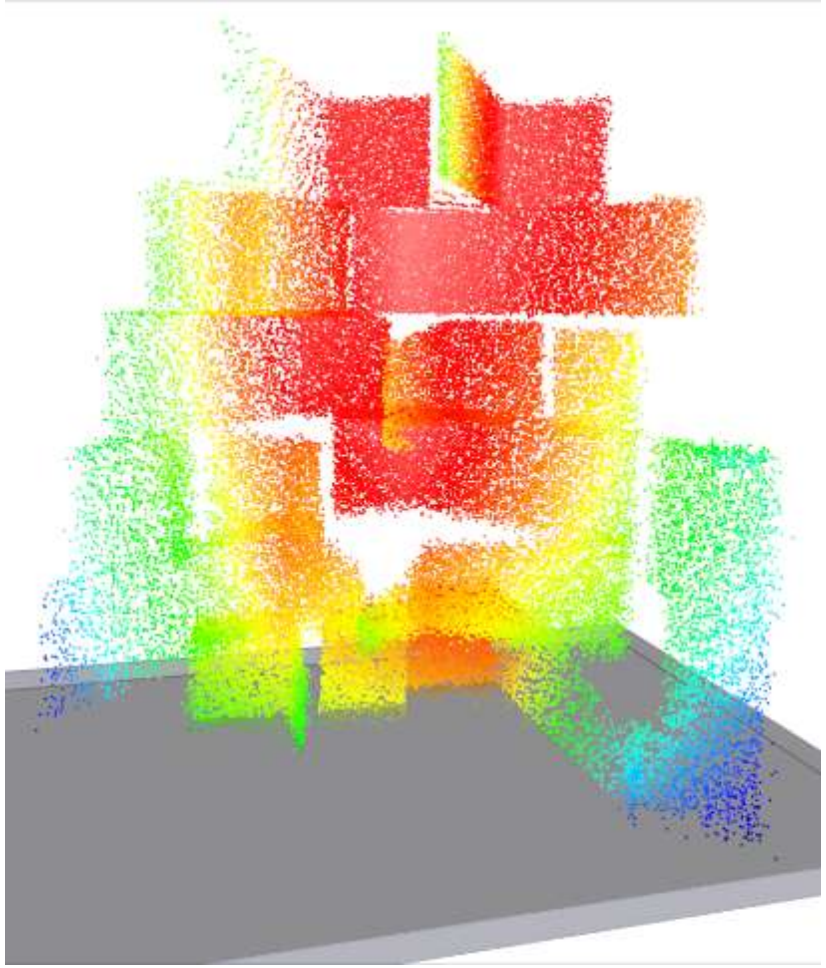


Robustness to scene complexity



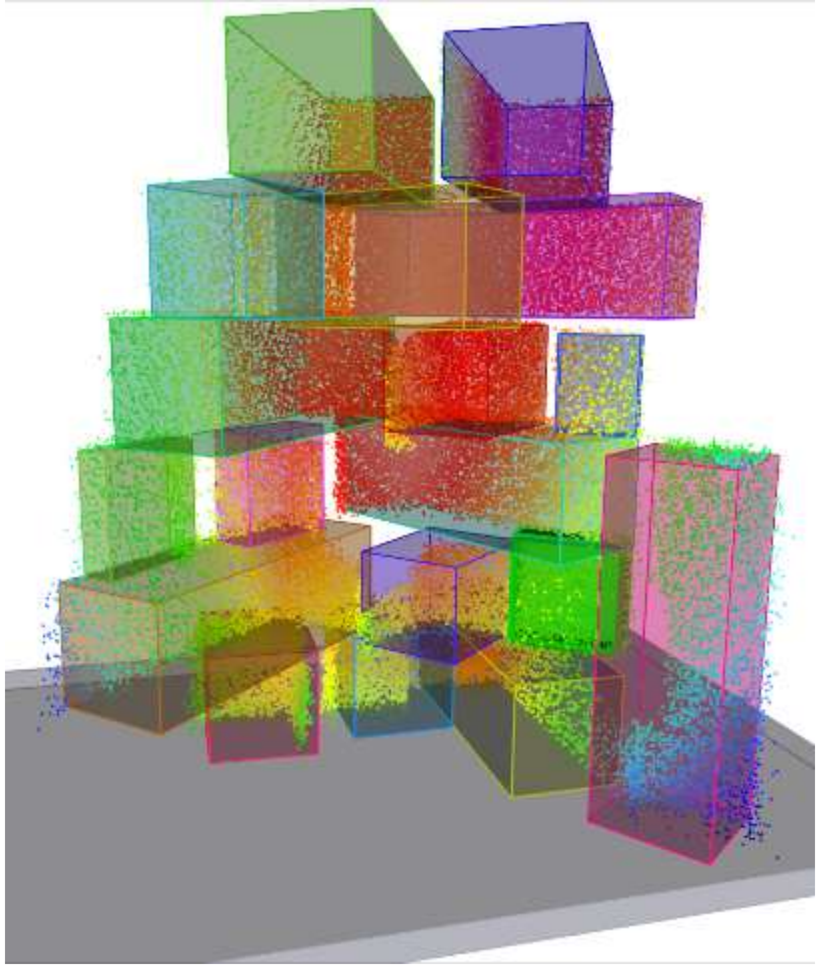
Input scene

Robustness to scene complexity



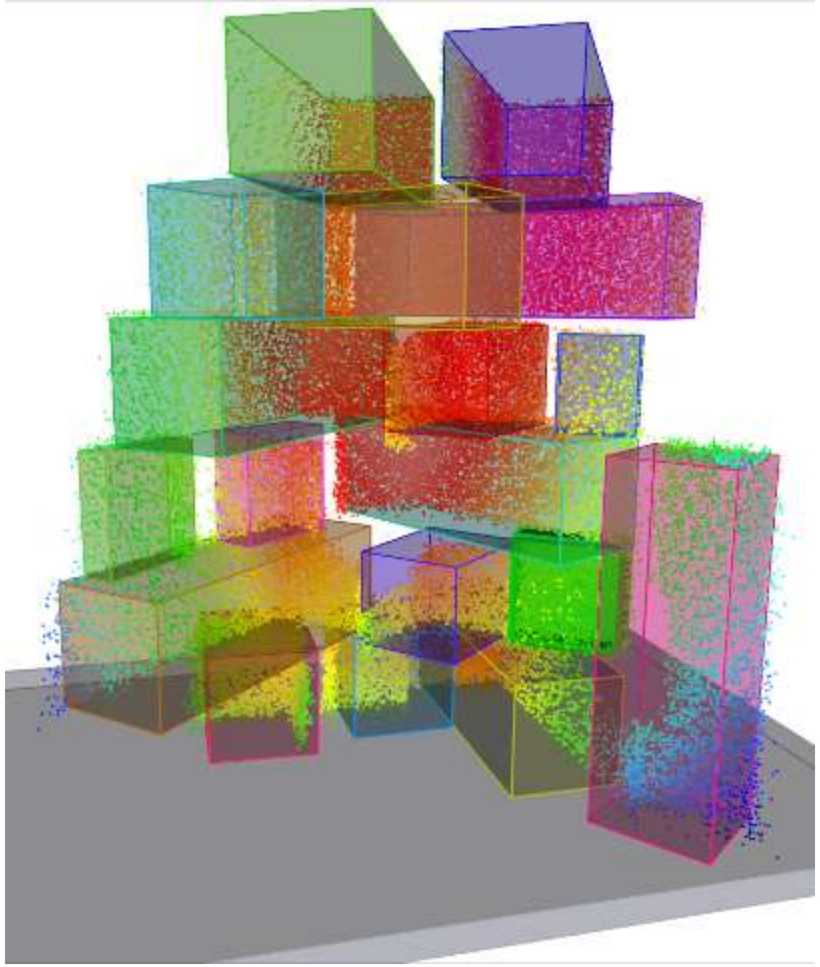
Input cloud (back view)

Robustness to scene complexity

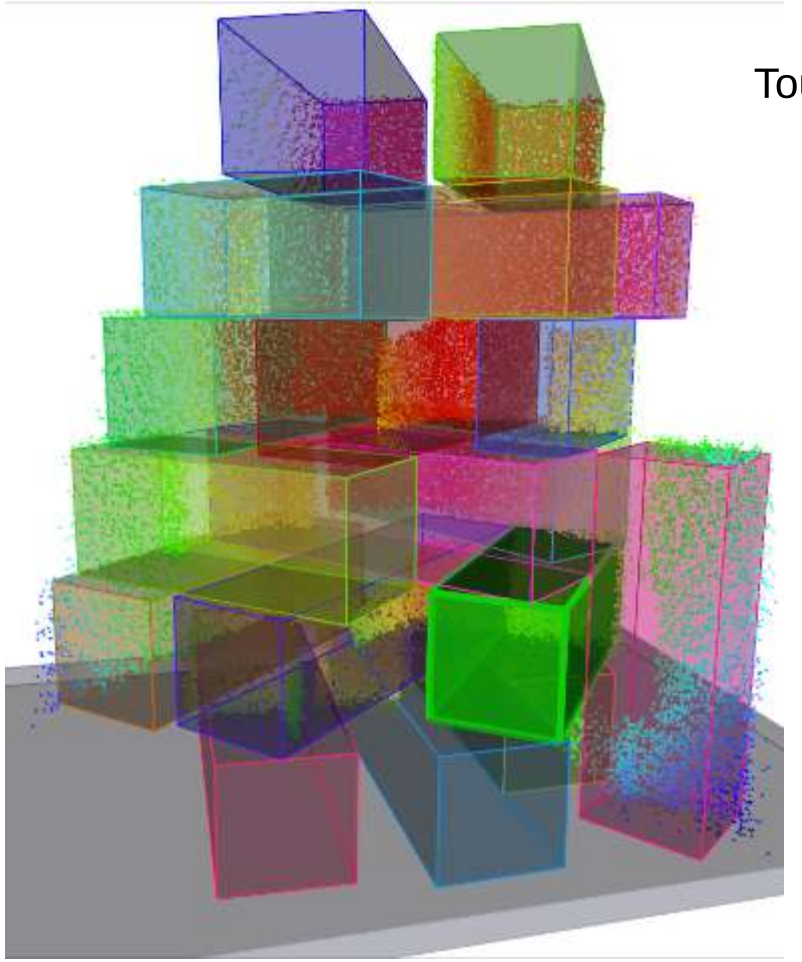


Initialization

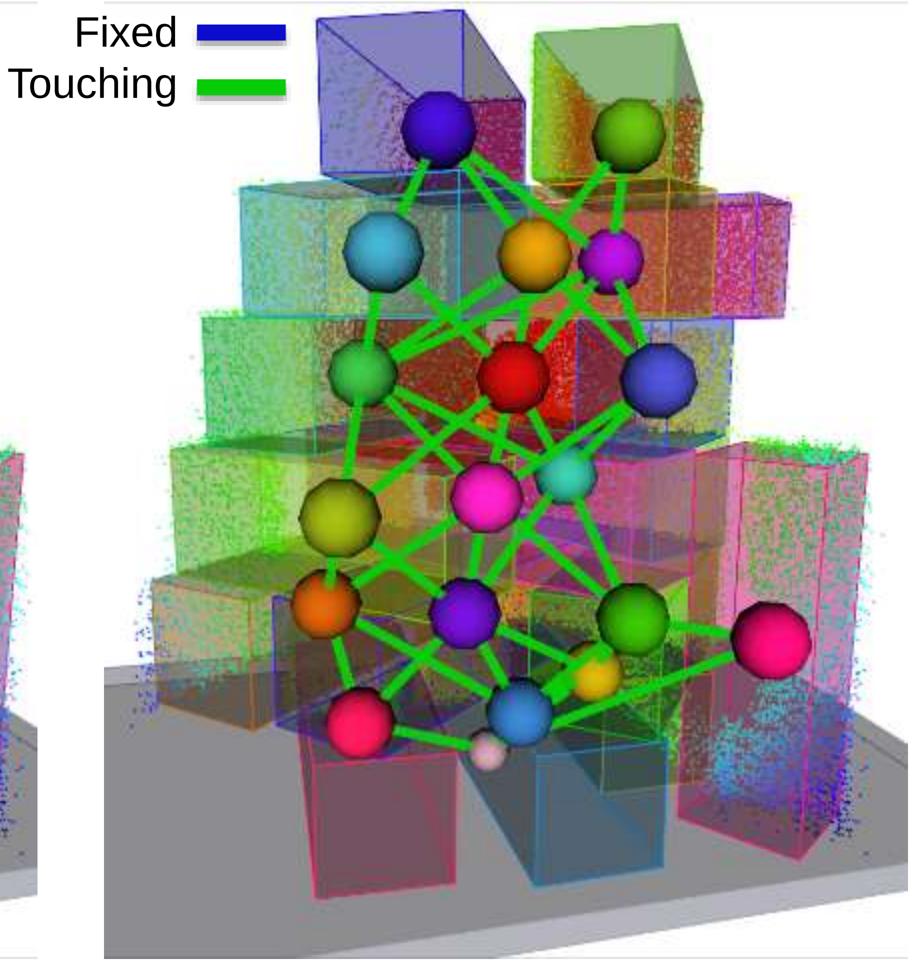
Robustness to scene complexity



Initialization

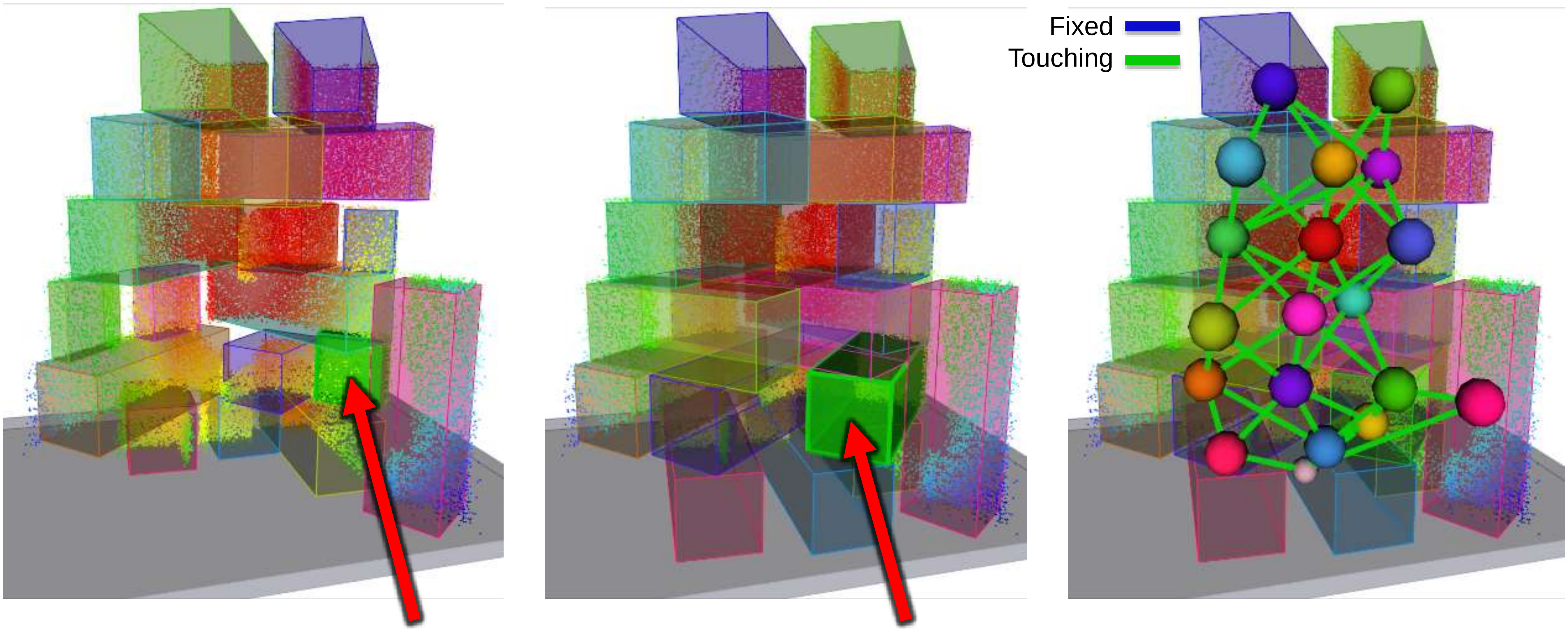


Optimized



Structure graph

Robustness to scene complexity



Initialization | Optimized | Structure graph

Overview

- Ground truth
- Metrics
- Robustness
- Validity
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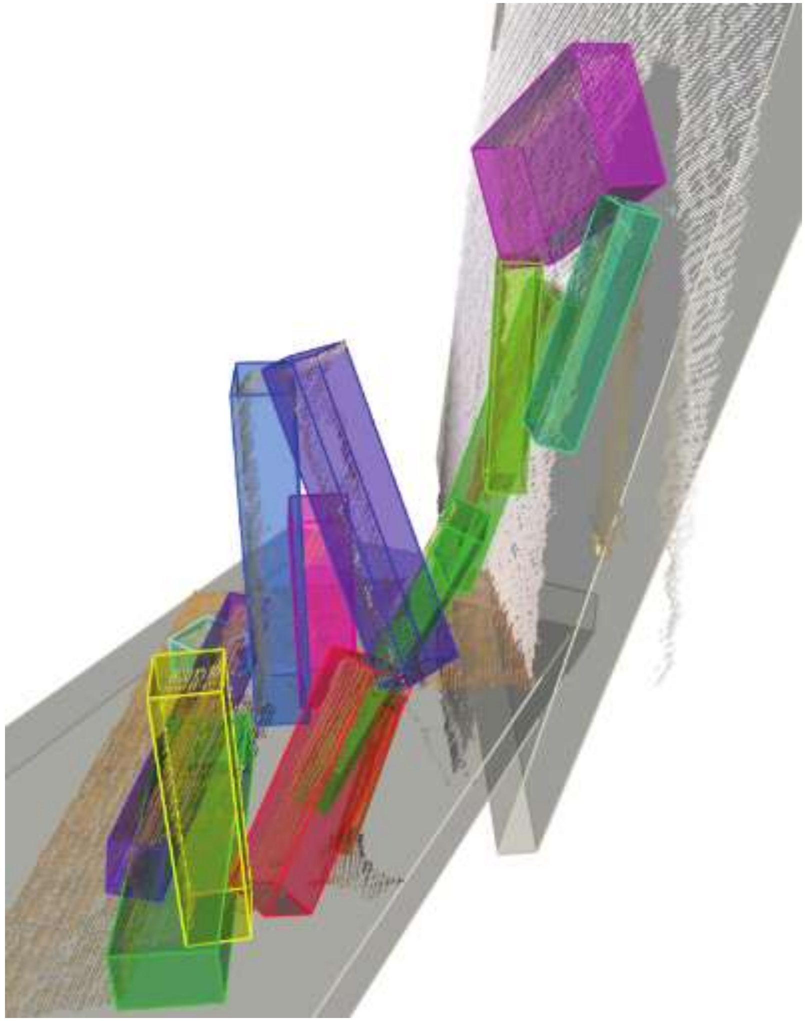
Evaluation – Validity

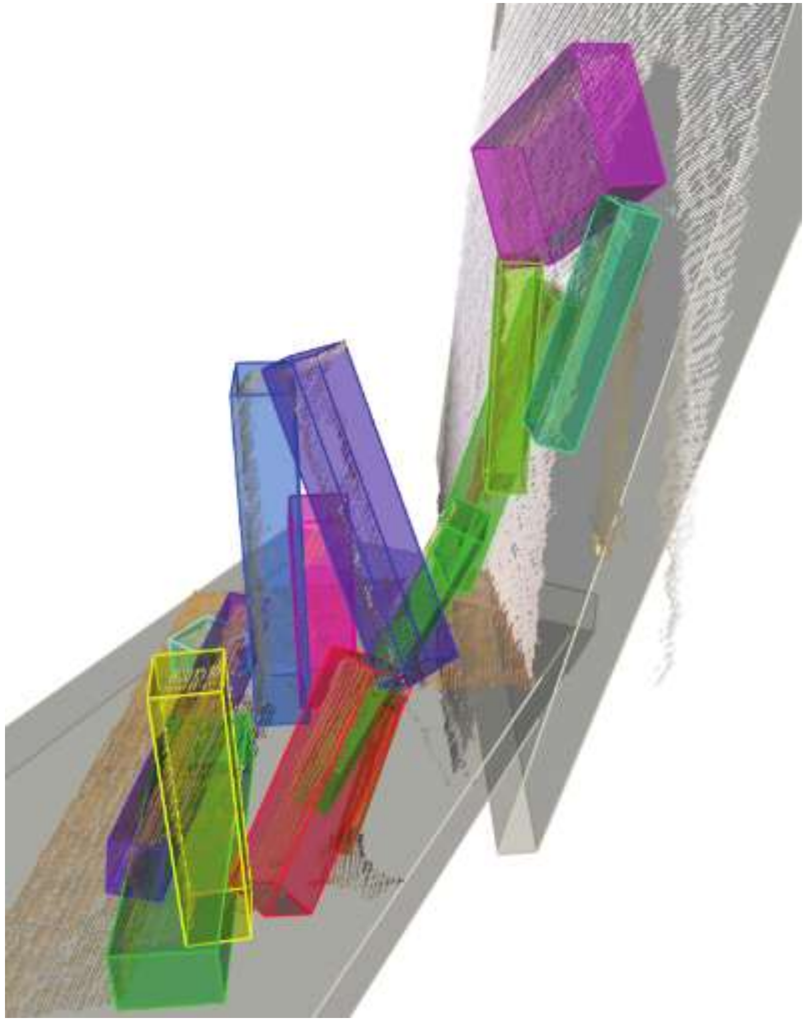
RGB-D input



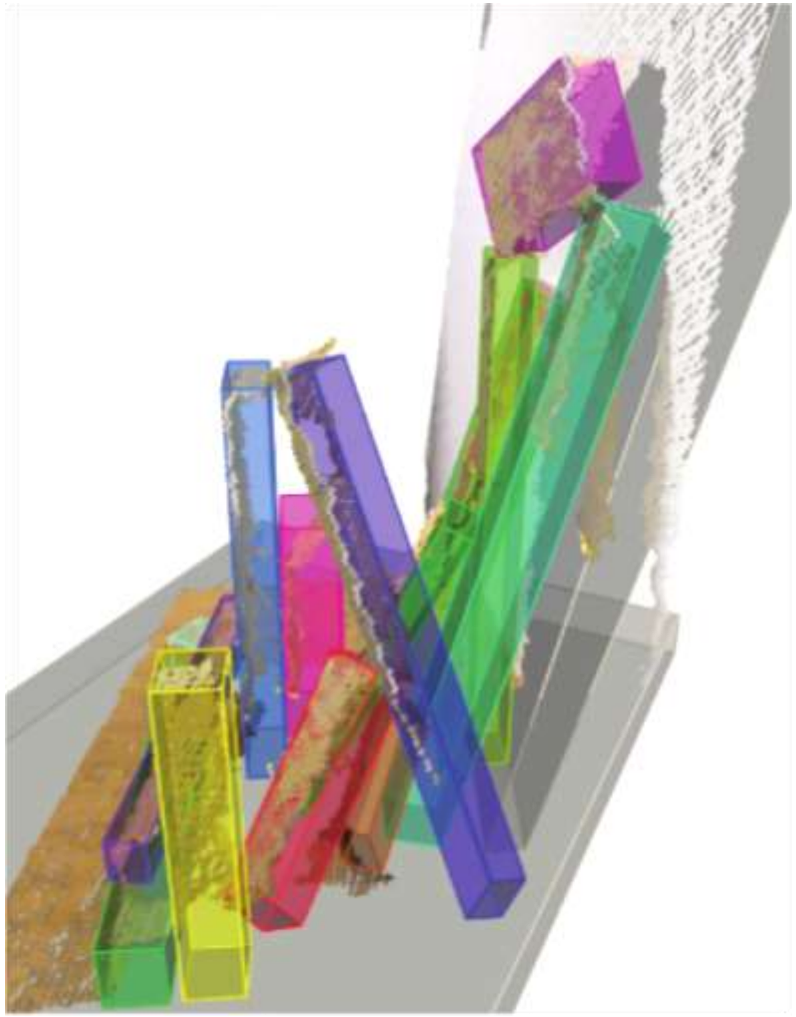
Initial (side view)

Evaluation – Validity

RGB-D input



Initial (side view)

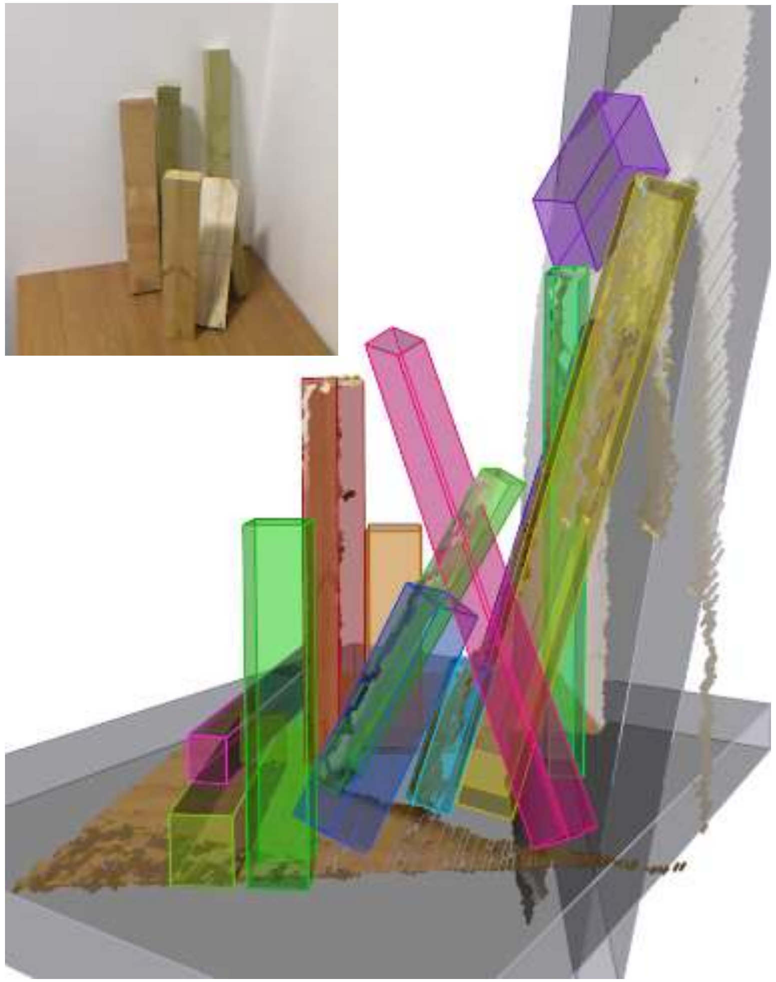


Optimized (side view)

Evaluation – Validity

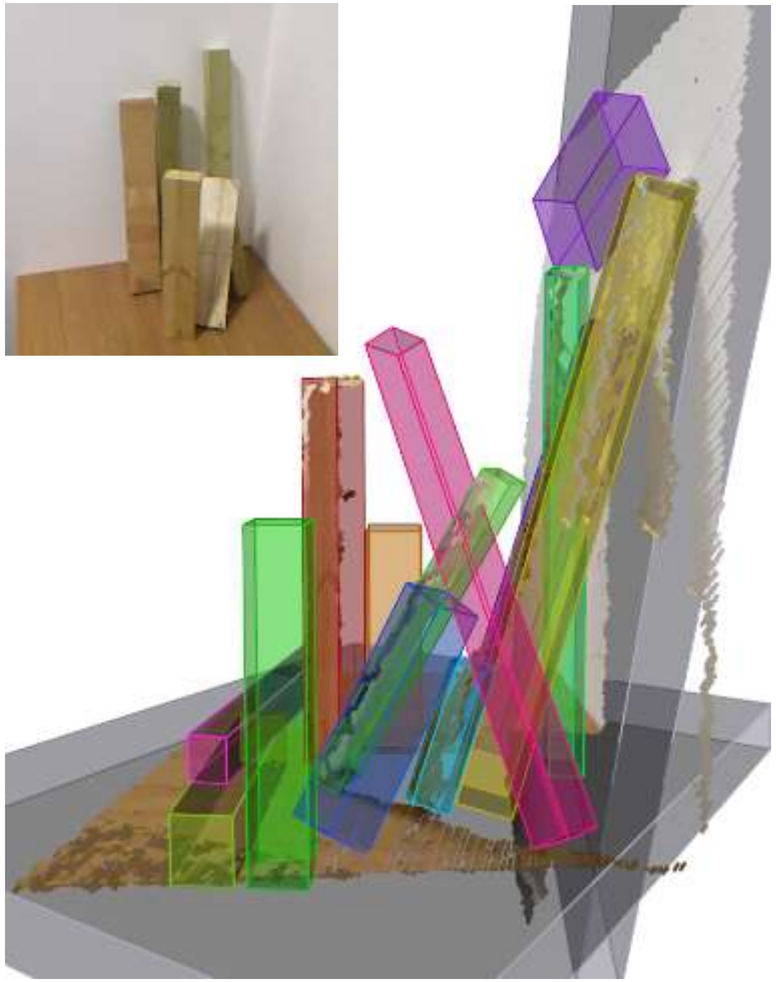
Less occluded scan

Evaluation – Validity

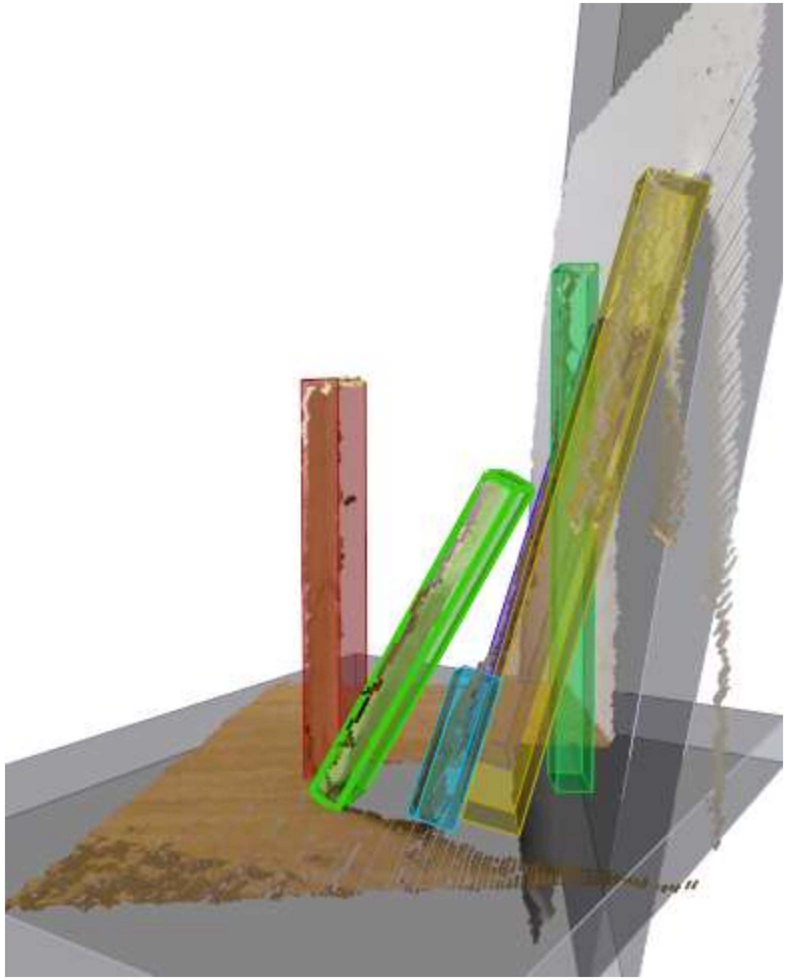


Less occluded scan
+ Optimized

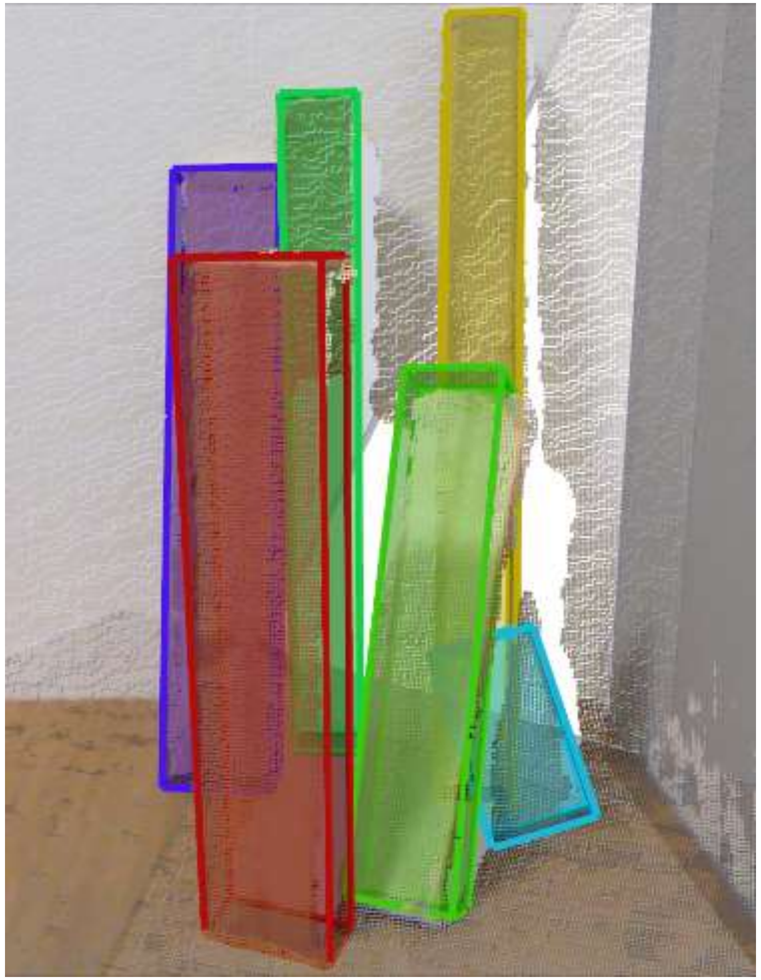
Evaluation – Validity



Less occluded scan
+ Optimized



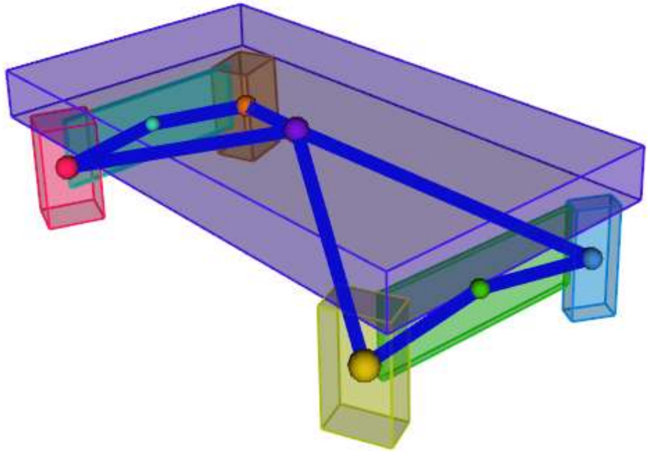
Extra proxies
removed



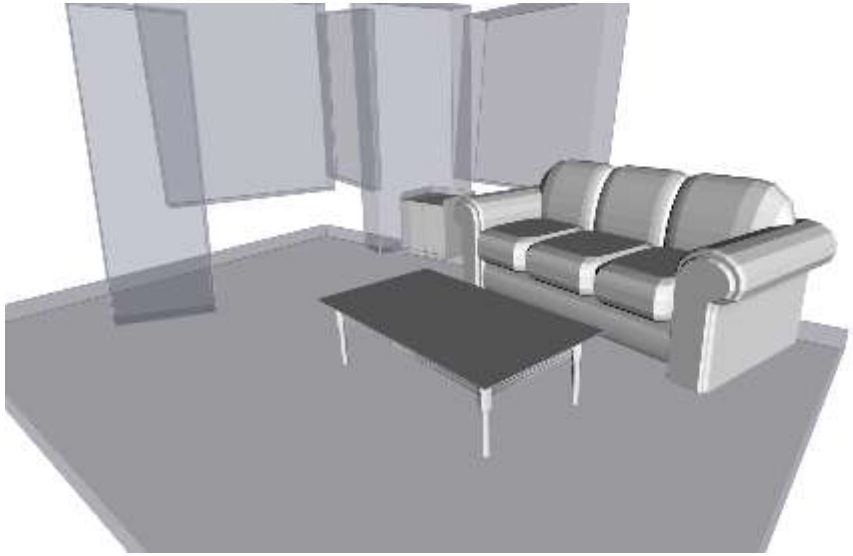
Front view

- Ground truth
- Metrics
- Robustness
- Validity
- Applications

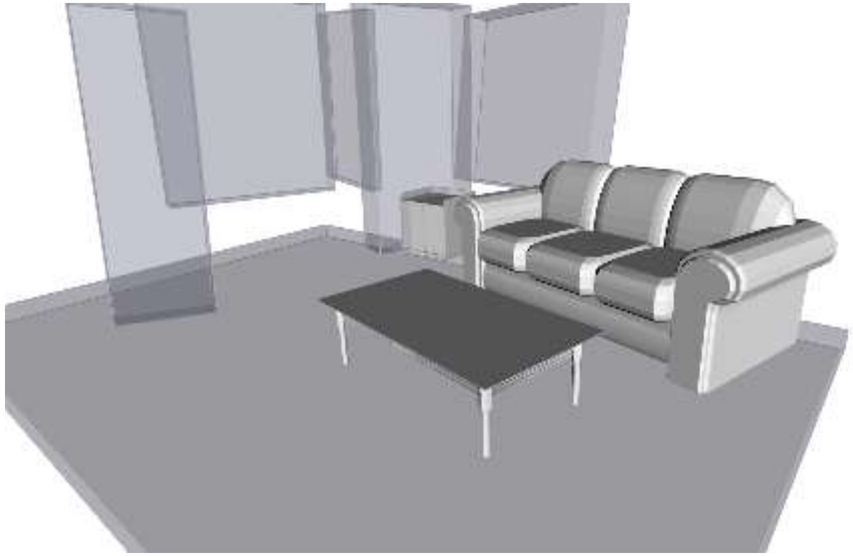
Applications #1 – Model retrieval



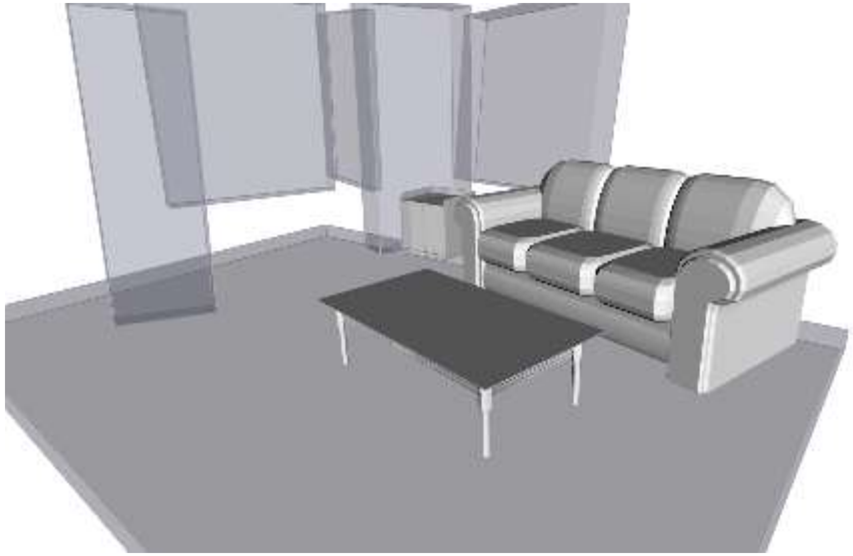
Applications #1 – Model retrieval



Applications #1 – Model retrieval



Applications #2 – Re-arrangement

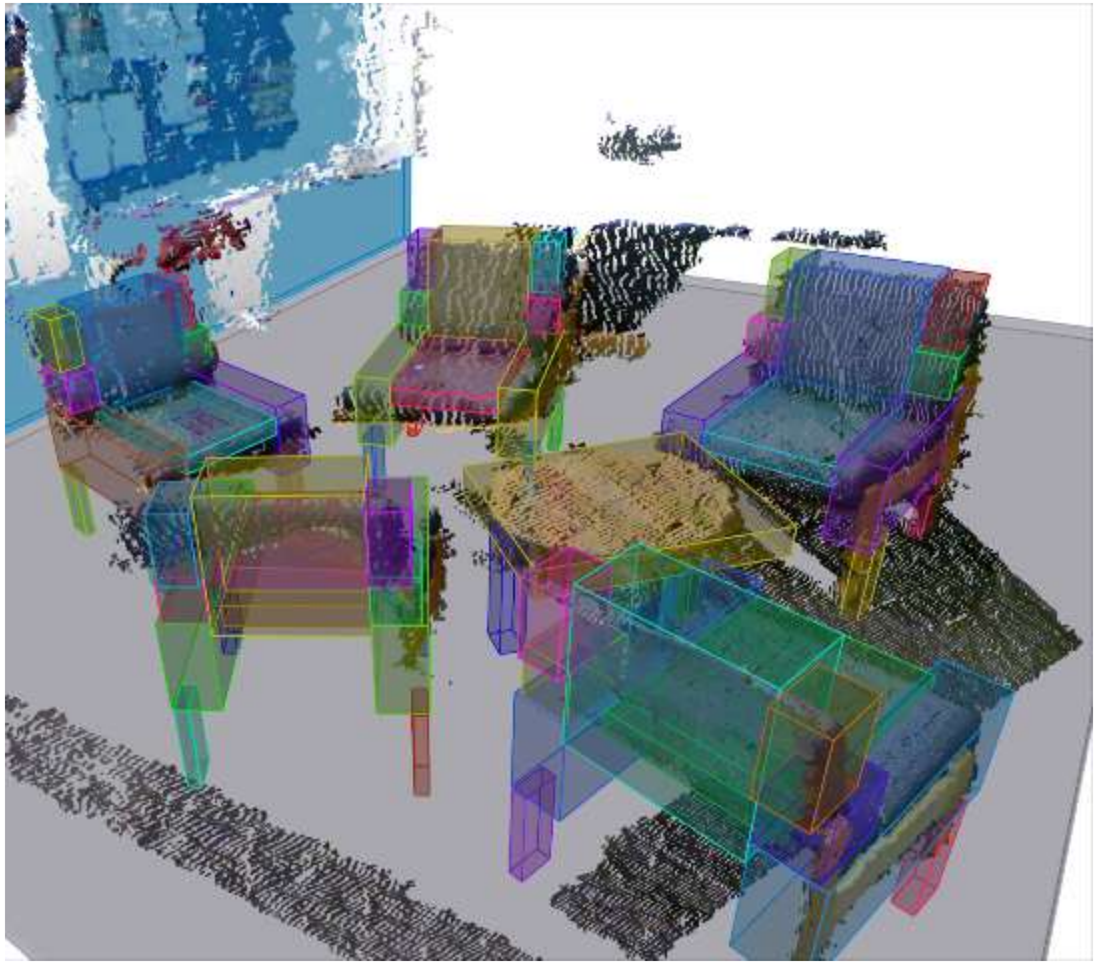

Applications #2 – Re-arrangement

Applications #3 - Completion

RGB-D Input

Applications #3 - Completion

RGB-D Input



Physically stable approximation

Applications #3 - Completion

RGB-D Input

Completed models

Applications #3 - Completion

RGB-D Input

Completed models

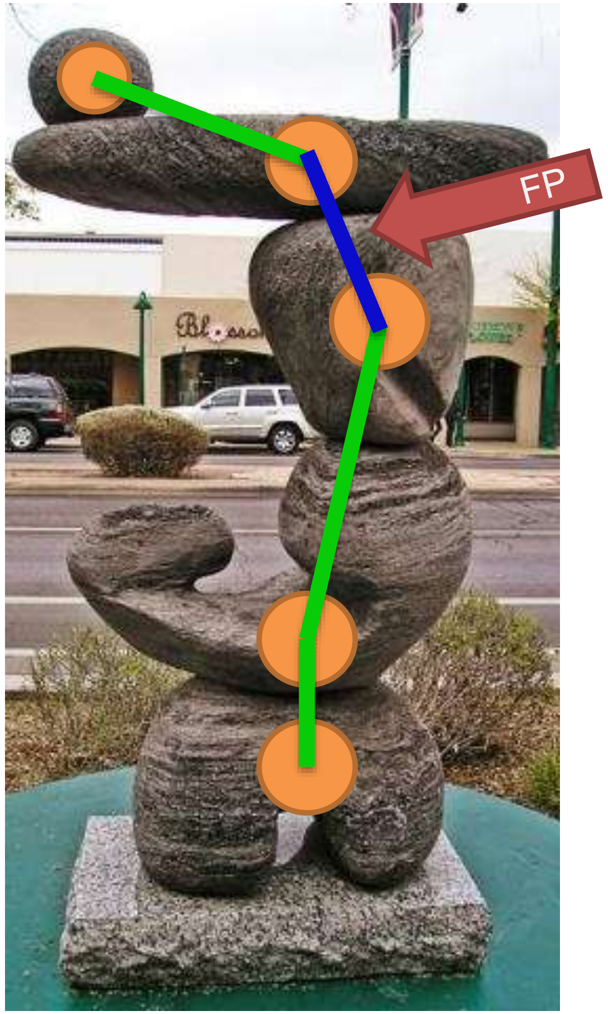
Limitations

heterogeneous

[http://azfoo.net/places/az/mesa/cemetery]

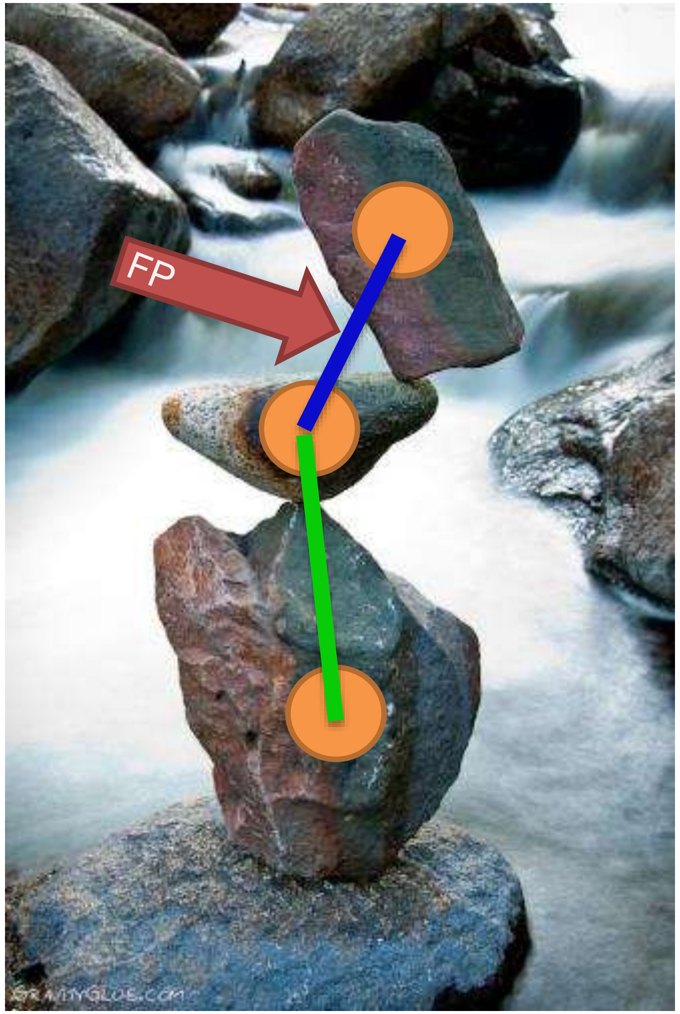
[GravityGlue.com]

Limitations



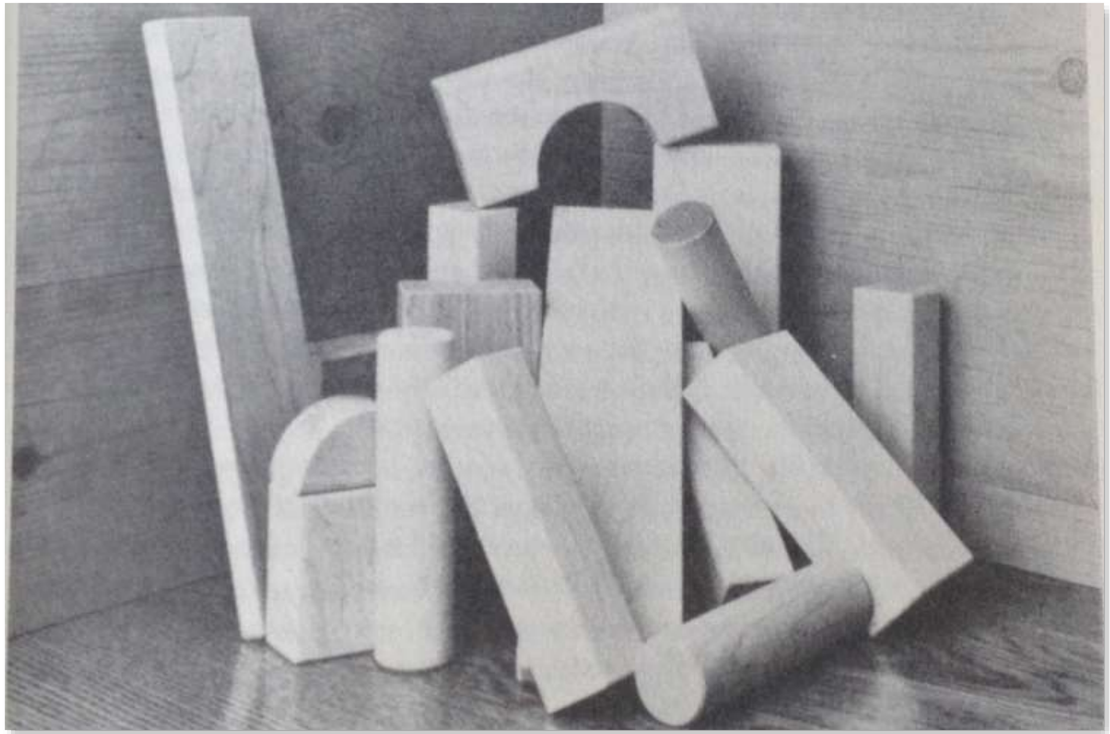
Fixed
Touching

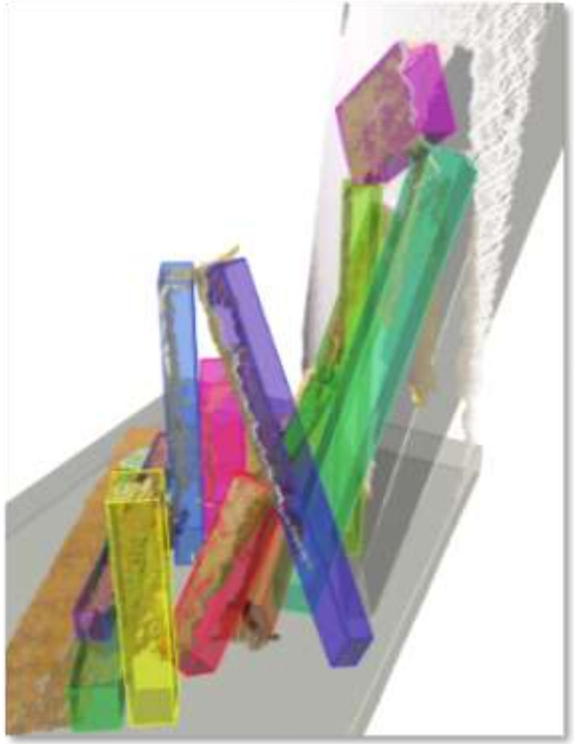
[http://azfoo.net/places/az/mesa/cemetery]



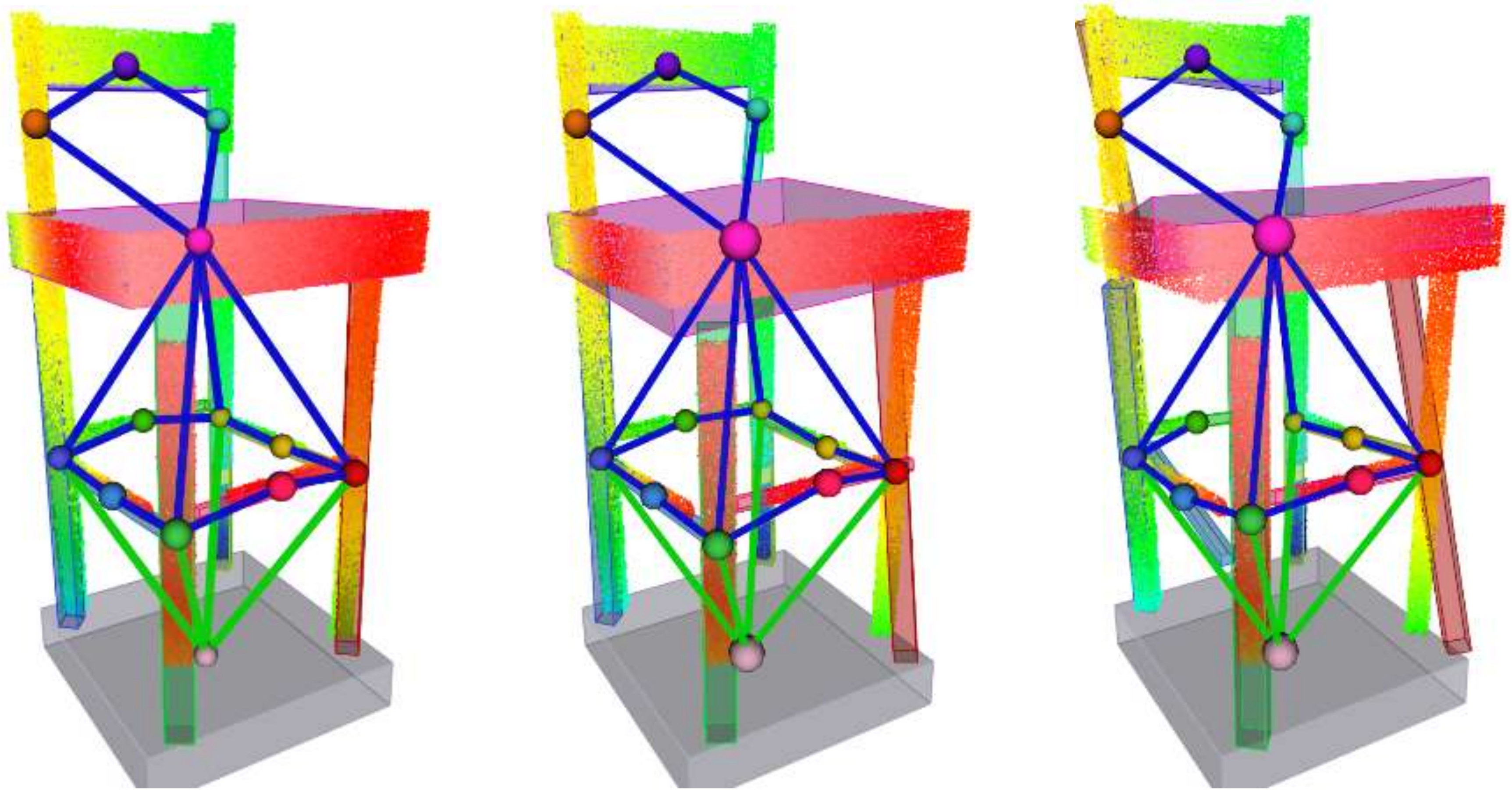
[GravityGlue.com]

Code + Data:





Robustness to initialization



No perturbation | 5° | 10°