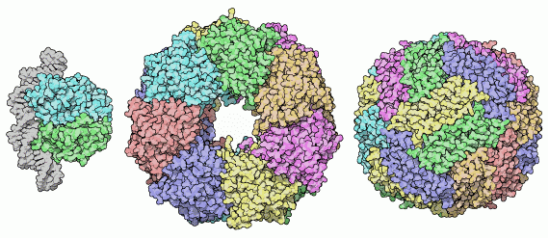
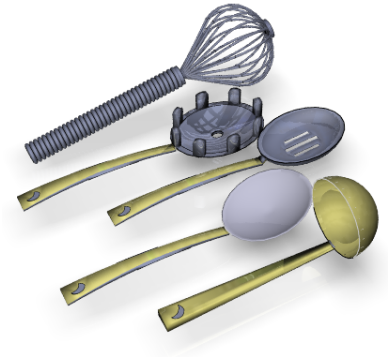
UC San Diego

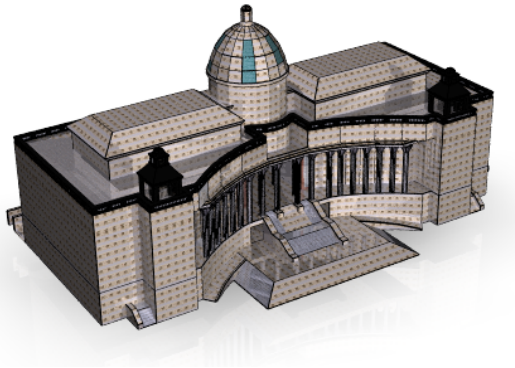
3D Deep Learning

Hao Su

@Stanford CS231n Guest Leture





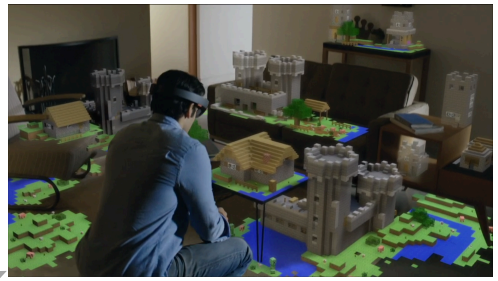


Broad Applications of 3D data

Robotics

Broad Applications of 3D data

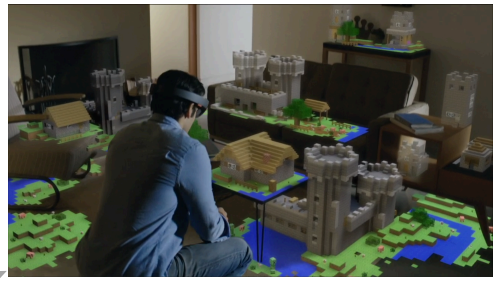
Robotics



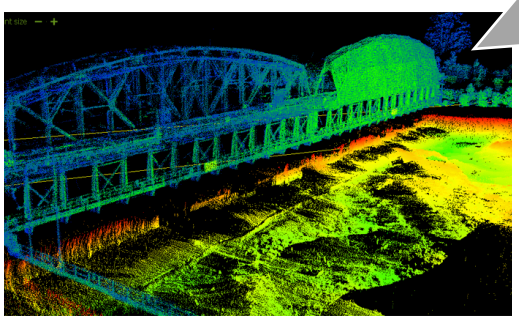
Augmented Reality

Broad Applications of 3D data

Robotics



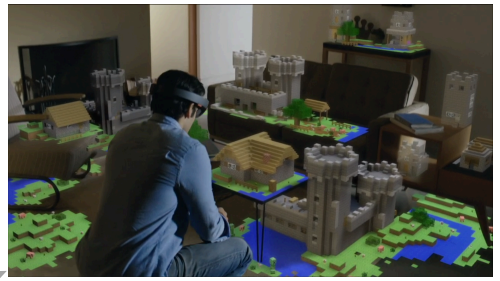
Augmented Reality



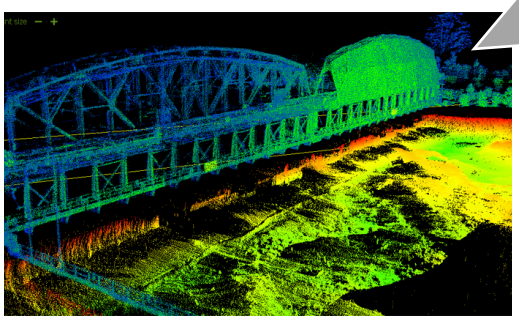
Autonomous driving

Broad Applications of 3D data

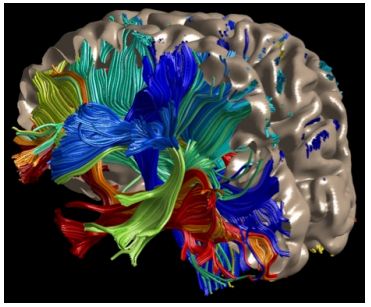
Robotics



Augmented Reality



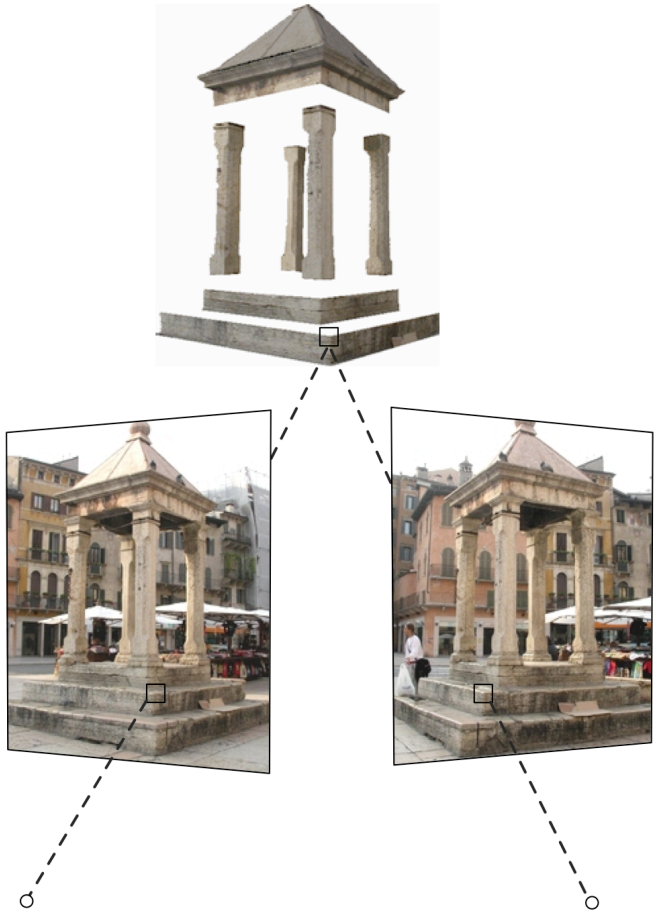
Autonomous driving



Medical Image Processing

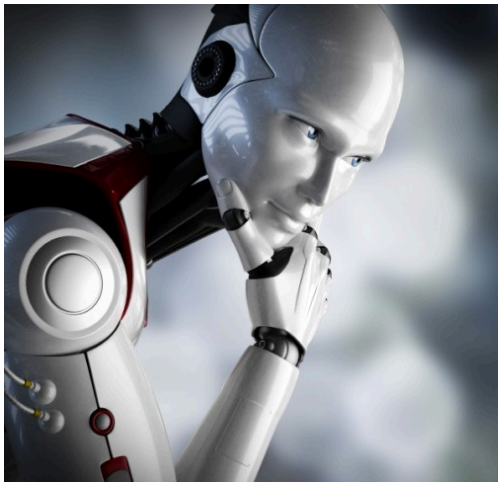
Traditional 3D Vision

Multi-view Geometry: Physics based

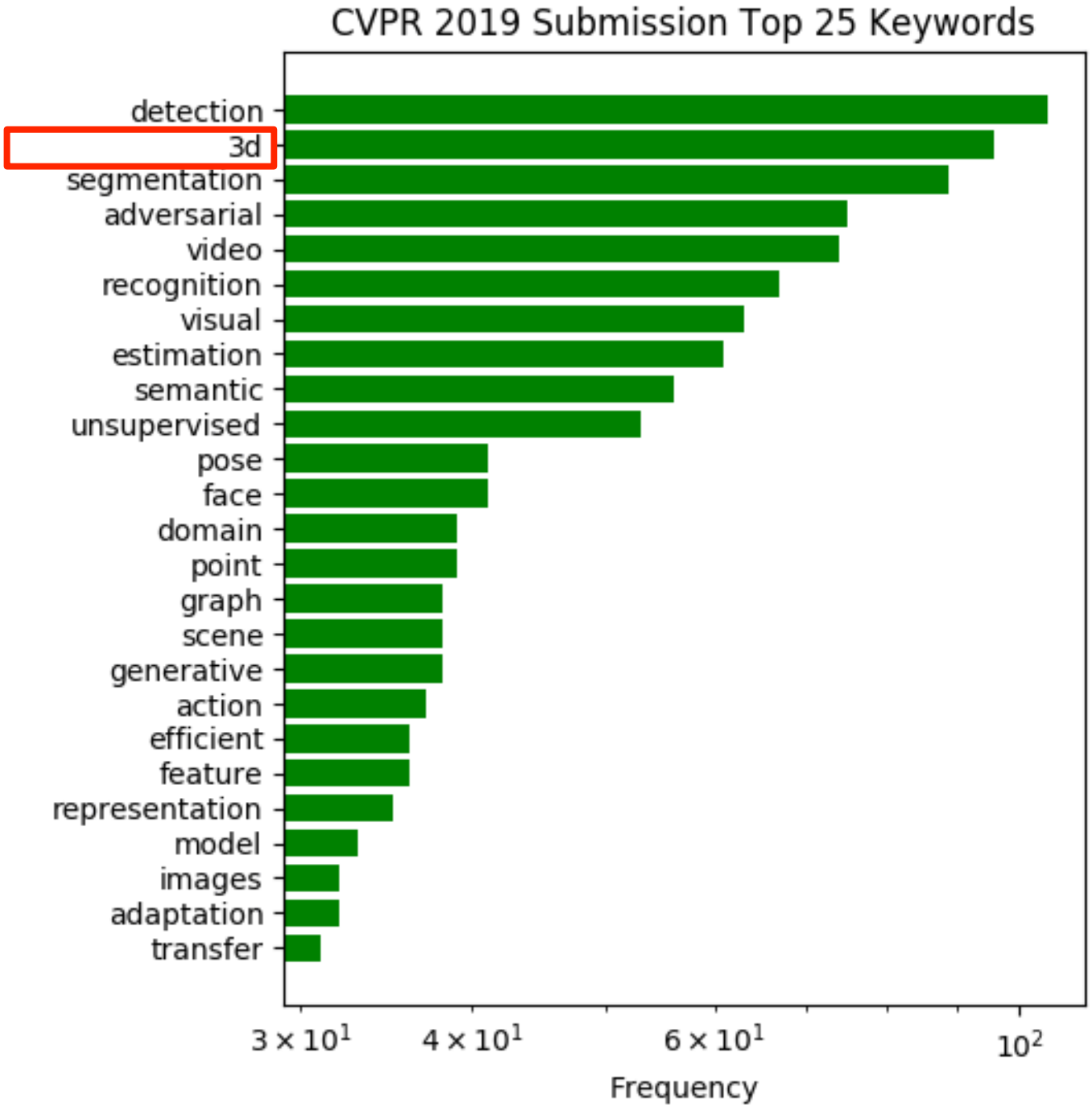


3D Learning: Knowledge Based

Acquire Knowledge of 3D World by Learning



A priori knowledge of the 3D world

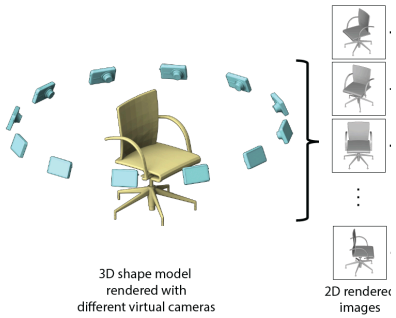

CVPR 2019 Submission Top 25 Keywords
detection
3d
segmentation
adversarial
video
recognition
visual
estimation
semantic
unsupervised
pose
face
domain
point
graph
scene
generative
action
efficient
feature
representation
model
images
adaptation
transfer
3×10^1
4×10^1
6×10^1
10^2
Frequency

The Representation Challenge of 3D Deep Learning

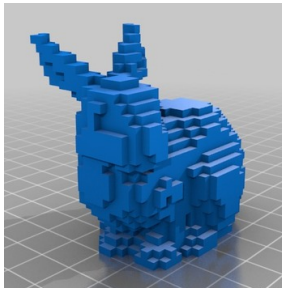
Rasterized form (regular grids)

Geometric form (irregular)

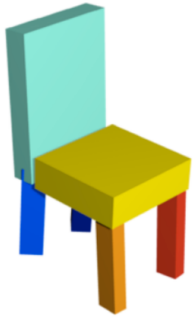
The Representation Challenge of 3D Deep Learning



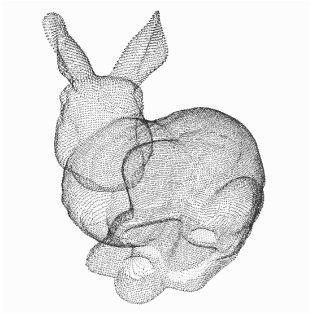
Multi-view



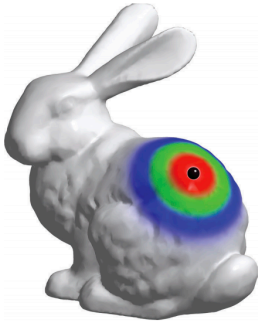
Volumetric



Part Assembly



Point Cloud



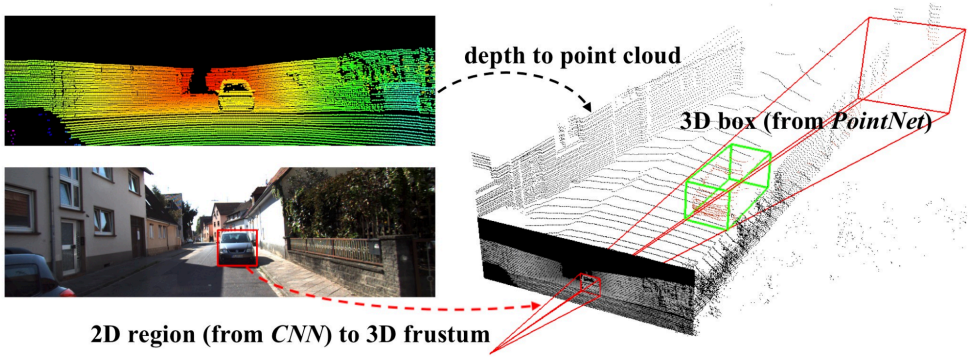
Mesh (Graph CNN)

$$F(x) = 0$$

Implicit Shape

The Richness of 3D Learning Tasks

3D Analysis



Detection

Classification

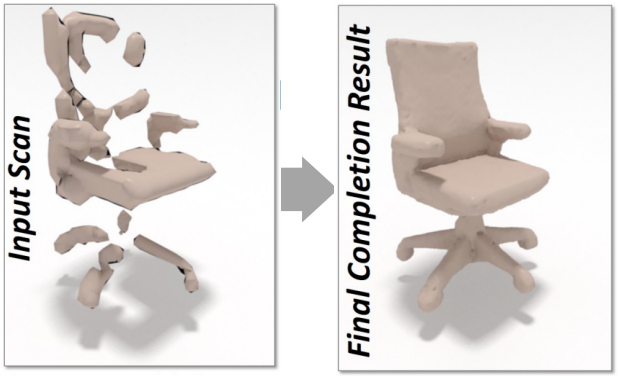
Segmentation (object/scene)

Correspondence

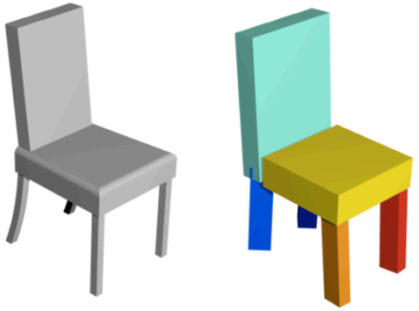
The Richness of 3D Learning Tasks

3D Synthesis

Monocular
3D reconstruction



Shape completion



Shape modeling

Agenda

- **3D Classification**
- **3D Reconstruction**
- **Others**

Volumetric CNN

Can we use CNNs but avoid projecting the 3D data to views first?

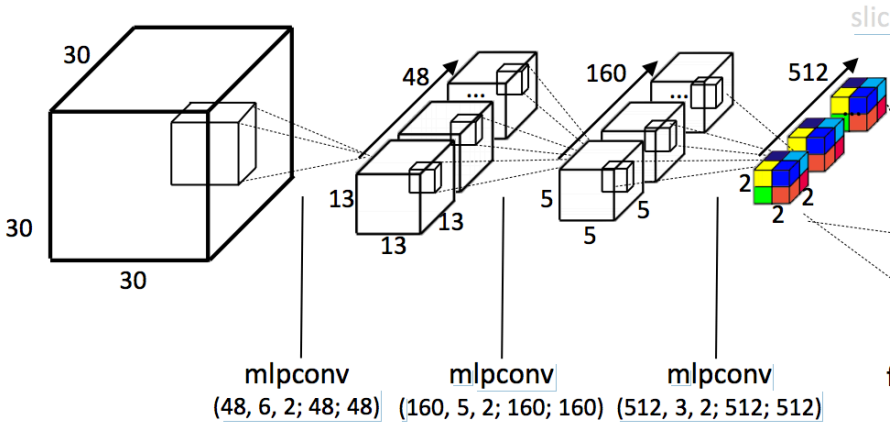
Straight-forward idea: Extend 2D grids 3D grids

Voxelization

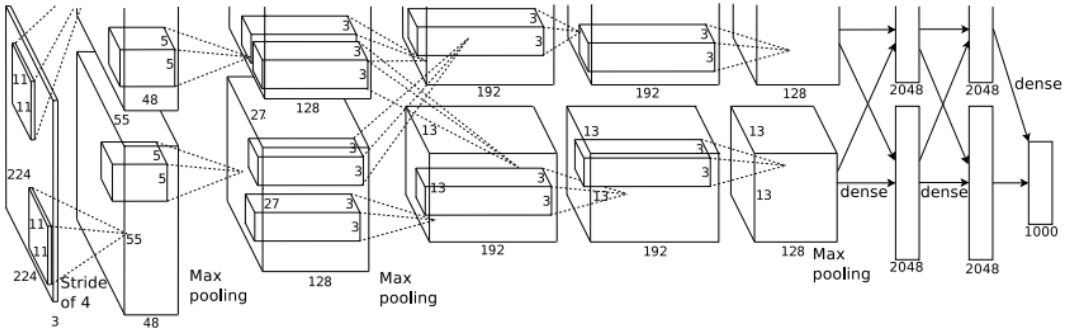
Represent the occupancy of regular 3D grids

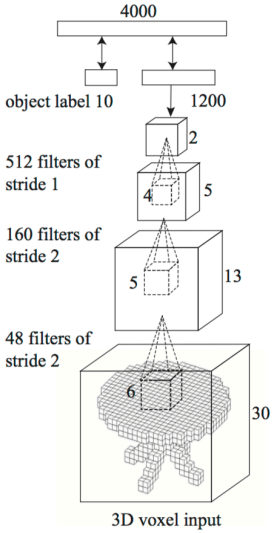
3D CNN on Volumetric Data

3D convolution uses 4D kernels



Complexity Issue





AlexNet, 2012

Input resolution: 224x224

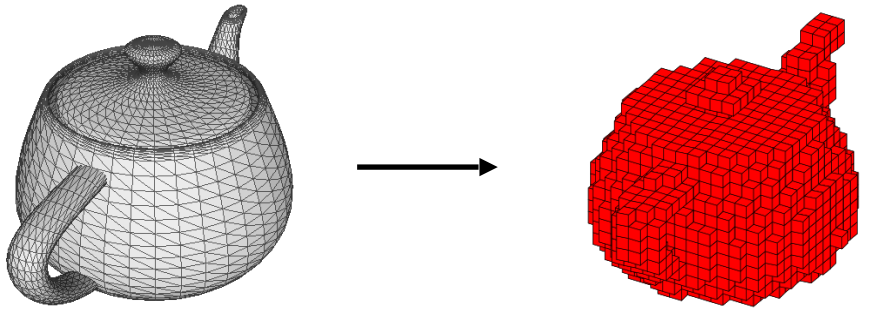
224x224=50176

3DShapeNets, 2015

Input resolution: 30x30x30

224x224=27000

Complexity Issue



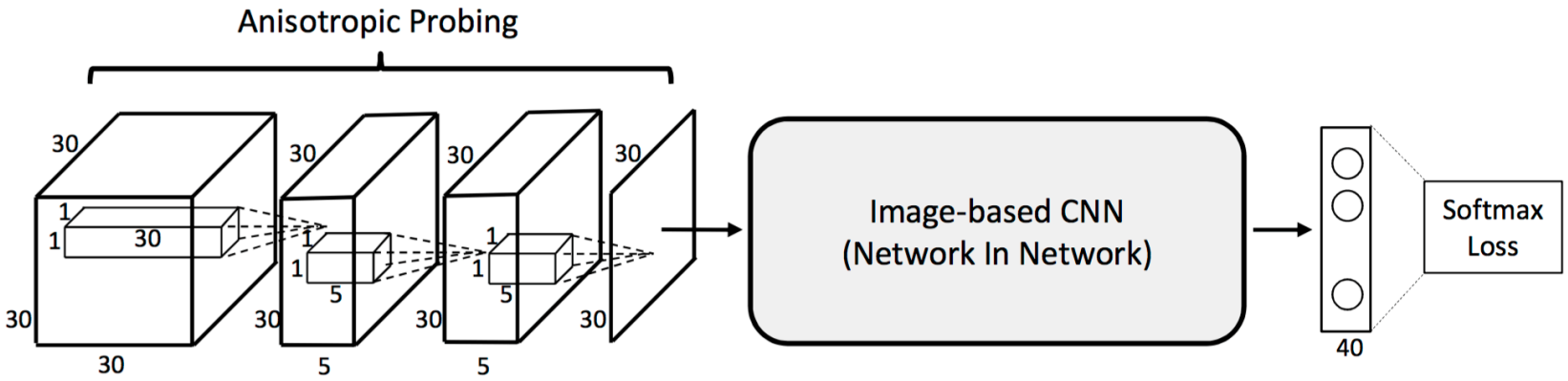
Polygon Mesh

Occupancy Grid
30×30×30

Information loss in voxelization

Idea 1: Learn to Project

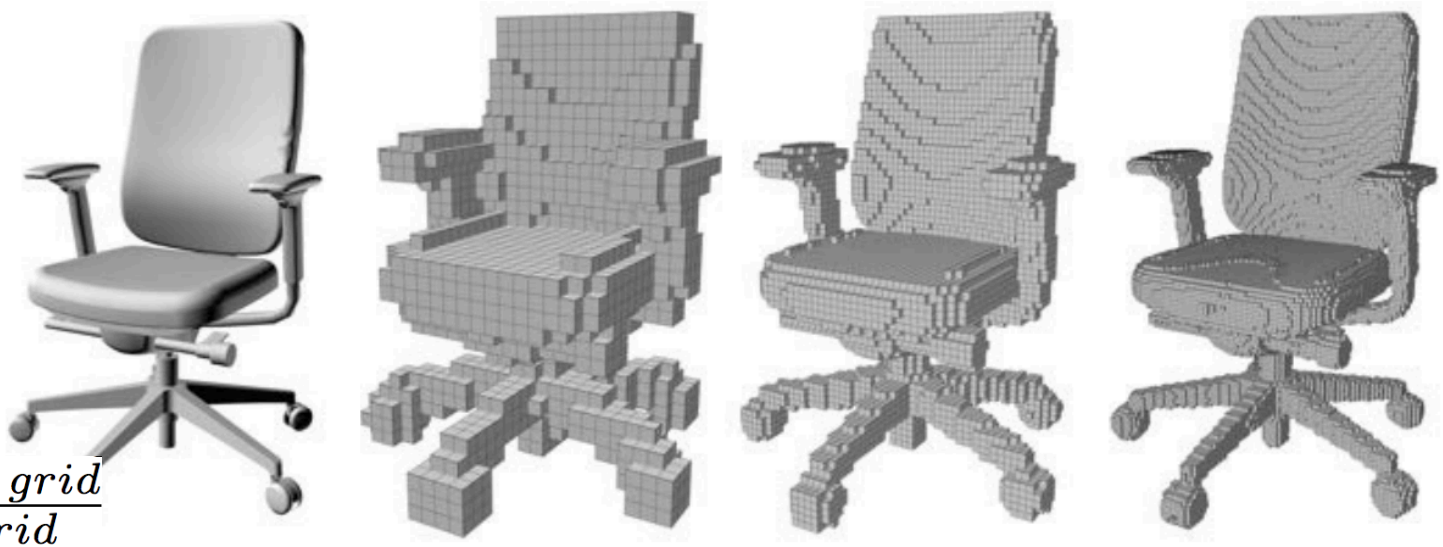
Idea: "X-ray" rendering + Image (2D) CNNs
very low #param, very low computation



Su et al., "**Volumetric and Multi-View CNNs for Object Classification on 3D Data**", *CVPR 2016*

Many other works in autonomous driving that uses **bird's eye view** for object detection

More Principled: Sparsity of 3D Shapes

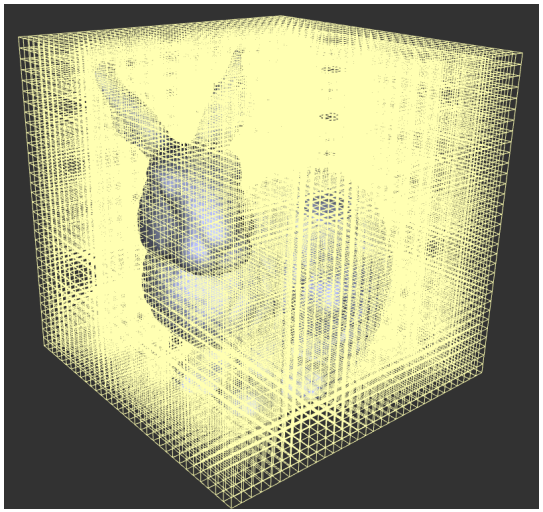


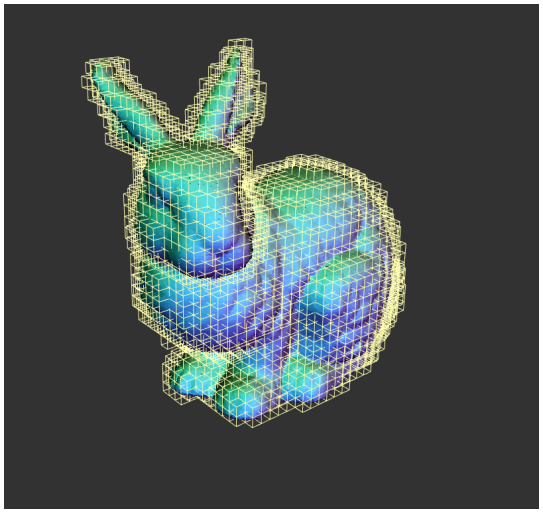
$$\frac{\#occupied\ grid}{\#total\ grid}$$

Occupancy:	10.41%	5.09%	2.41%
Resolution:	32	64	128

Store only the Occupied Grids

- Store the sparse surface signals
- Constrain the computation near the surface

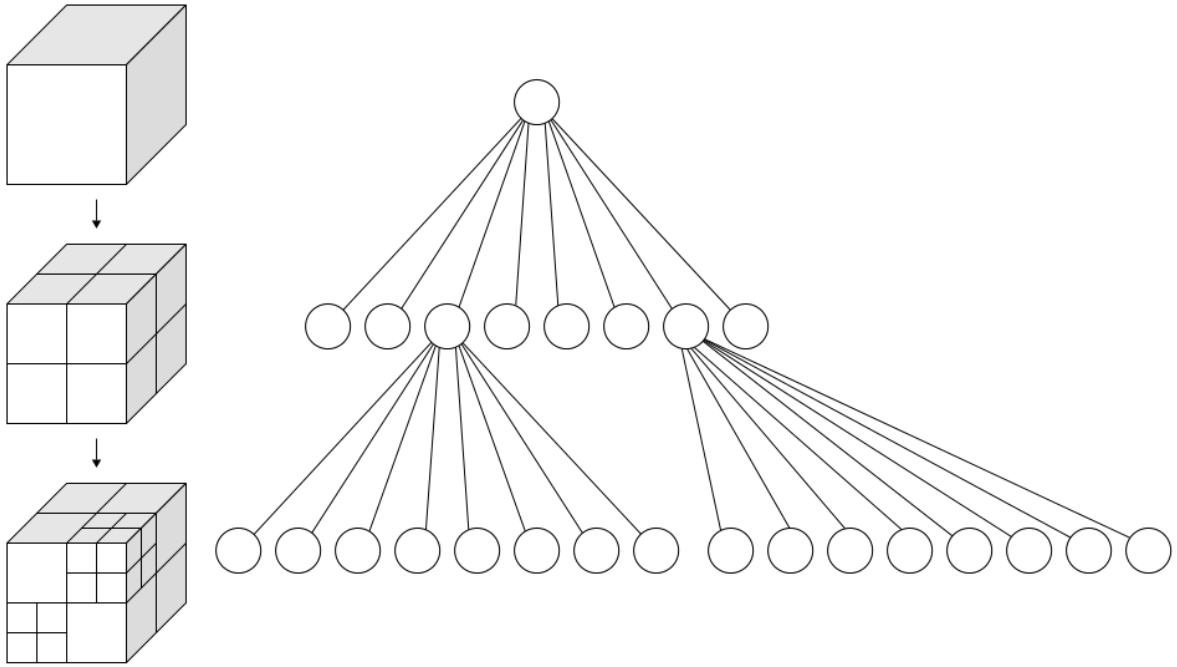




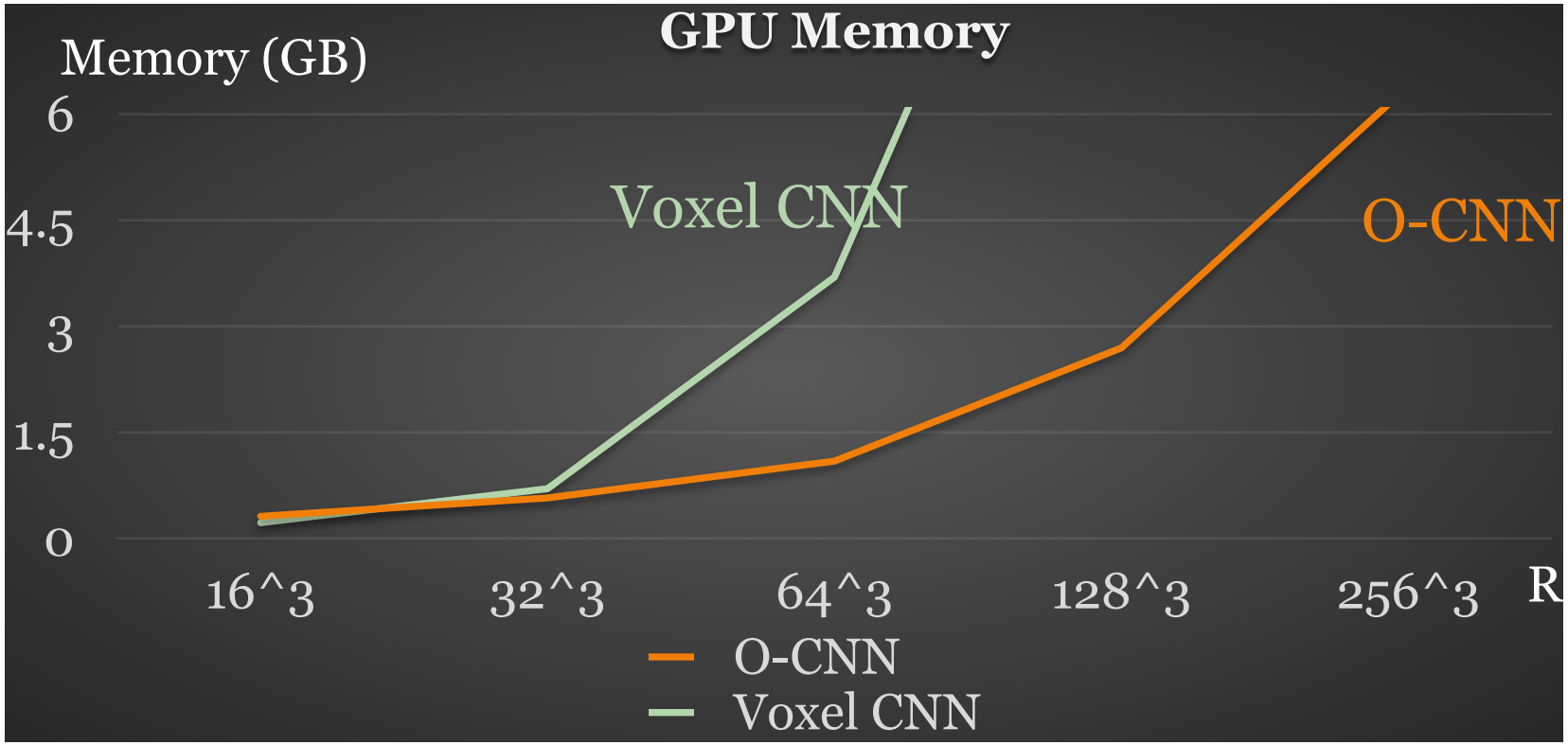
Octree: Recursively Partition the Space

Each internal node has exactly eight children

Neighborhood searching: Hash table



Memory Efficiency

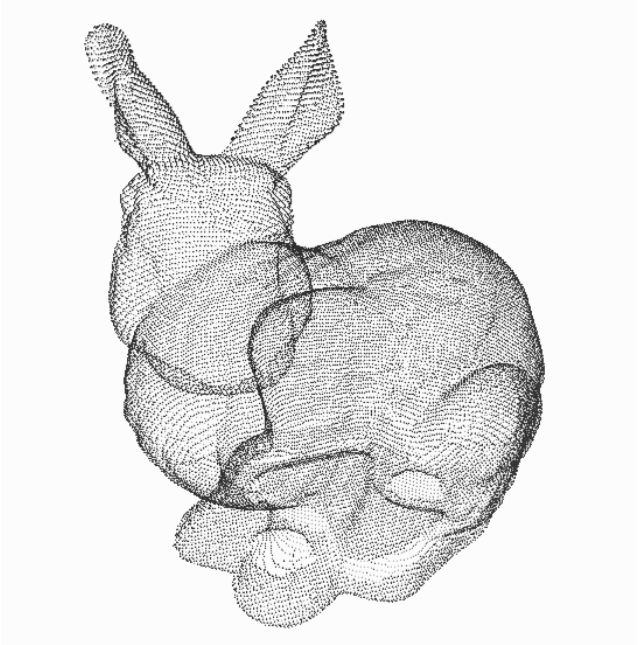


Implementation

- SparseConvNet
  - https://github.com/facebookresearch/SparseConvNet
  - Uses ResNet architecture
  - State-of-the-art for 3D analysis
  - Takes time to train

Graham et al., "**Submanifold Sparse Convolutional Networks**", *arxiv*

Point Networks



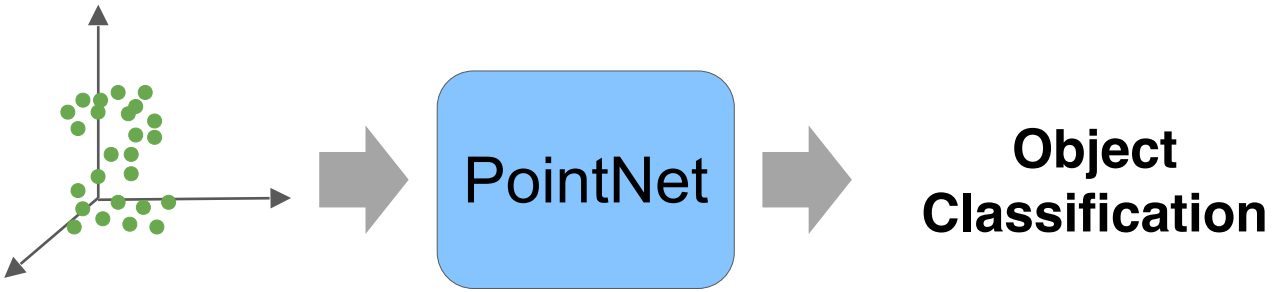
Point cloud

(The most common 3D sensor data)

Directly Process Point Cloud Data

End-to-end learning for **unstructured,**

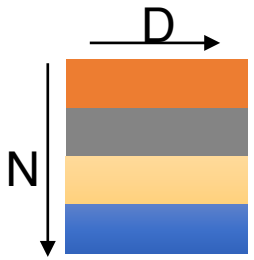
unordered point data



Qi, Charles R., et al. "**Pointnet: Deep learning on point sets for 3d classification and segmentation**", CVPR 2017
Zaheer, Manzil, et al. "**Deep sets**", NeurIPS 2017

Permutation invariance

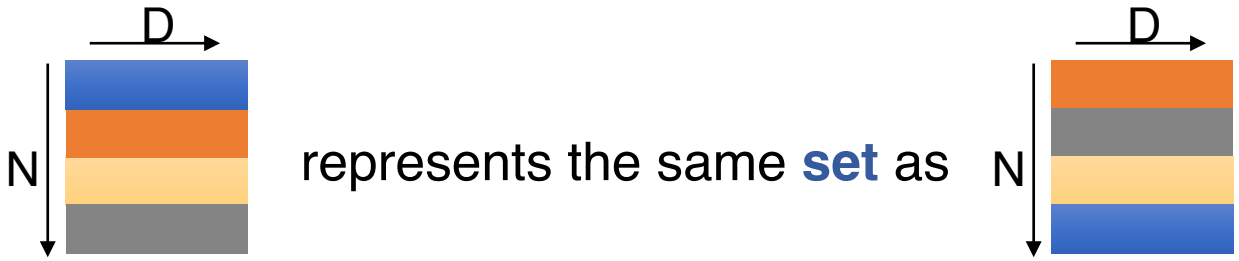
Point cloud: N **orderless** points, each represented by a D dim coordinate



2D array representation

Permutation invariance

Point cloud: N **orderless** points, each represented by a D dim coordinate

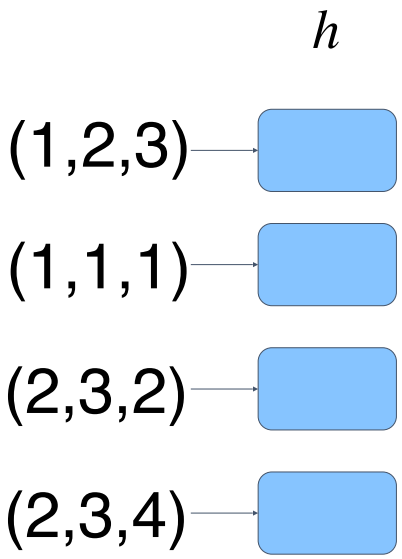


2D array representation

Construct a Symmetric Function

Observe:

$f(x_1, x_2, \ldots, x_n) = \gamma \circ g(h(x_1), \ldots, h(x_n))$ is symmetric if g is symmetric



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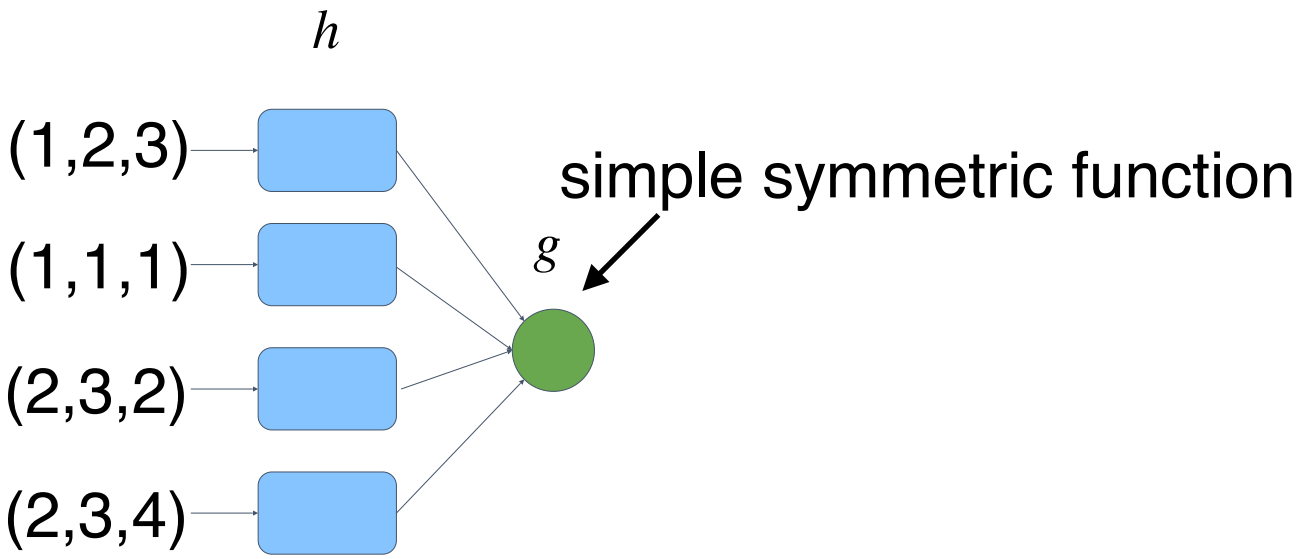

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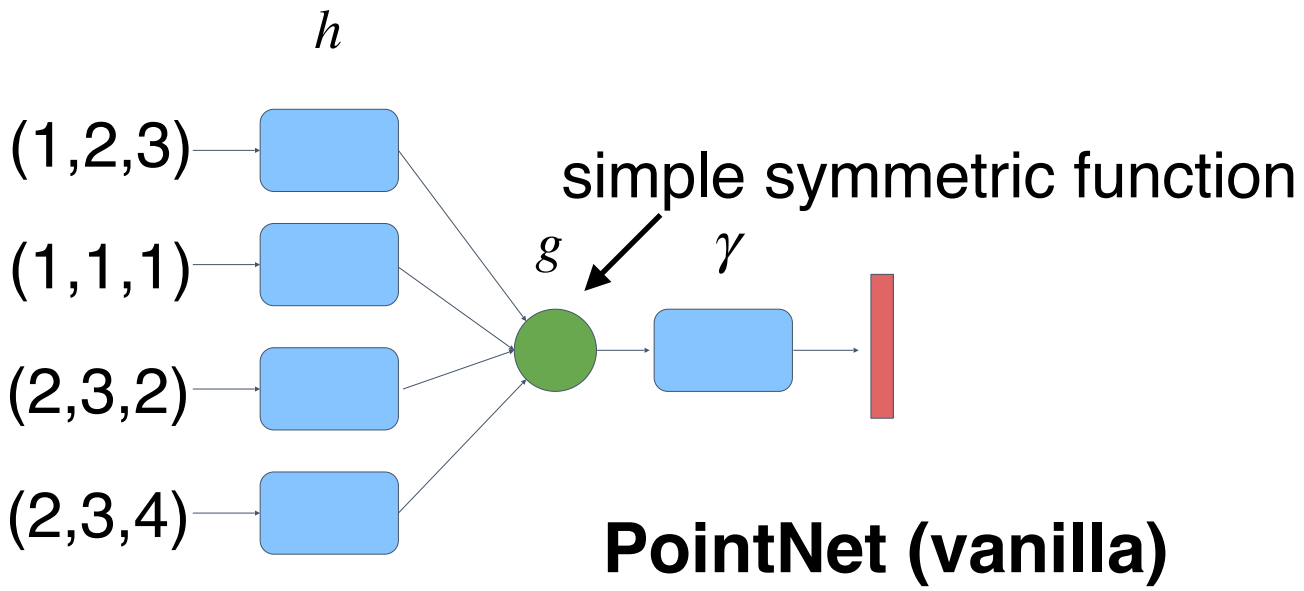
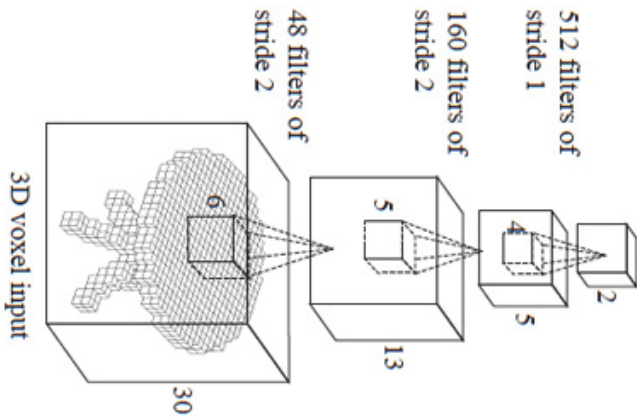


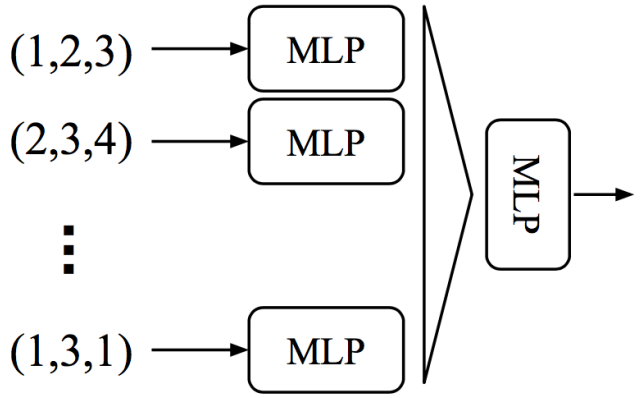
Limitations of PointNet

Hierarchical feature learning
Multiple levels of abstraction



3D CNN (Wu et al.)

Global feature learning
Either one point or all points



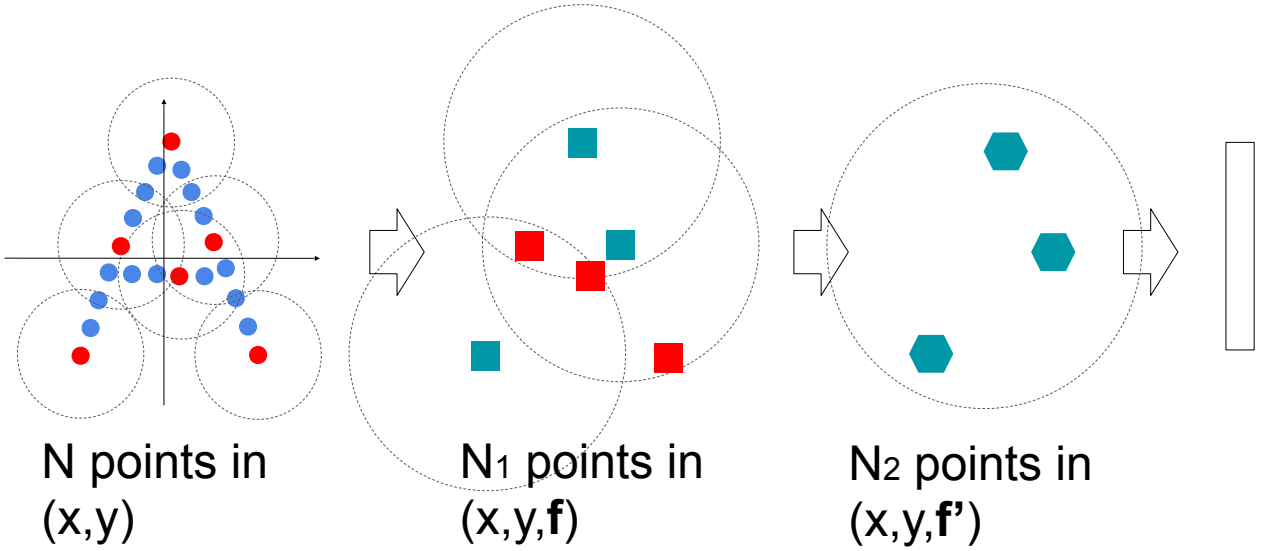
PointNet (vanilla) (Qi et al.)

- No local context for each point!
- Global feature depends on absolute coordinate. Hard to generalize to unseen scene configurations!

Points in Metric Space

- Learn “kernels” in 3D space and conduct convolution
- Kernels have compact spatial support
- For convolution, we need to find neighboring points
- Possible strategies for range query
  - Ball query (results in more stable features)
  - k-NN query (faster)

PointNet v2.0: Multi-Scale PointNet

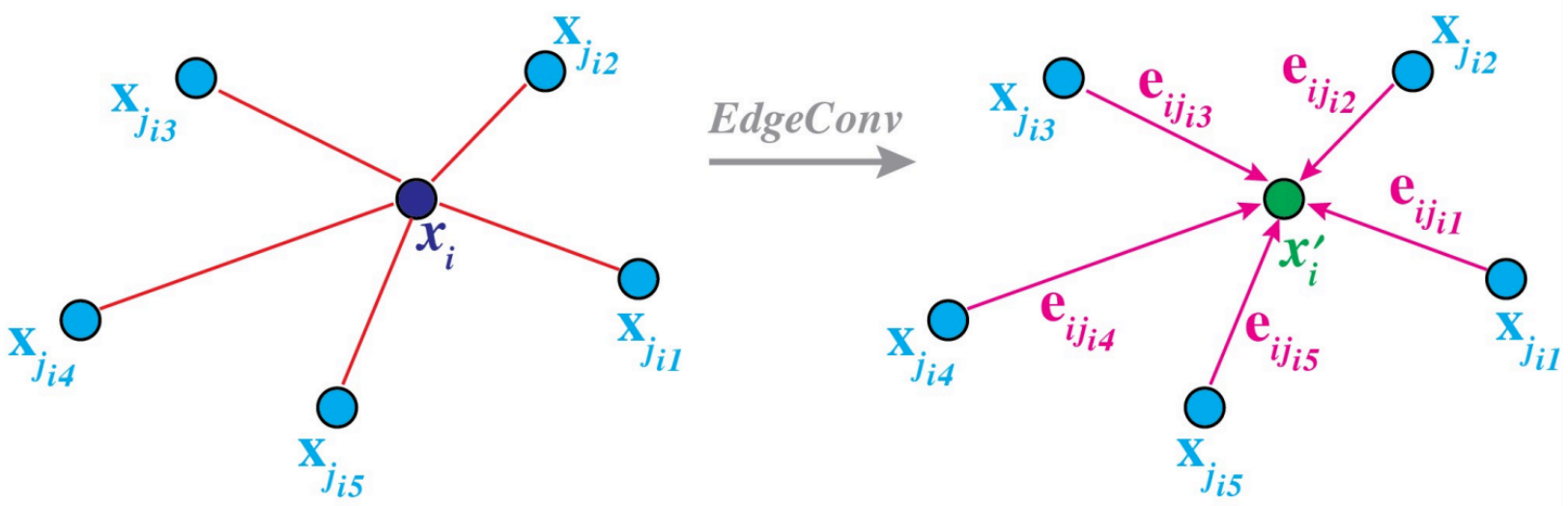


Repeat

- Sample anchor points
- Find neighborhood of anchor points
- Apply PointNet in each neighborhood to mimic convolution

Point Convolution As Graph Convolution

- Points -> Nodes
- Neighborhood -> Edges
- Graph CNN for point cloud processing



Wang et al., "**Dynamic Graph CNN for Learning on Point Clouds**", *Transactions on Graphics, 2019*

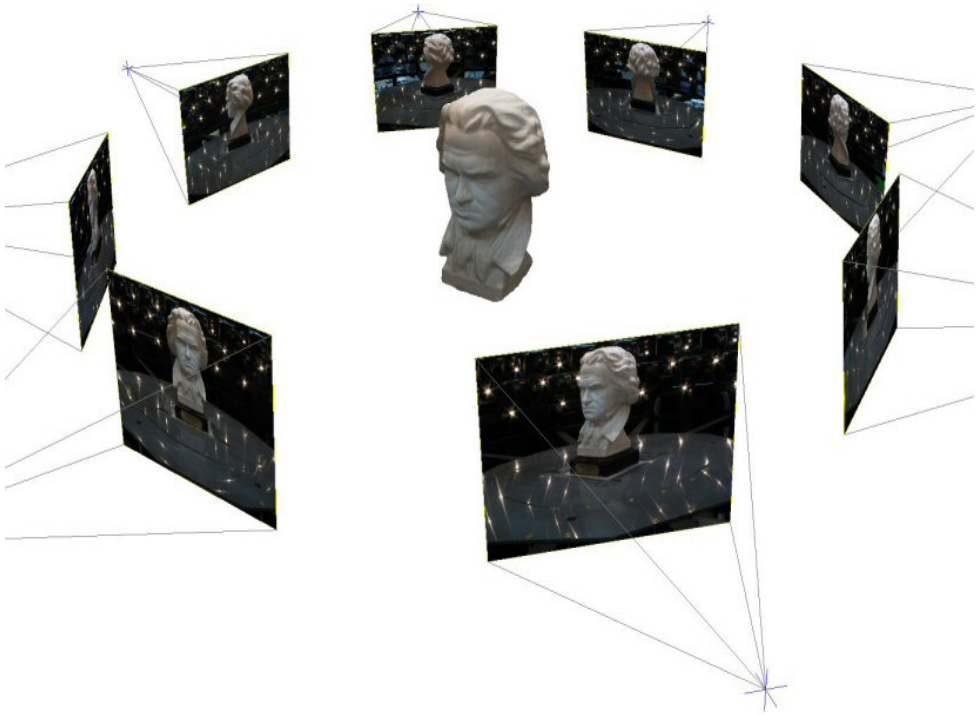
Liu et al., "**Relation-Shape Convolutional Neural Network for Point Cloud Analysis**", *CVPR 2019*

Agenda

- 3D Classification
- **3D Reconstruction**
- Others

Multi-View Stereo (MVS)

Reconstruct the dense 3D shape from a set of **images** and **camera parameters**



1. Goldlucke et al. “A Super-resolution Framework for High-Accuracy Multiview Reconstruction”

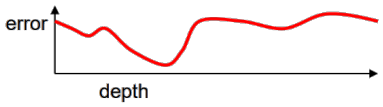
Requirements of MVS

Applications	Range	Accuracy	Time Efficiency	Computation Efficiency
Remote Sensing	★★★★★	★★	★	★★
Autonomous Driving	★★★★	★★	★★★★	★★★★
AR/VR	★★	★★★	★★★★★	★★★★★
Robot Manipulation	★	★★★★	★★★	★★★★
Inverse Engineering	★	★★★★★	★★	★★

Reconstruction from Photo-Consistency

NCC (Normalized Cross Correlation)

$$\frac{\sum_{x,y}(W_1(x,y)-\overline{W_1})(W_2(x,y)-\overline{W_2})}{\sigma_{W_1}\sigma_{W_2}}$$



SSD (Sum Squared Distance)

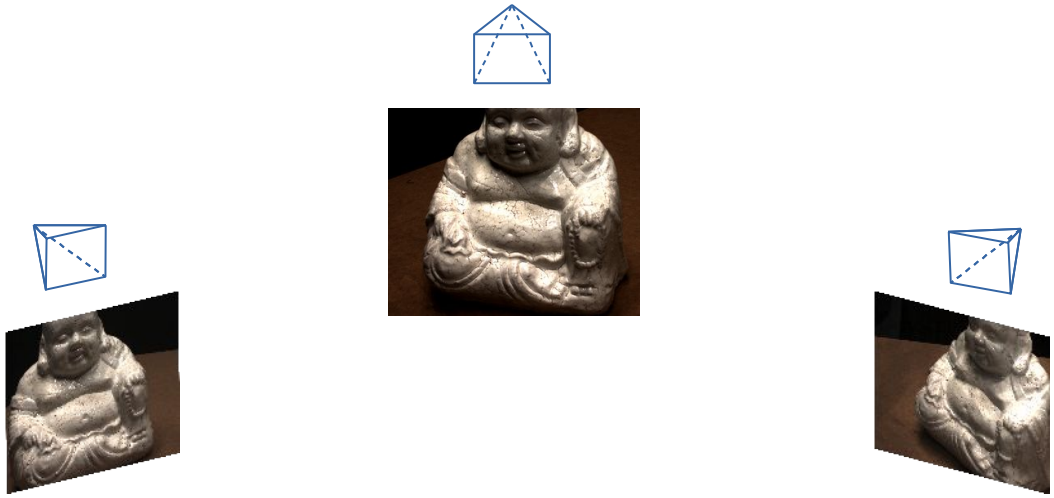
$$\sum_{x,y}|W_1(x,y)-W_2(x,y)|^2$$

- Requires texture
- Sensitive to Non-lambertian area

Image source: UW CSE455

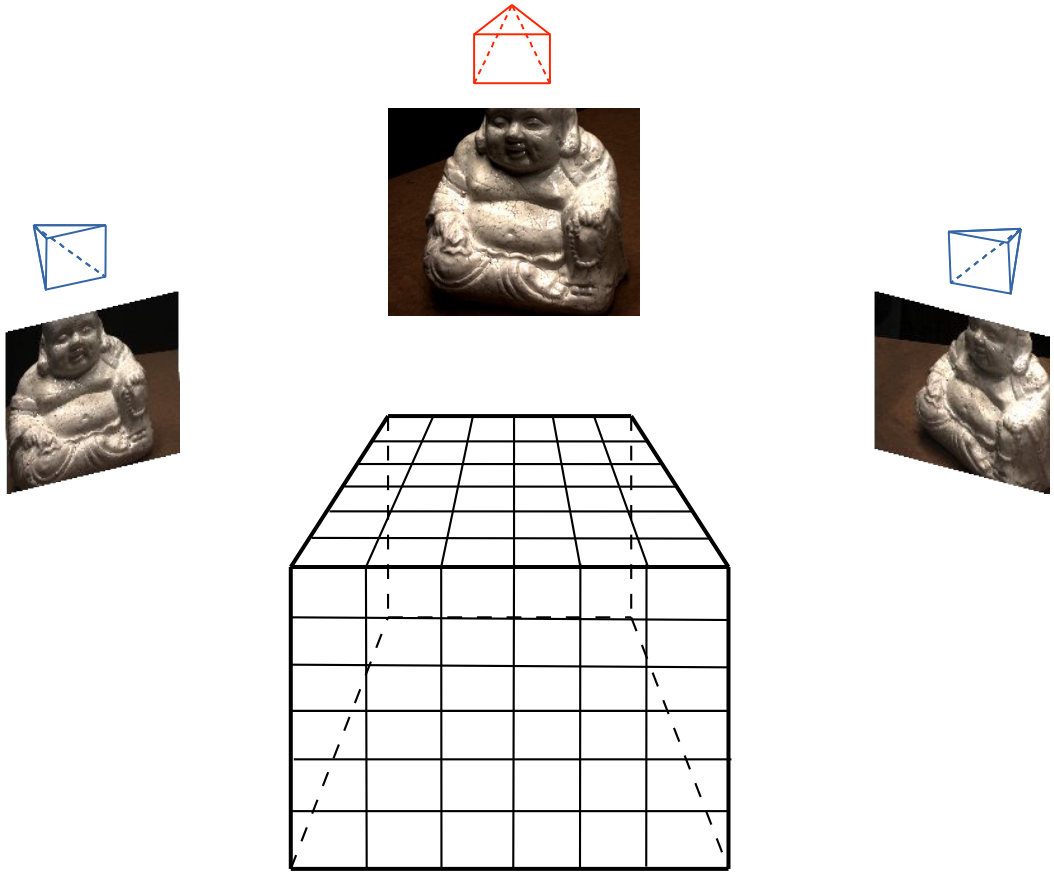
Cost-Volume-based MVS

Multi-view images and camera parameters

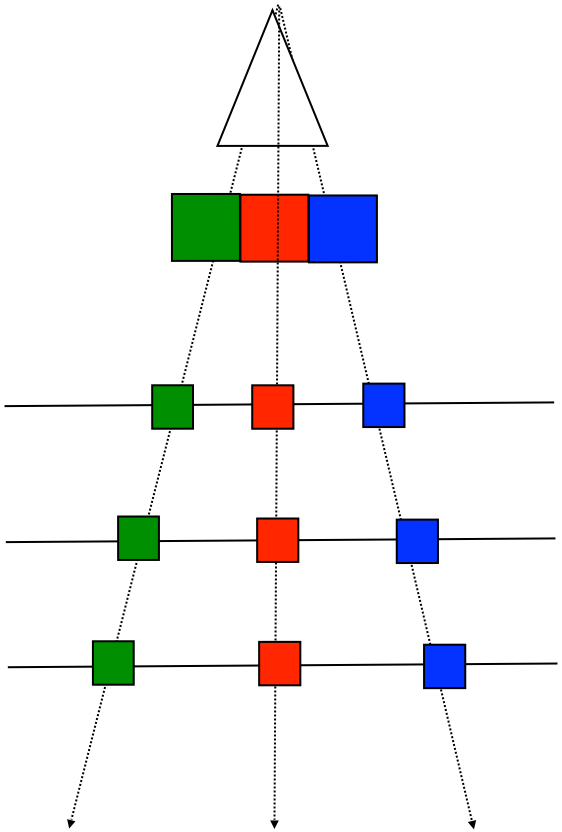


Cost-Volume-based MVS

Build 3D cost volume in reference view frustum



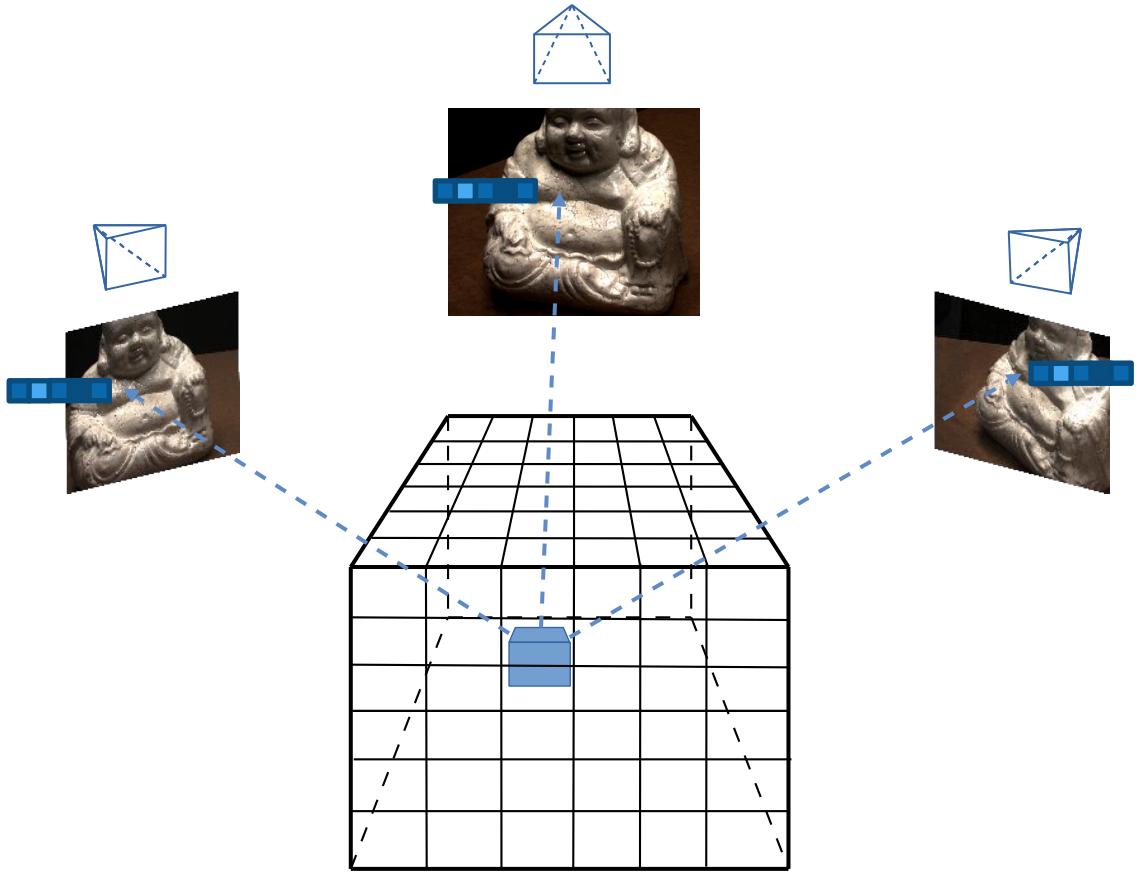
Topdown View of Cost Volume



Cost-Volume-based MVS

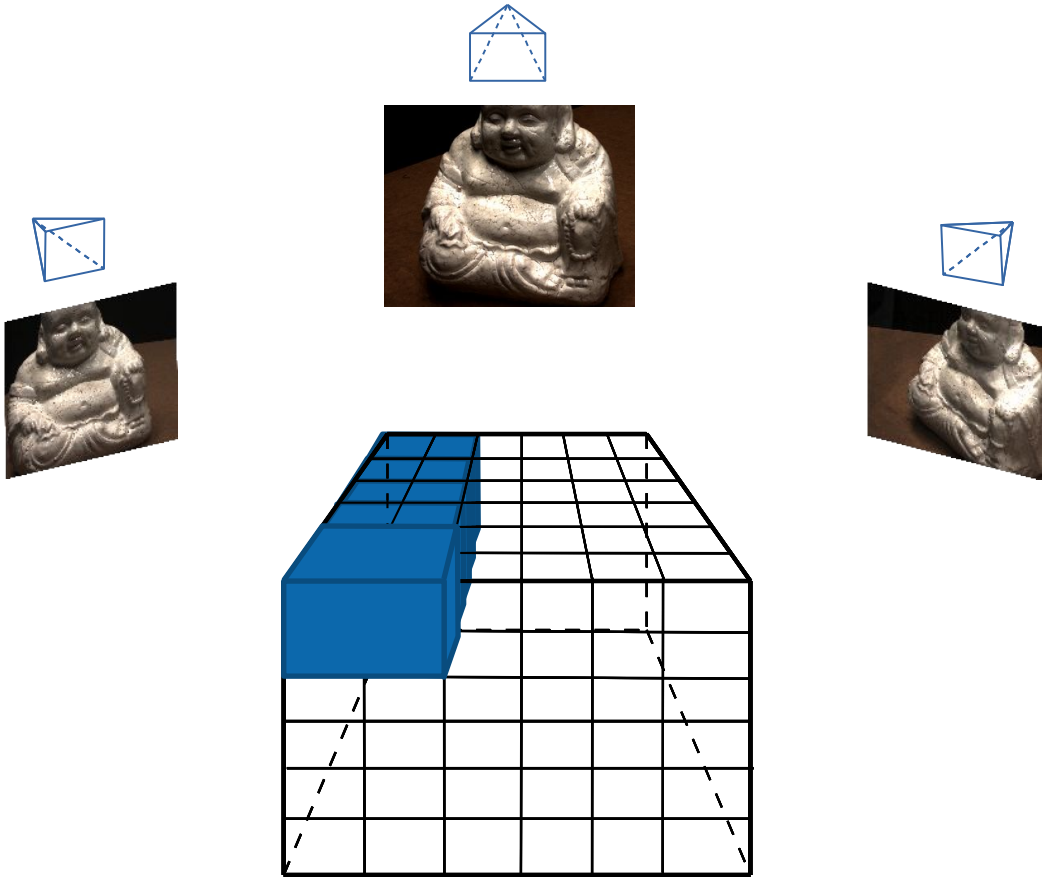
Fetch images features for each voxel

- Voxel in ground truth surface shows feature consistency



Cost-Volume-based MVS

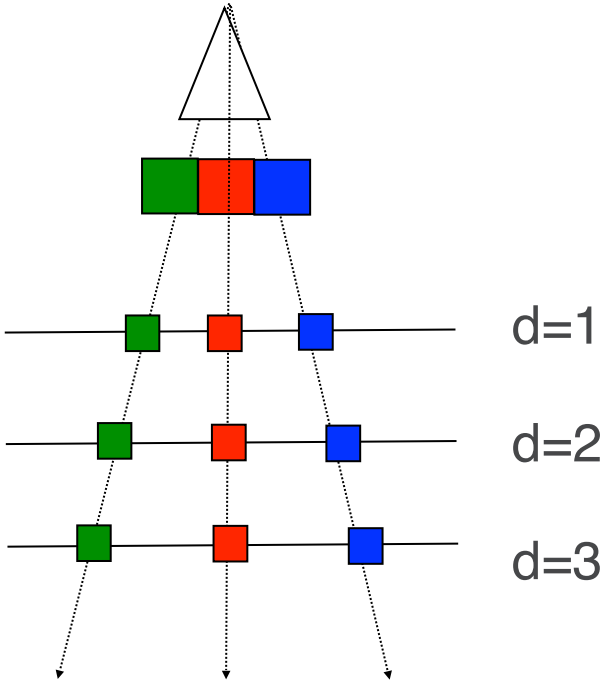
Dense 3D CNNs



Improve Output Resolution

- Differentiable soft-argmin to achieve sub-pixel accuracy.

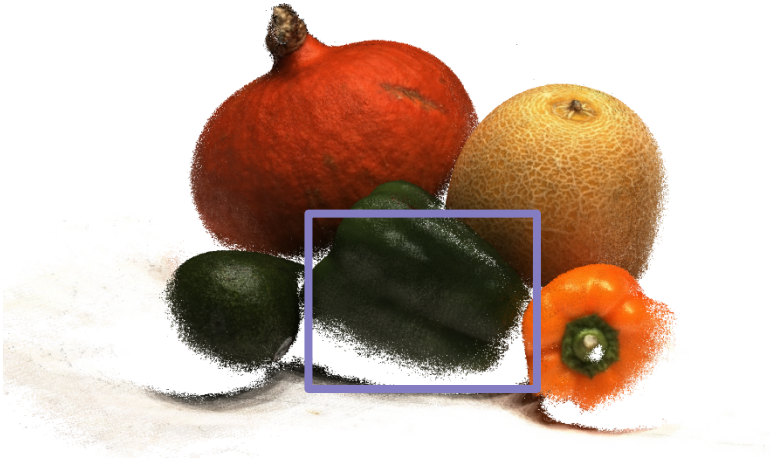
$$soft\ argmin := \sum_{d=0}^{D_{max}} d \times \sigma(-c_d)$$



Kendall et al., "**End-to-End Learning of Geometry and Context for Deep Stereo Regression**", *ICCV 2017*

Reconstruction is More Complete

Camp [2]



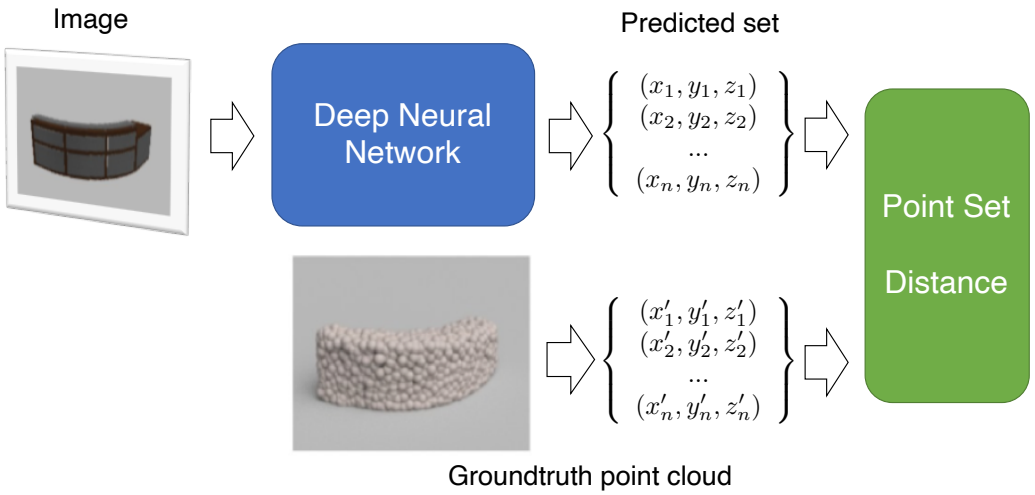
Ours

Agenda

- 3D Classification
- 3D Reconstruction
- **Others**

From Single Image to Point Cloud

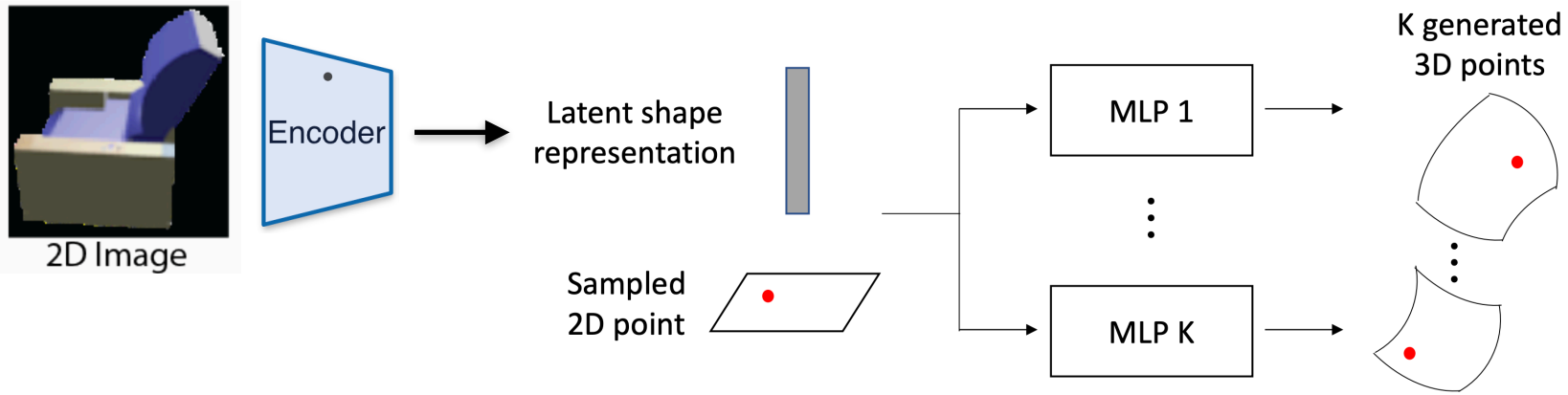
- It is possible to generate a **set** (permutation invariant)



Fan et al., "**A Point Set Generation Network for 3D Object Reconstruction from a Single Image**", *CVPR 2017*

From Image to Surface

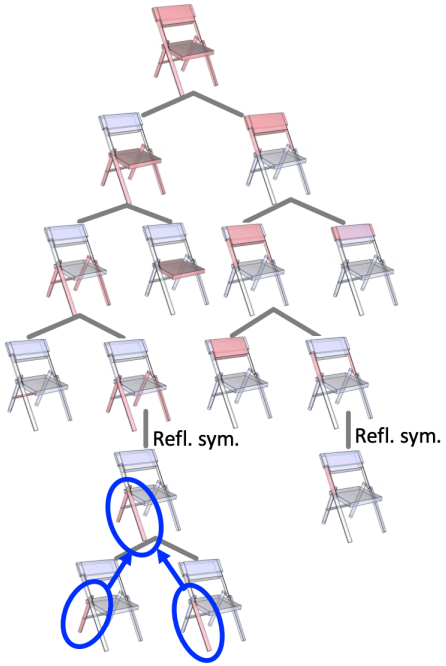
- Learn to warp a plane to surface

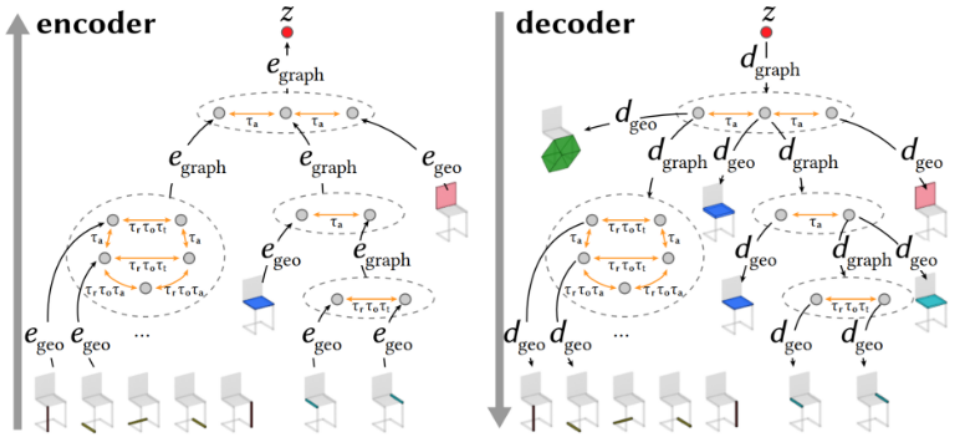


Groueix et al., "**AtlasNet: A Papier-Mâché Approach to Learning 3D Surface Generation**", *CVPR 2018*
*Yang, Yaoqing, et al. "**Foldingnet: Point cloud auto-encoder via deep grid deformation**", CVPR 2018*

Structured Prediction: Part-based

Recursive Network for Hierarchical Graph AE





Li, Jun et al., "**GRASS: Generative Recursive Autoencoders for Shape Structures**", *Siggraph 2017*

Mo, Kaichun et al., "**StructureNet, a hierarchical graph network for learning PartNet shape generation**", *Siggraph Asia 2019*

Structured Prediction: Part-based

Mo et al., "**StructureNet, a hierarchical graph network for learning PartNet shape generation**", *Siggraph Asia 2019*

Many More to Explore…