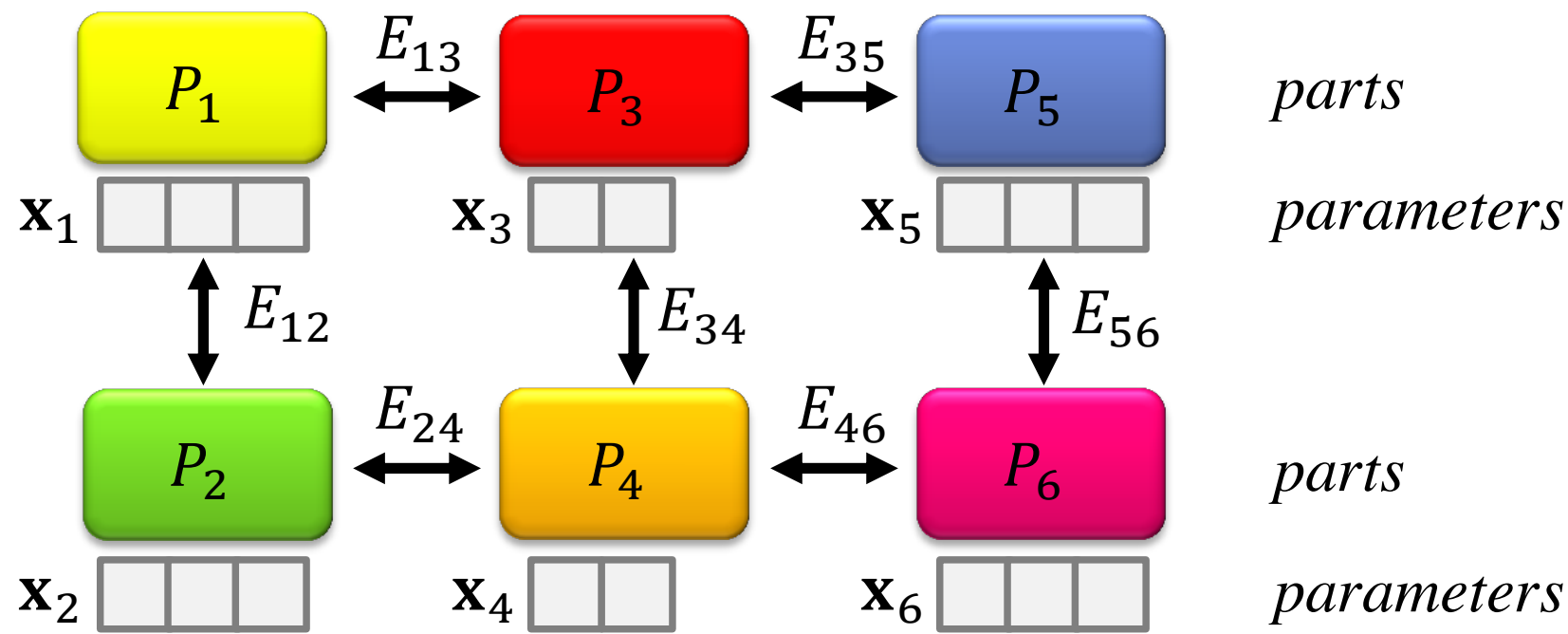


Structure-Aware Shape Processing



Niloy J. Mitra



Michael Wand



Universiteit Utrecht

Hao Zhang



Daniel Cohen-Or



Vladimir Kim Qi-Xing Huang



SA2013.SIGGRAPH.ORG

Course: Structure-Aware Shape Processing

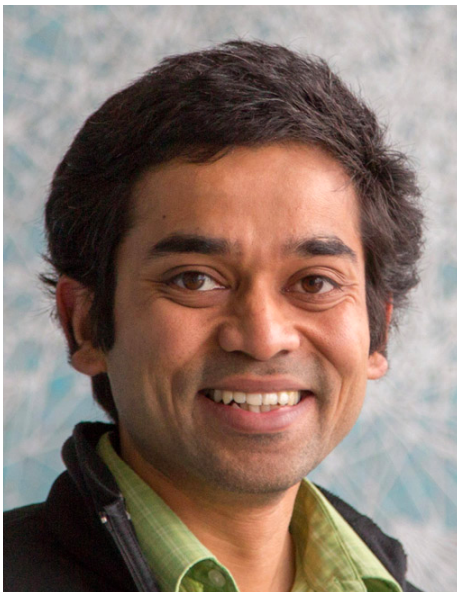
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Course Organizers

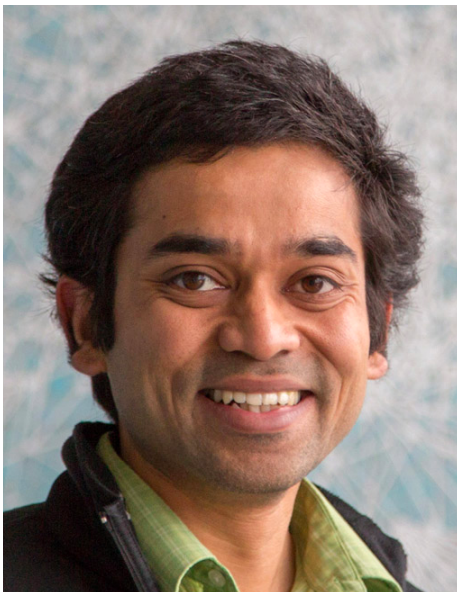
People

People



Niloy Mitra

People

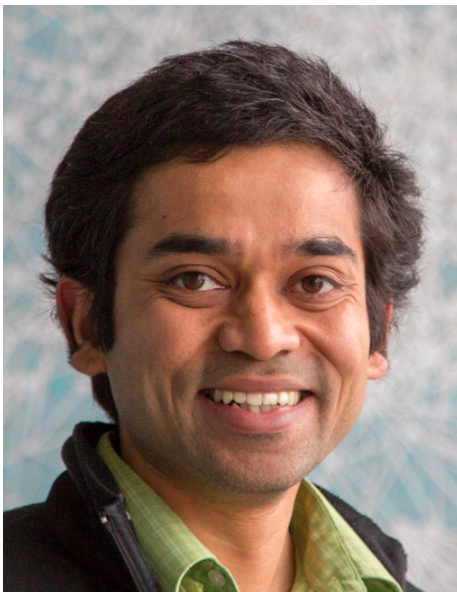


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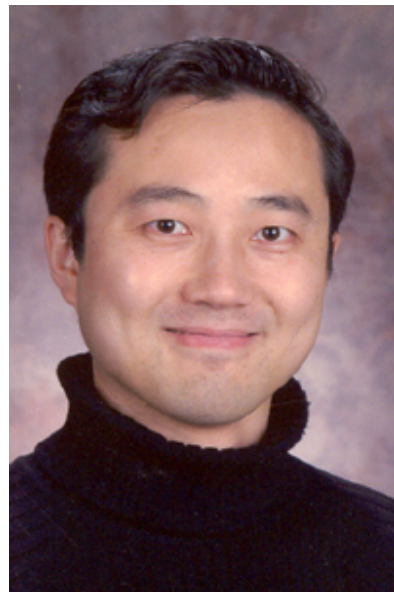
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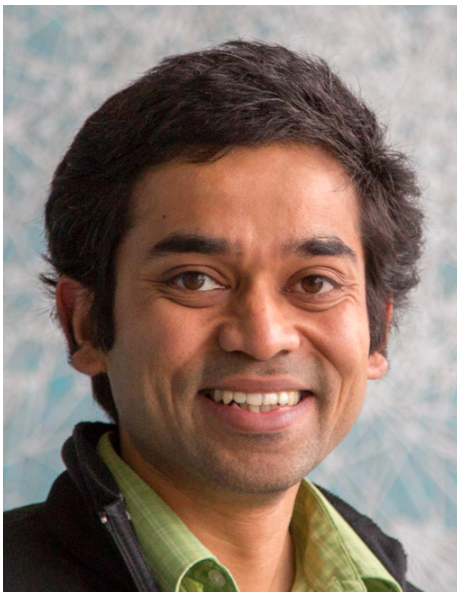


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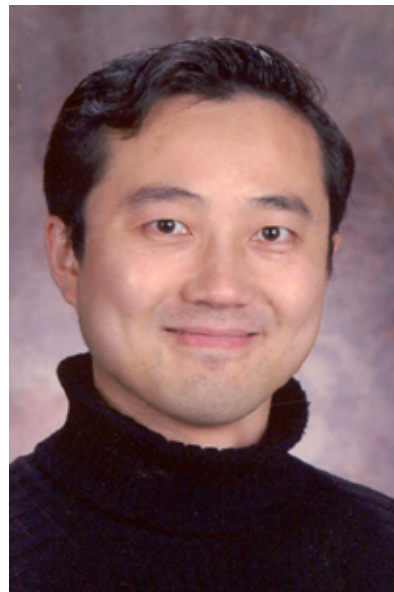
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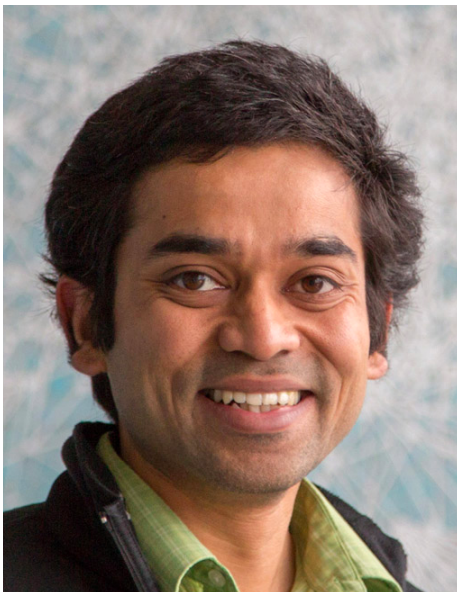


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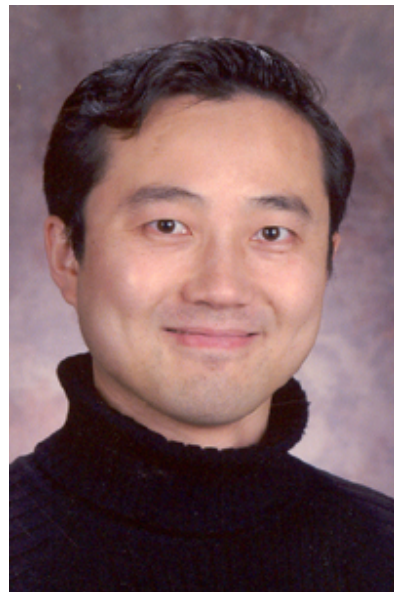
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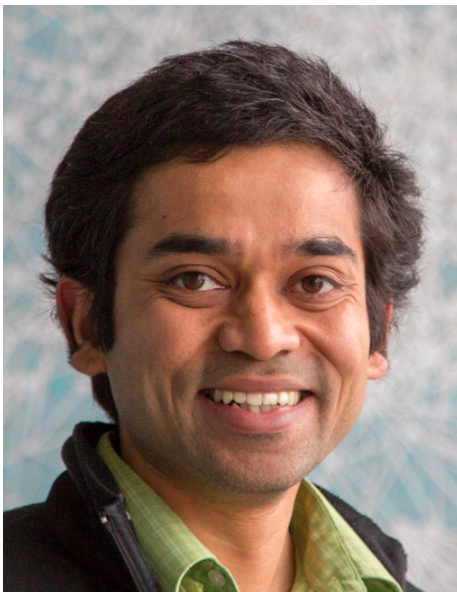


Daniel Cohen-Or



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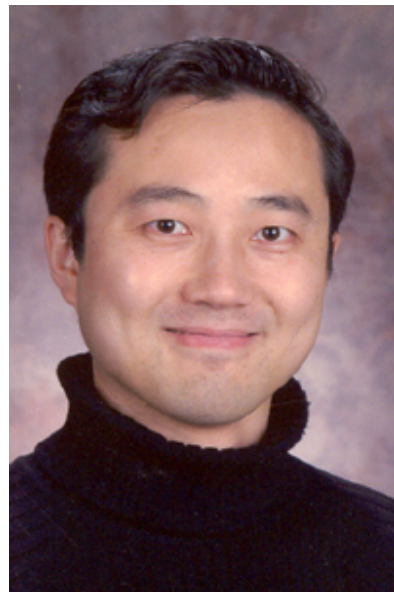
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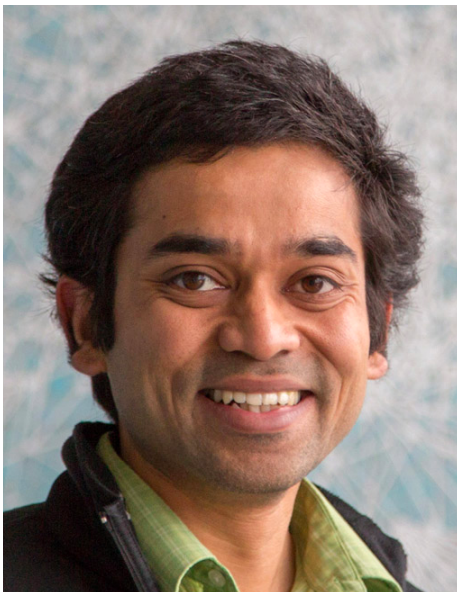


Vladimir Kim

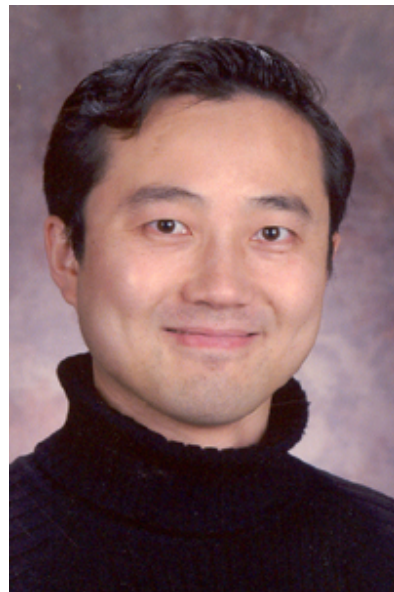


Qi-Xing Huang

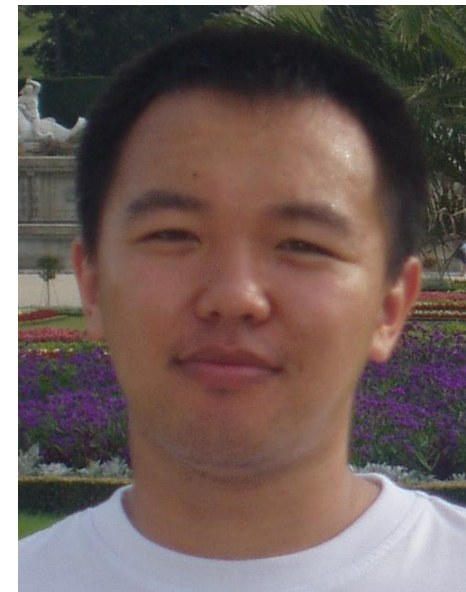
People



Niloy Mitra



Hao Zhang



Qi-Xing Huang

Course Structure

Course Structure

- **Introduction to Geometric ‘Structure’**

Course Structure

- **Introduction to Geometric ‘Structure’**
- **Extracting Structures**
 - analysis of Individual Models
 - analysis of Shape Collections (co-analysis)
 - encoding Structural Hierarchy

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- **Future Directions**

Introduction

Structure

*a **complex system** considered
from the point of view of the **whole**
rather than of any single part*

*a **complex system** considered
from the point of view of the **whole**
rather than of any single part*

*anything **composed of parts**
arranged together in some way
an organization*

On Growth and Form

744 THE THEORY OF TRANSFORMATIONS [CH.

in which we may inscribe the outline of the lobster becomes a shortened triangle in the case of the crab. In a little more detail we may compare the outline of the carapace in various crabs one with another: and the comparison will be found easy and significant, even, in many cases, down to minute details, such as the

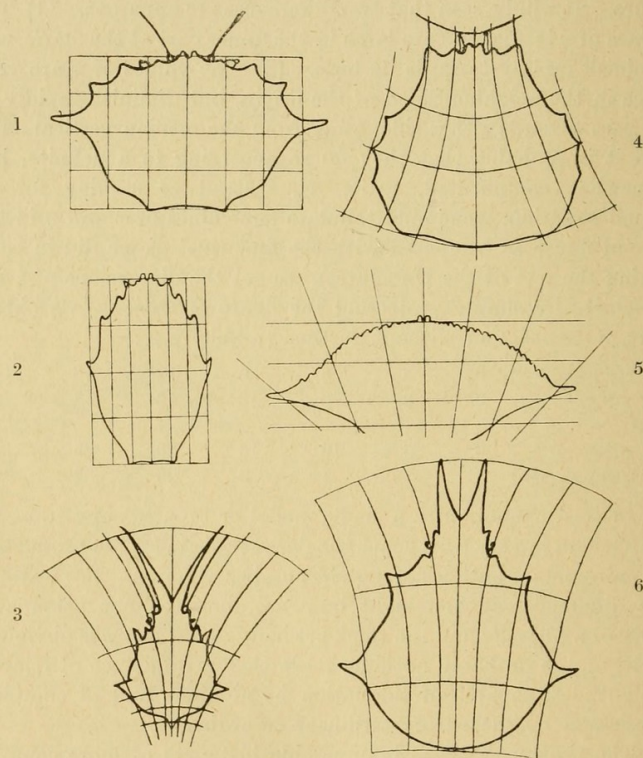


Fig. 369. Carapaces of various crabs. 1, *Geryon*; 2, *Corystes*; 3, *Scyramathia*; 4, *Paralomis*; 5, *Lupa*; 6, *Chorinus*.

number and situation of the marginal spines, though these are in other cases subject to independent variability.

If we choose, to begin with, such a crab as *Geryon* (Fig. 369, 1), and inscribe it in our equidistant rectangular co-ordinates, we shall see that we pass easily to forms more elongated in a transverse

For it is not a bundle of parts but an organization of parts, of parts in their ***relative arrangement***, . . . the coordinated parts, now as related and fitted *to the end or function* of the whole, and now as related to or resulting ***from the physical causes*** inherent in the entire system of forces to which the whole has been exposed.

Chapter XVI [Thompson 1892]

Structure in Shapes

Structure in Shapes

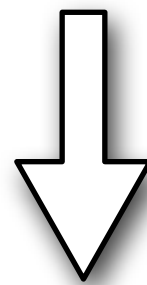


structures in nature

Structure in Shapes

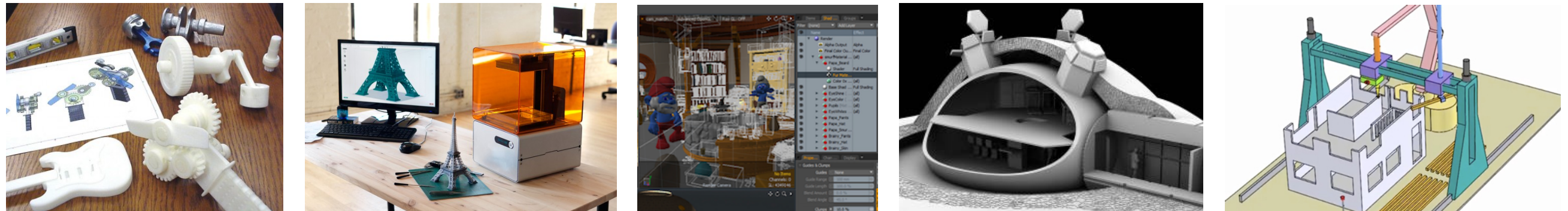


structures in nature

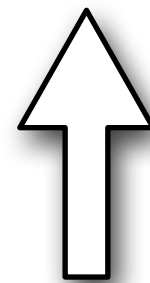


‘structures’ as captured

Structure in Shapes



back to the physical world



‘structures’ as captured

Shape Synthesis

Shape Synthesis

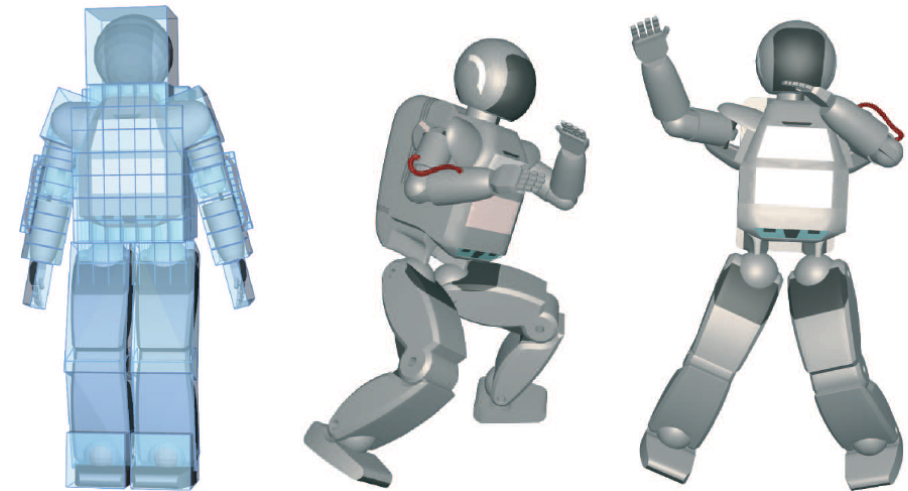


[Funkhouser et al. 04]

Shape Synthesis



[Funkhouser et al. 04]

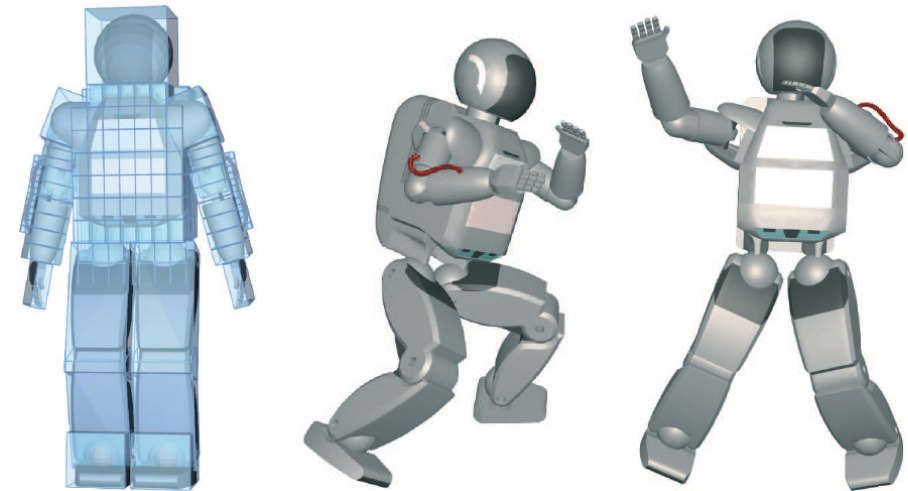


[Xu et al. 09]

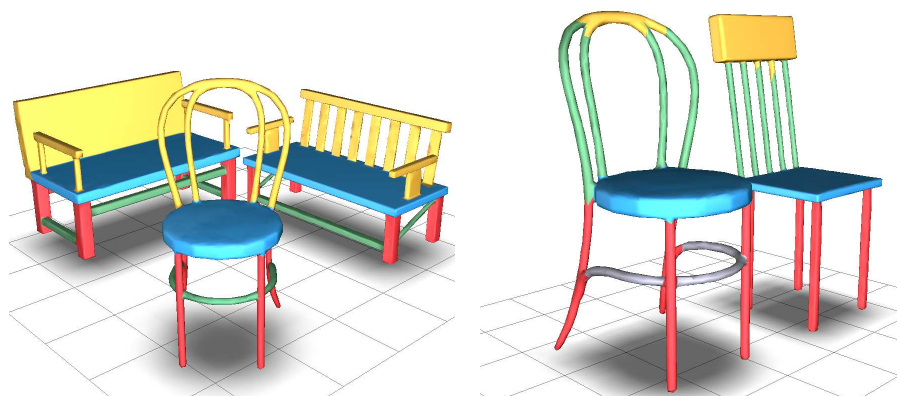
Shape Synthesis



[Funkhouser et al. 04]



[Xu et al. 09]

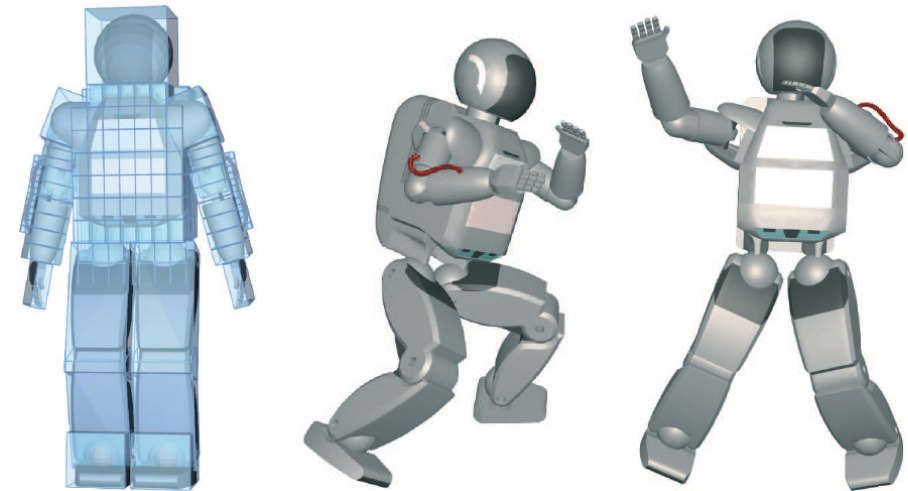


[Laga et al. 13]

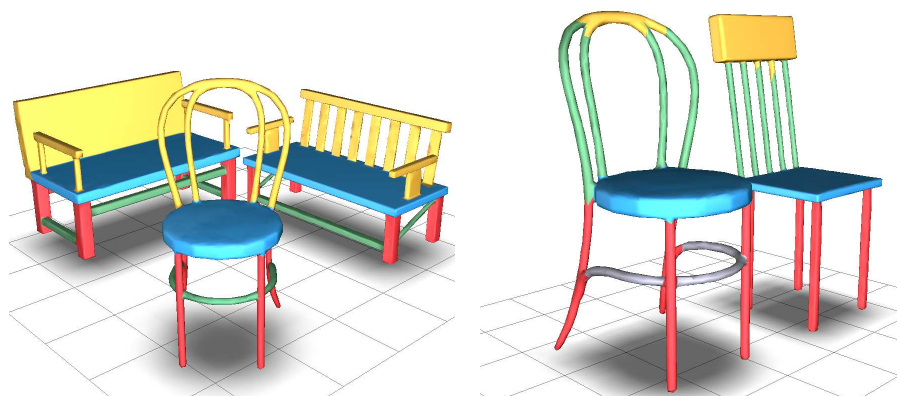
Shape Synthesis



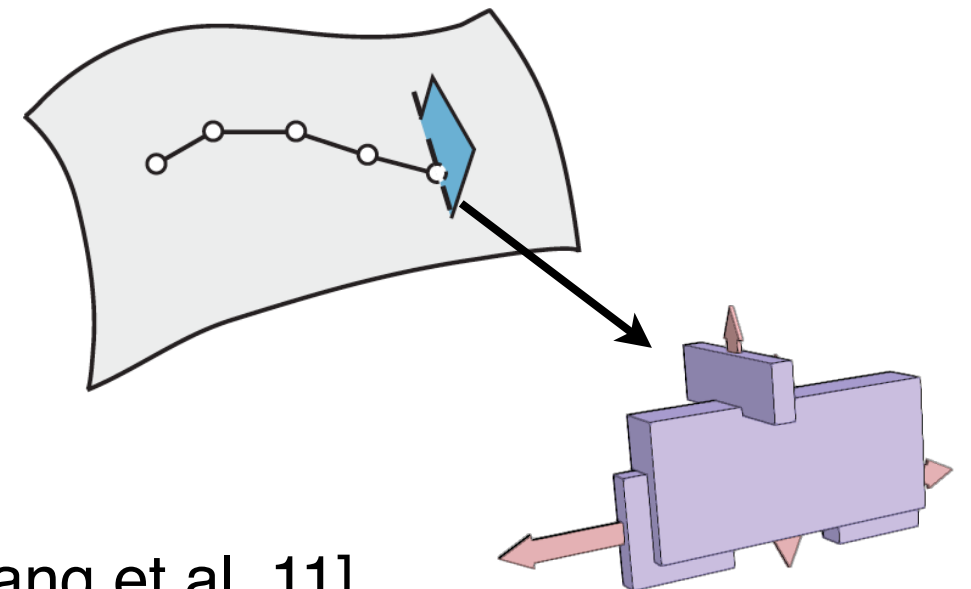
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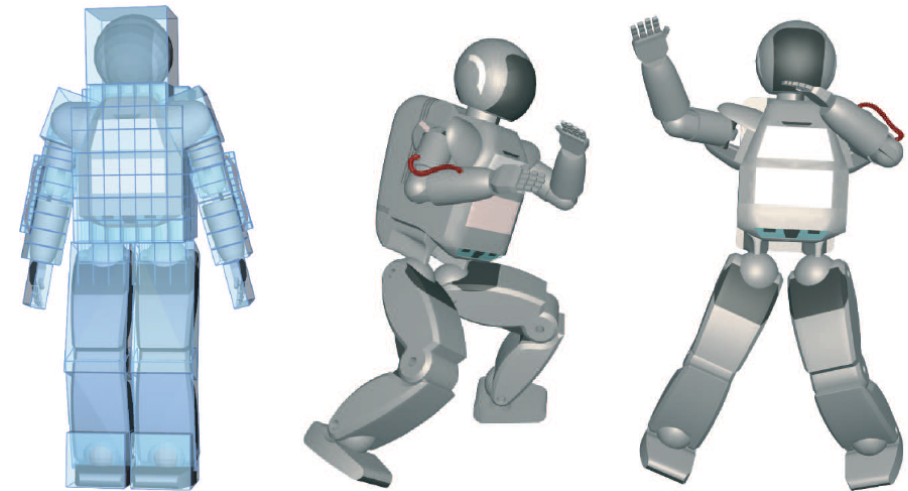


[Yang et al. 11]

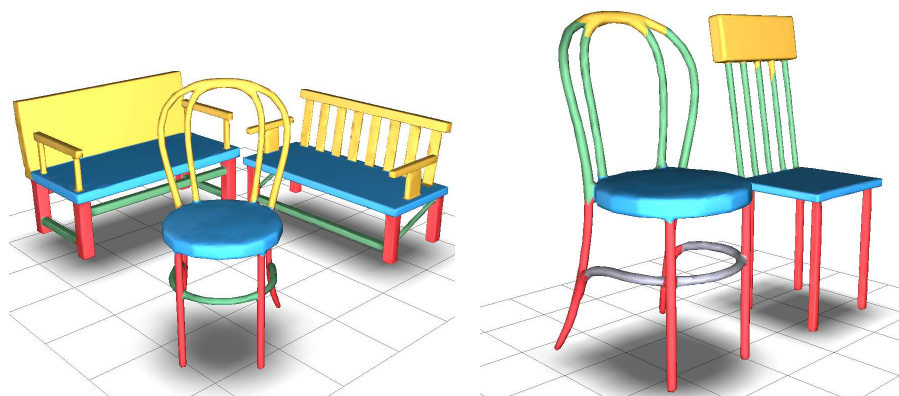
Shape Synthesis



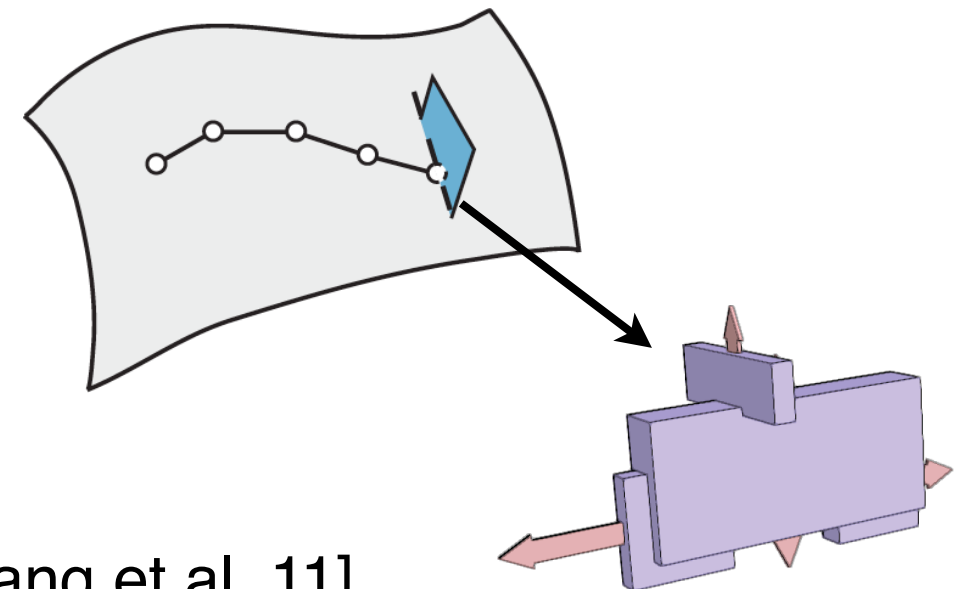
[Funkhouser et al. 04]



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and much much more ...

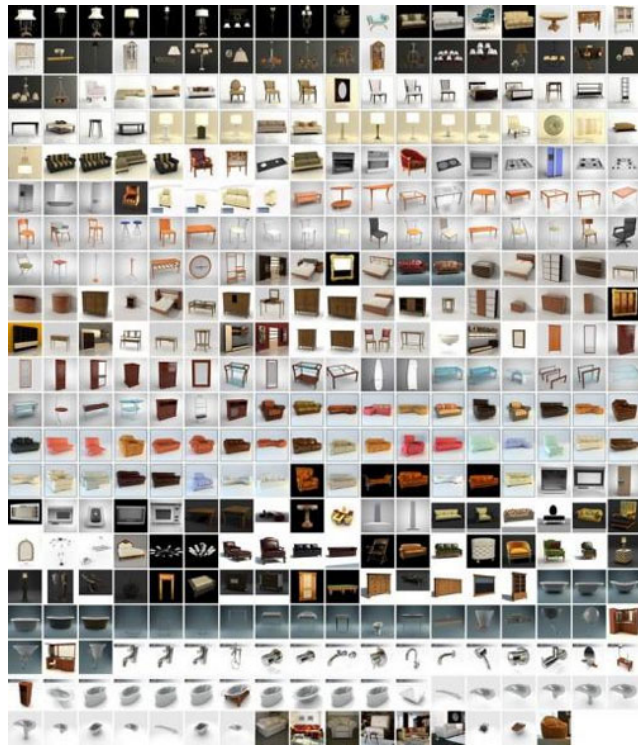
- Model retrieval
- Reconstruction
- Deformation
- Synthesis
- Form-finding
- Design exploration

and much much more ...

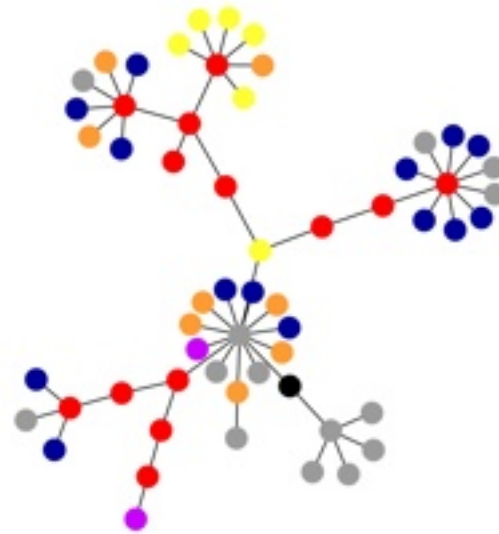
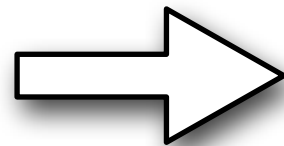
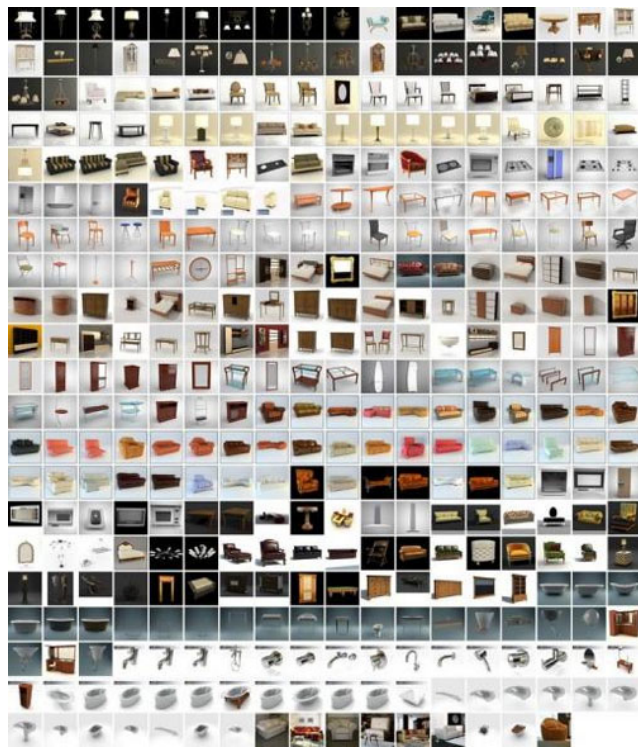
- Model retrieval
- Reconstruction
- Deformation
- Synthesis
- Form-finding
- Design exploration

structure of individual shapes and among shape collections

Structure-aware Shape Processing

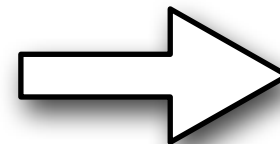
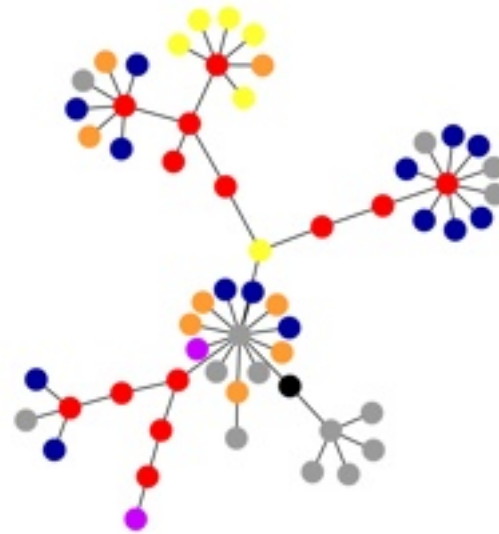
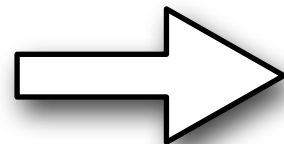
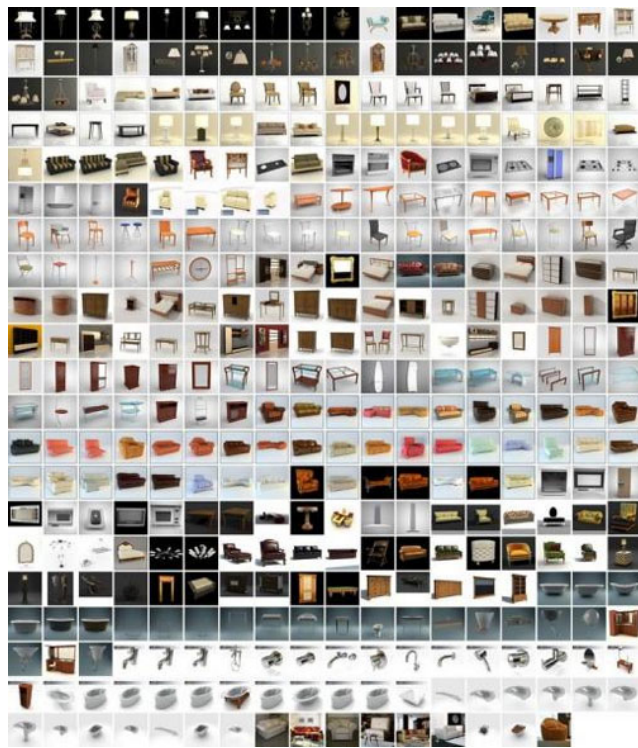


Structure-aware Shape Processing



analysis

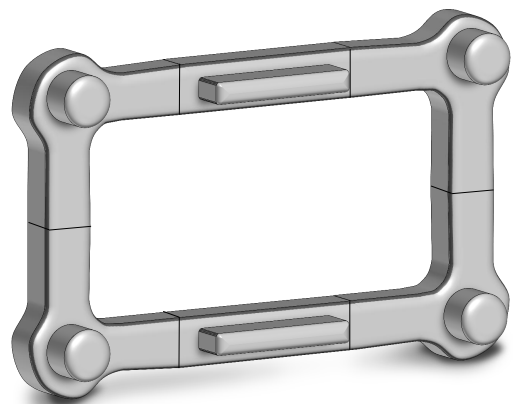
Structure-aware Shape Processing



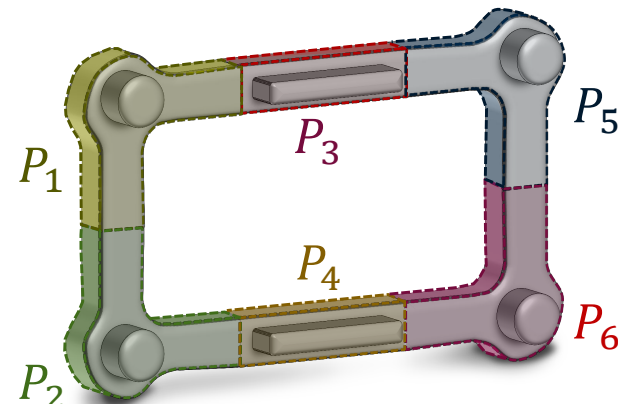
analysis

synthesis

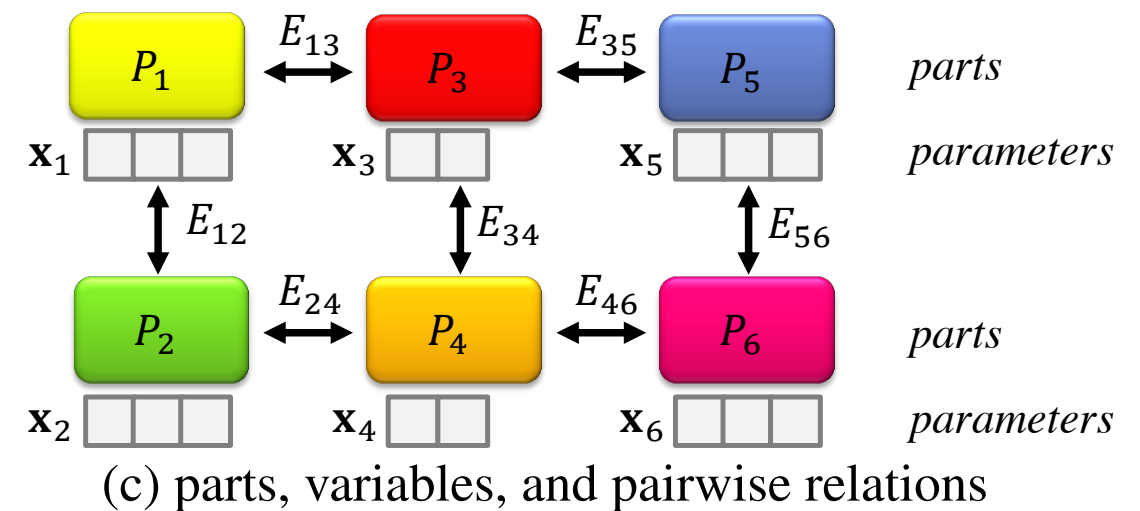
Encoding Structure



(a) a piece of geometry \mathcal{S}

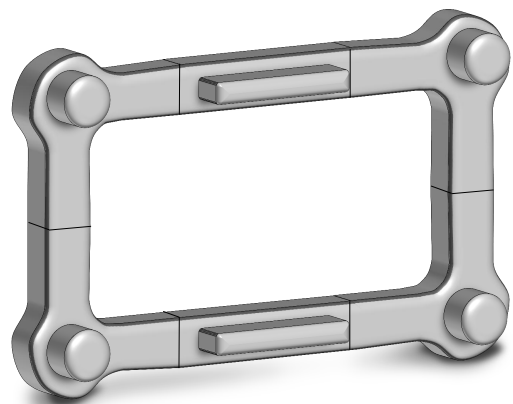


(b) parts and part geometry

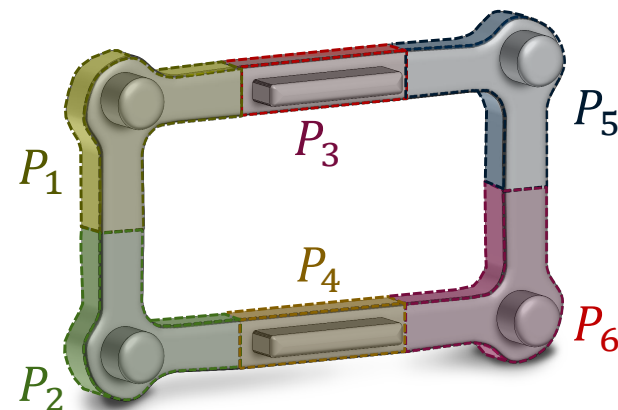


Encoding Structure

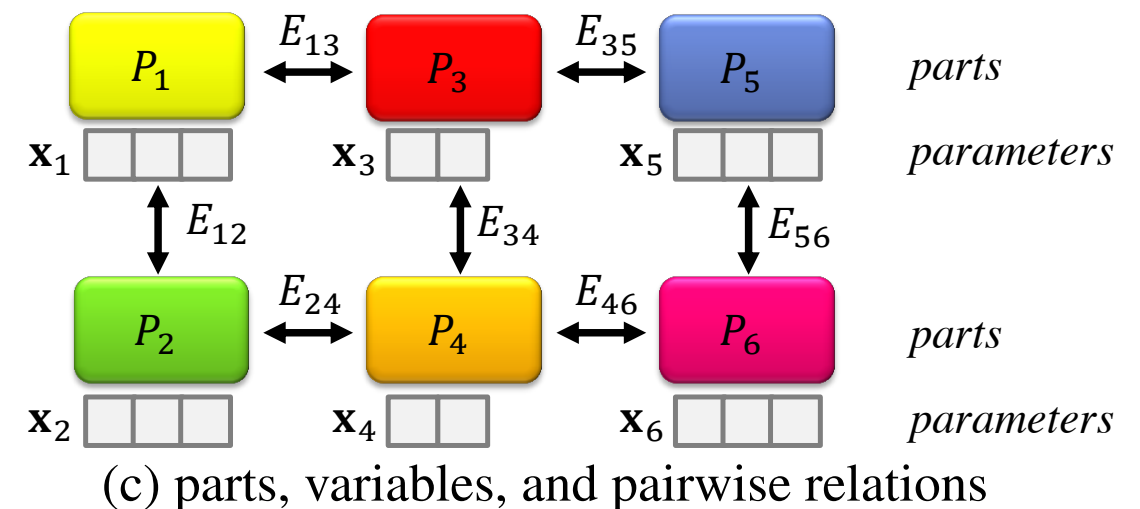
What are the parts?



(a) a piece of geometry \mathcal{S}



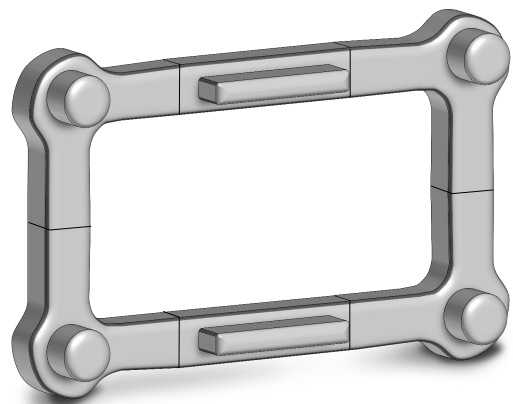
(b) parts and part geometry



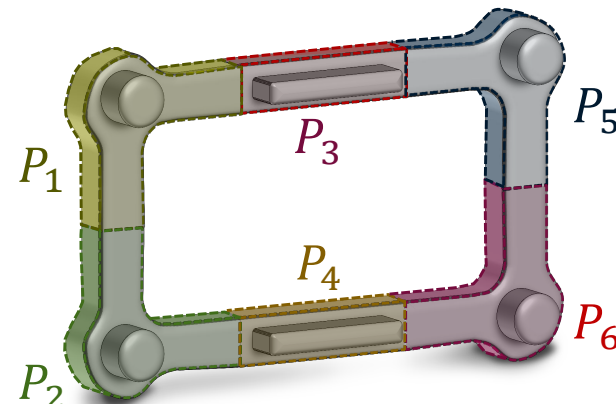
Encoding Structure

What are the parts?

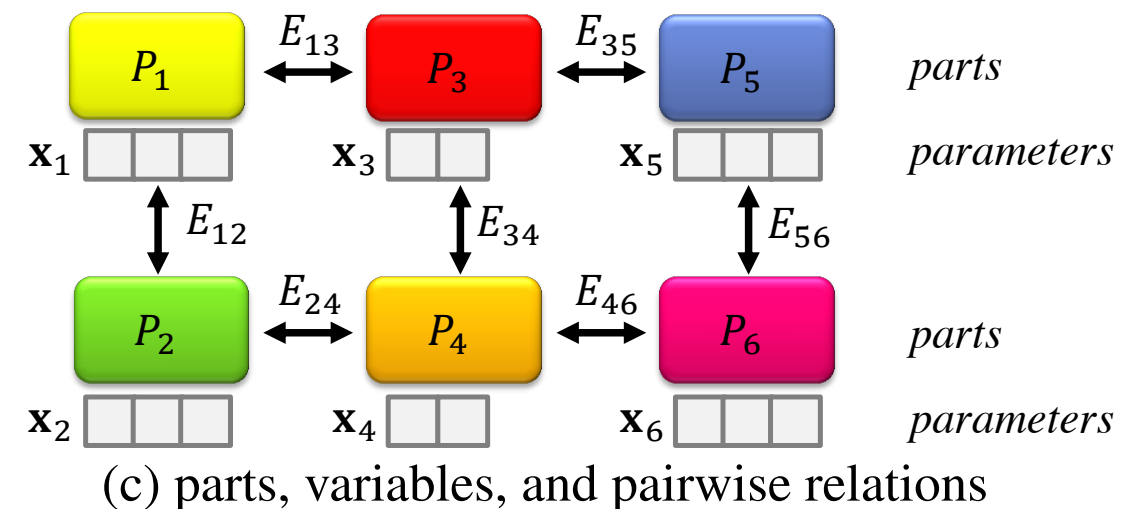
How do the parts relate in/across models?



(a) a piece of geometry \mathcal{S}



(b) parts and part geometry

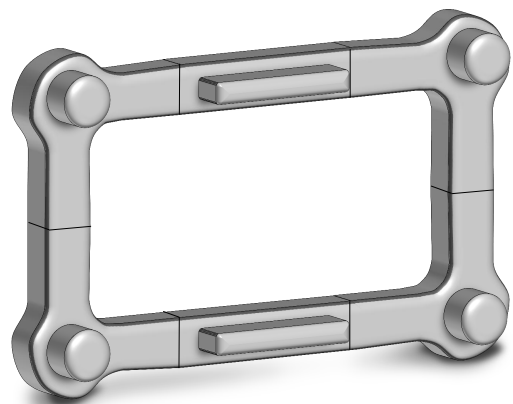


Encoding Structure

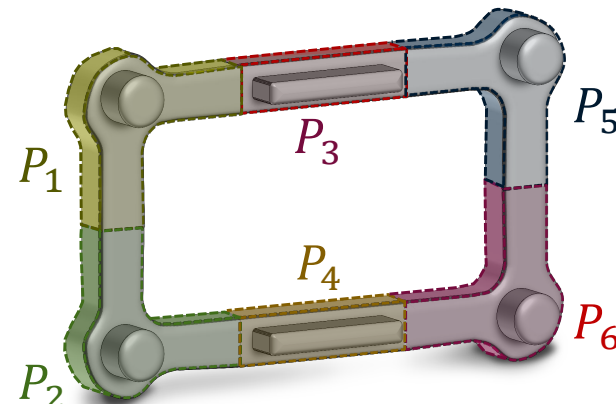
What are the parts?

How do the parts relate in/across models?

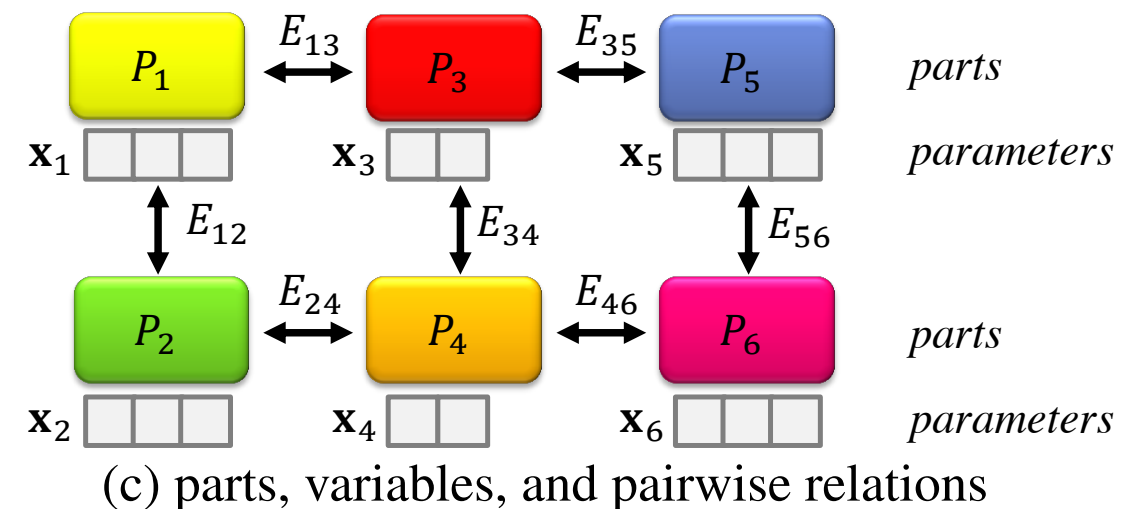
How do the parts vary across the models?



(a) a piece of geometry \mathcal{S}



(b) parts and part geometry

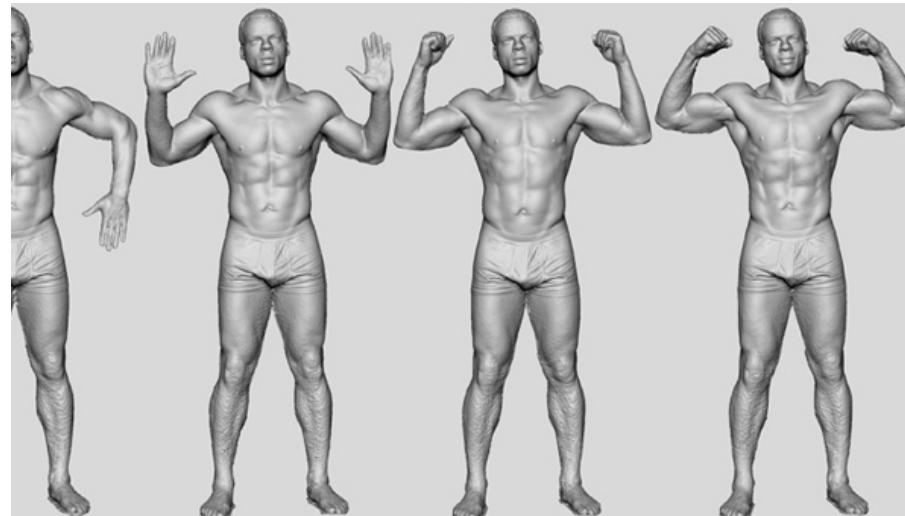


New Sources of Data

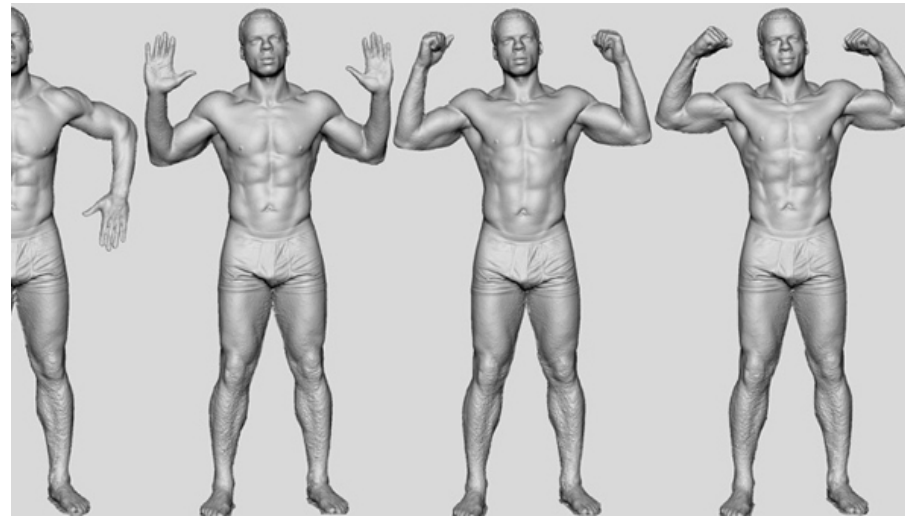
New Sources of Data



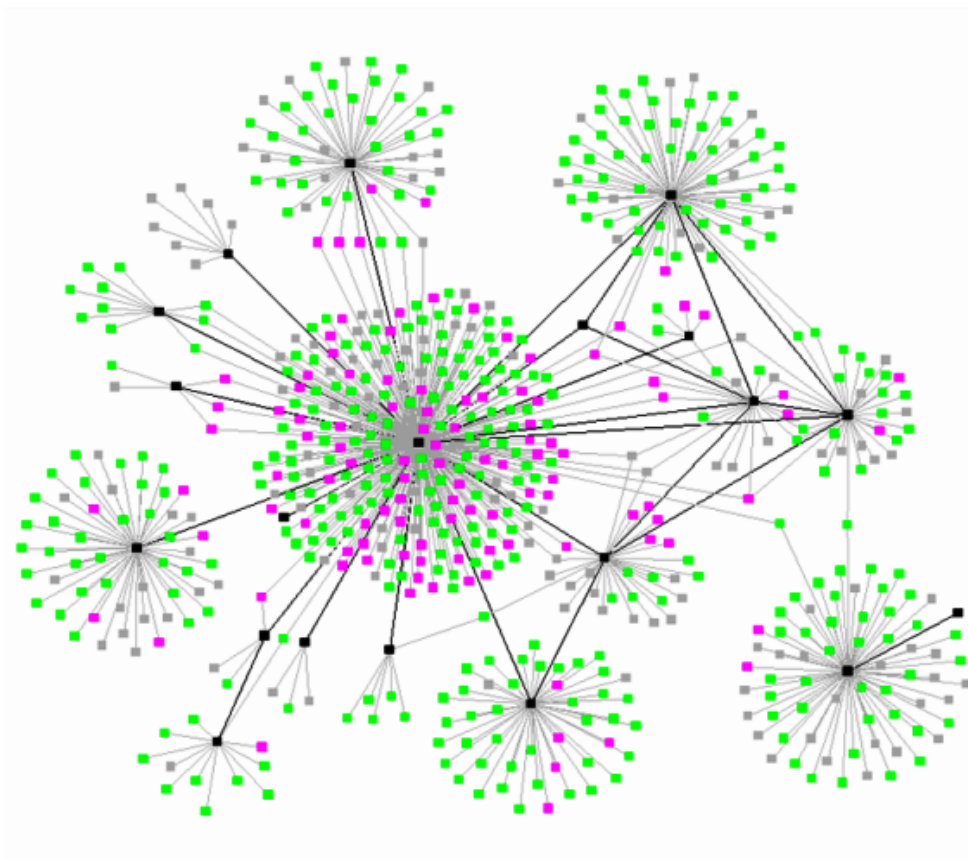
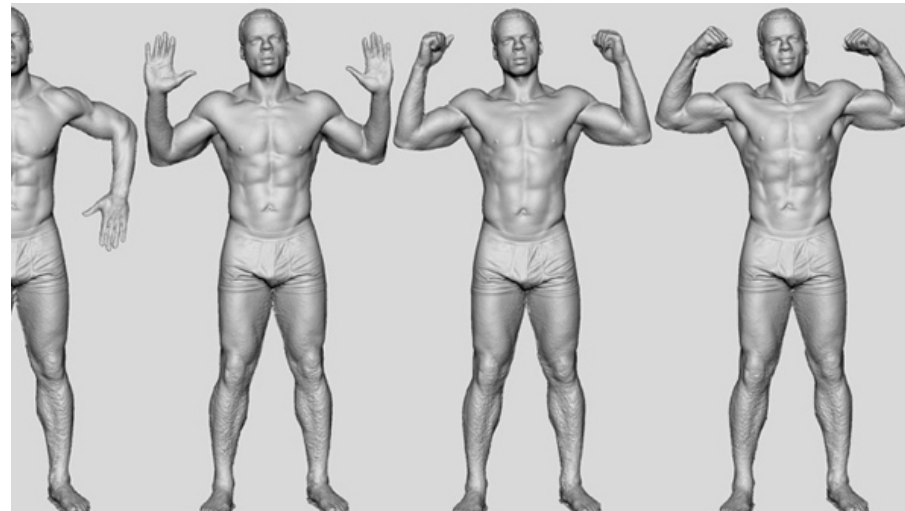
New Sources of Data



New Sources of Data



New Sources of Data

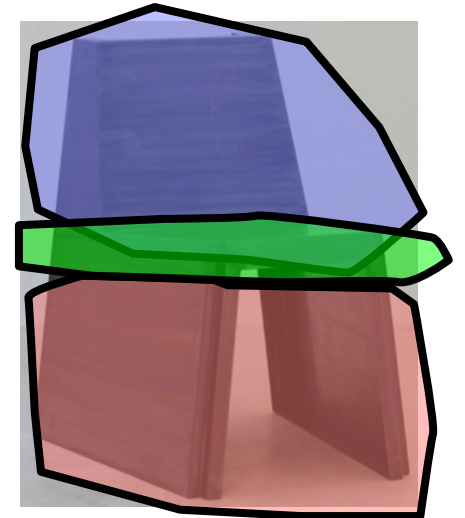
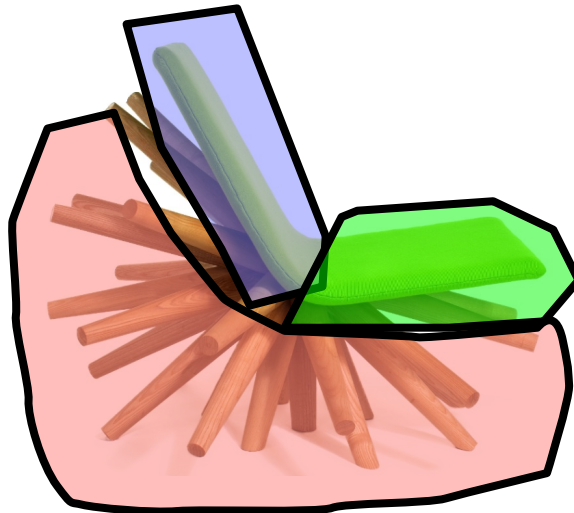
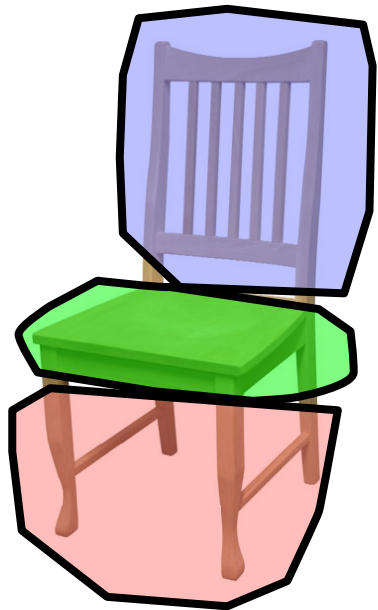


network of parts

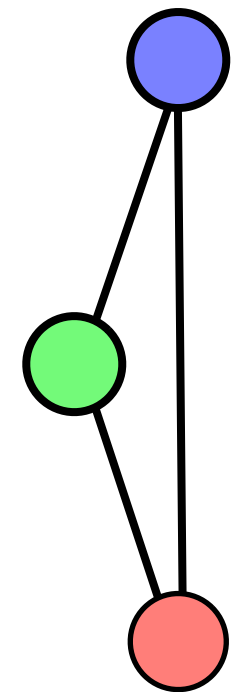
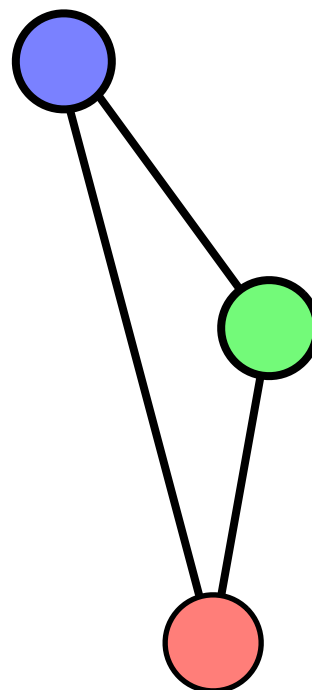
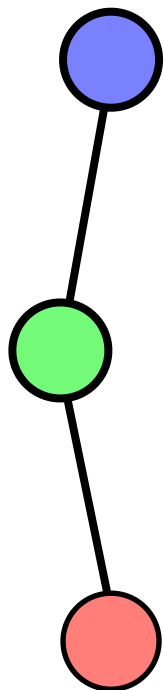
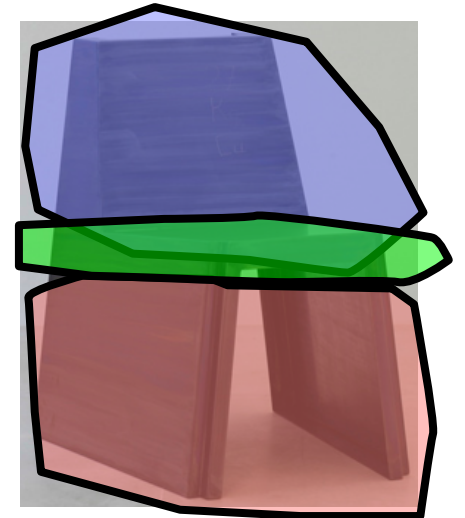
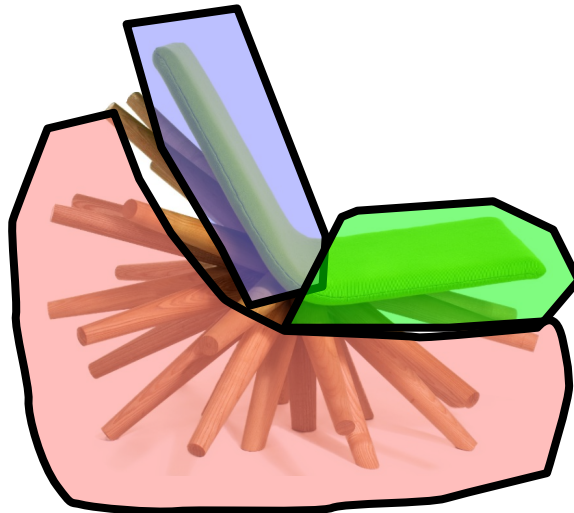
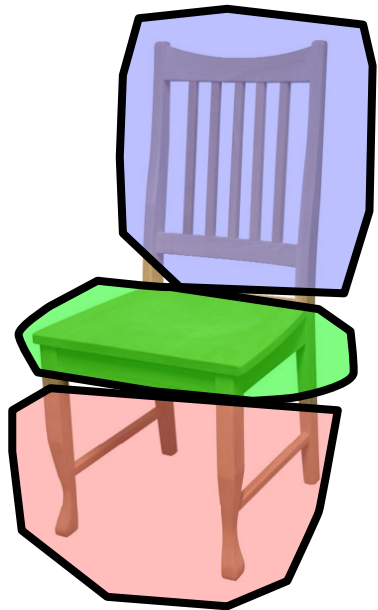
Why Structures?



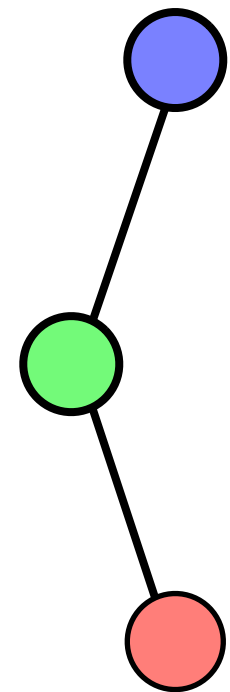
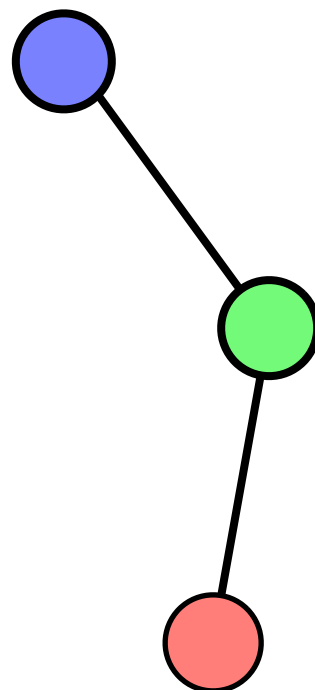
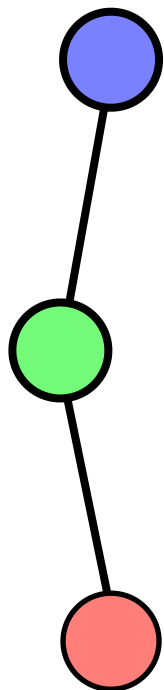
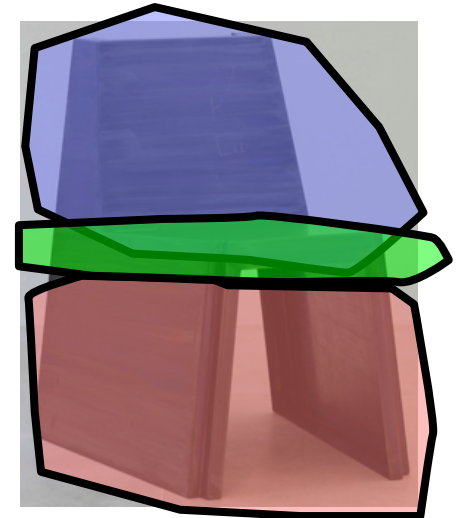
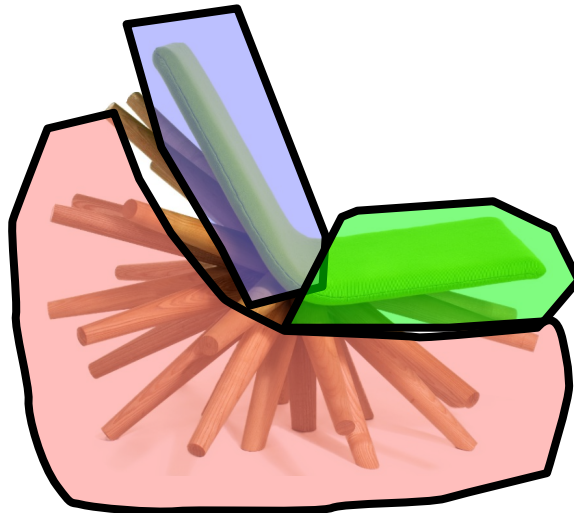
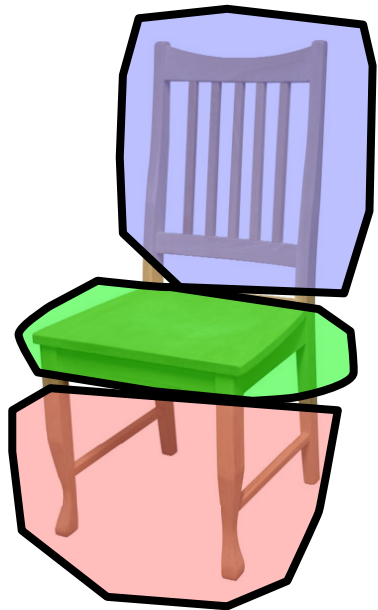
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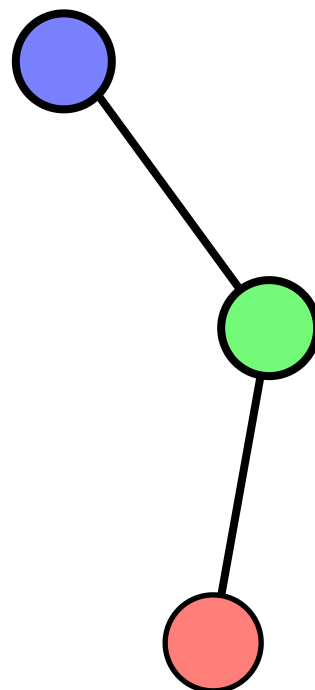
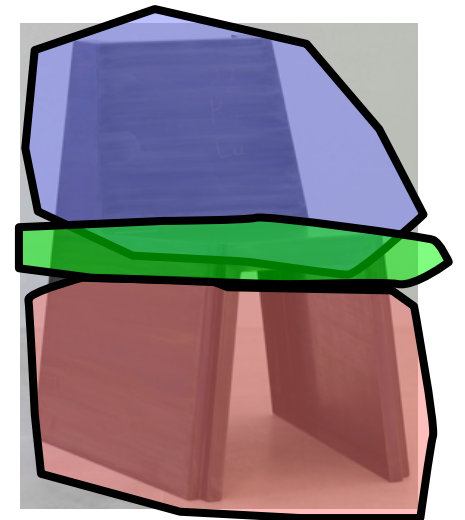
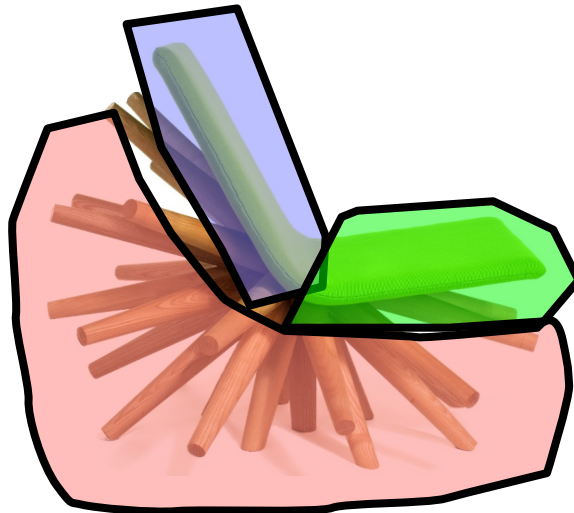
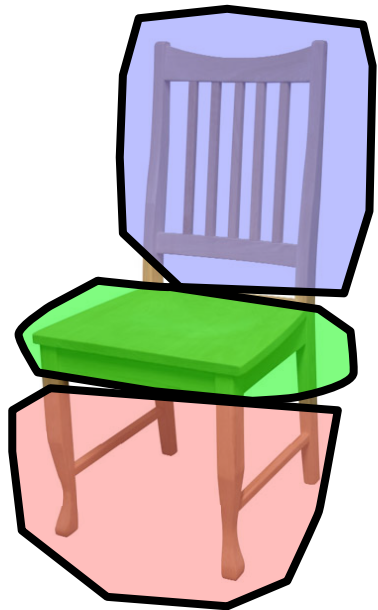
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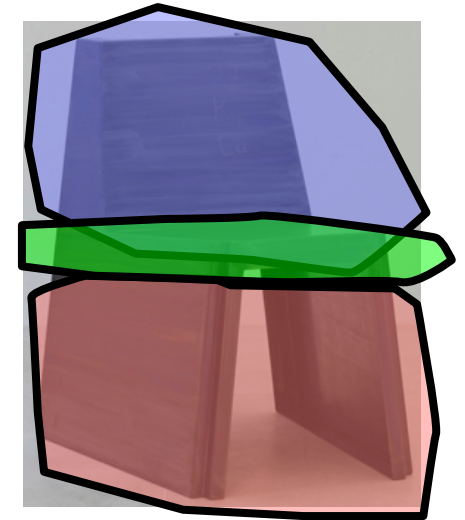
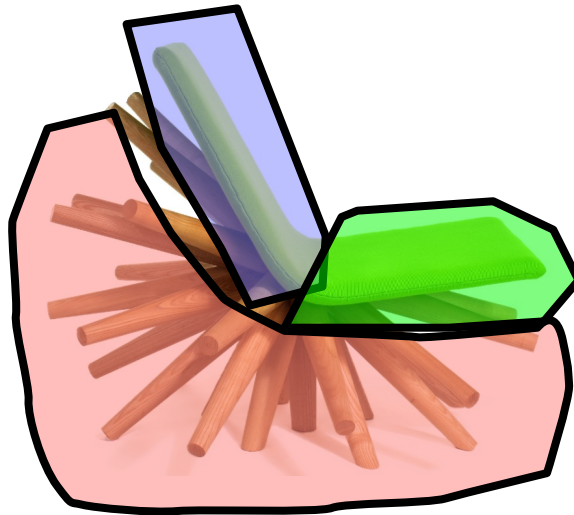
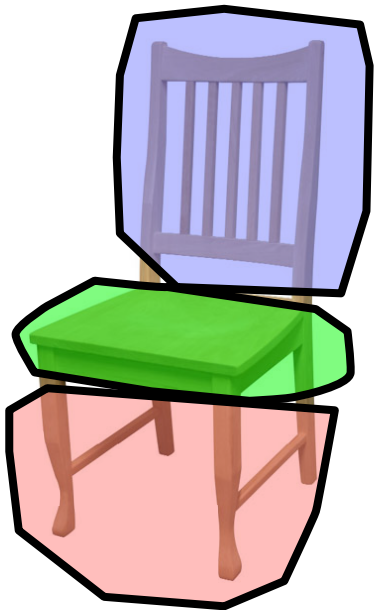
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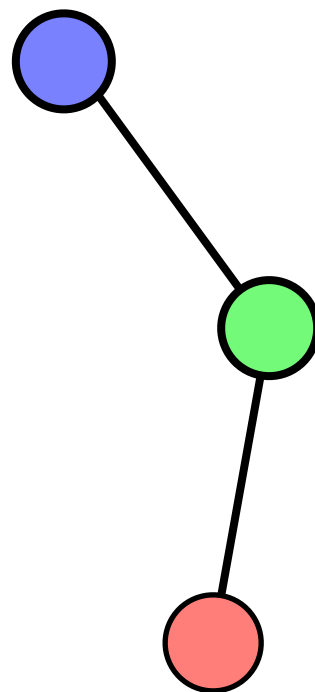
Why Structures?



Why Structures?



relation graph + variations ~ captures semantics?



Historical Perspective

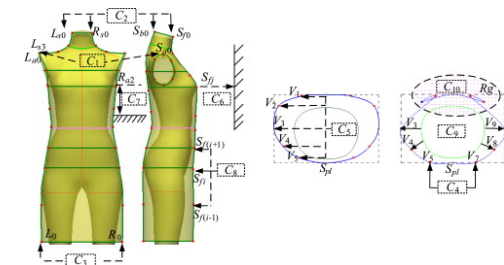
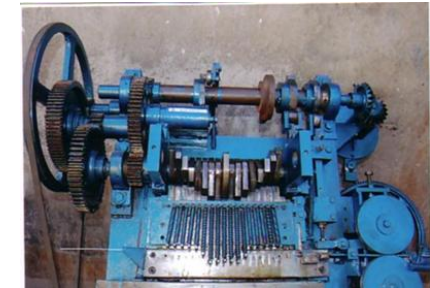
Historical Perspective

- Mechanical assemblies



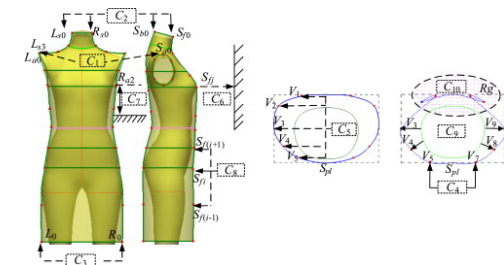
Historical Perspective

- Mechanical assemblies
- CAD community: constrained editing



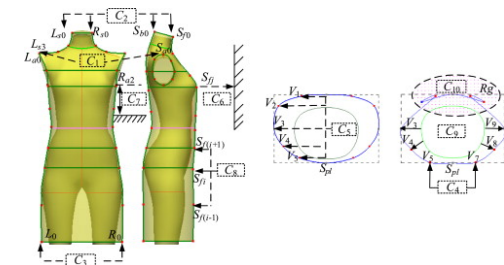
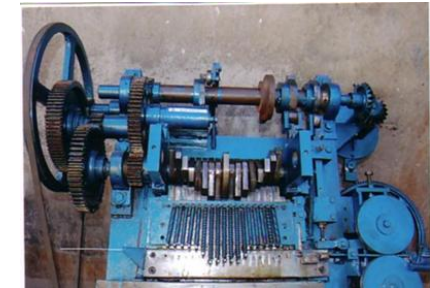
Historical Perspective

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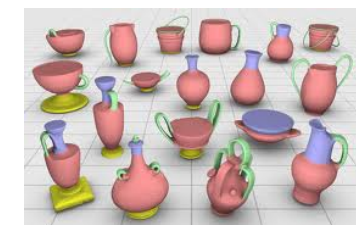
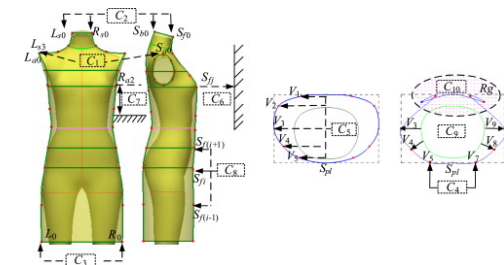
Historical Perspective

- Mechanical assemblies
- CAD community: constrained editing
- Compositional modeling
- Symmetry analysis



Historical Perspective

- Mechanical assemblies
- CAD community: constrained editing
- Compositional modeling
- Symmetry analysis
- Co-analysis of model collections, etc.



Discovering Structure

Discovering Structure

What are the parts (and their parameters)?

Segmentation

Discovering Structure

What are the parts (and their parameters)?

Segmentation

How do the parts relate in/across models?

Correspondence

Discovering Structure

What are the parts (and their parameters)?

Segmentation

How do the parts relate in/across models?

Correspondence

How do the parts vary across the models?

Deformation

Identifying Parts

Identifying Parts

- user annotated

Identifying Parts

- user annotated
- template fitting

Identifying Parts

- user annotated
- template fitting
- supervised learning
(e.g., classifiers on labeled parts)

Identifying Parts

- user annotated
- template fitting
- supervised learning
(e.g., classifiers on labeled parts)
- unsupervised learning
(e.g., spectral clustering)

Extracting Part Parameters

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- User specified parameters

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- Model fitting
(e.g., RANSAC, primitive fitting)

Extracting Part Parameters

- User specified parameters
- Model fitting
(e.g., RANSAC, primitive fitting)
- Learned from data
(e.g., PCA, manifold learning, etc.)

Extracting Relations

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(e.g., constrained-modeling)

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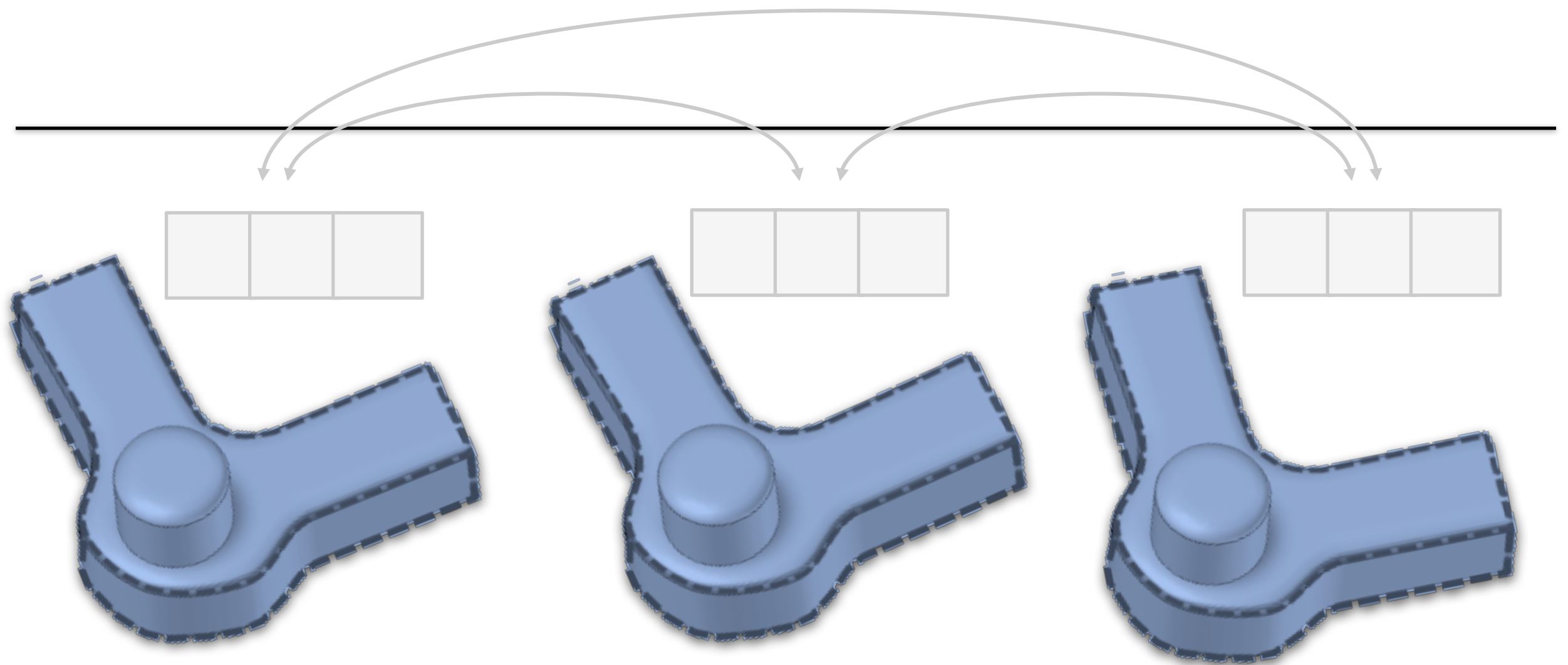
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Parts

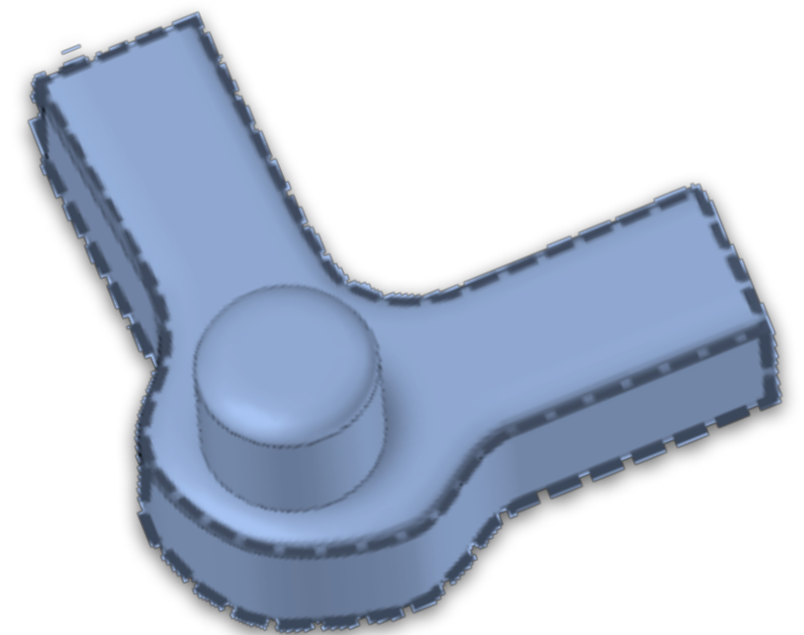
Parameters

Relations



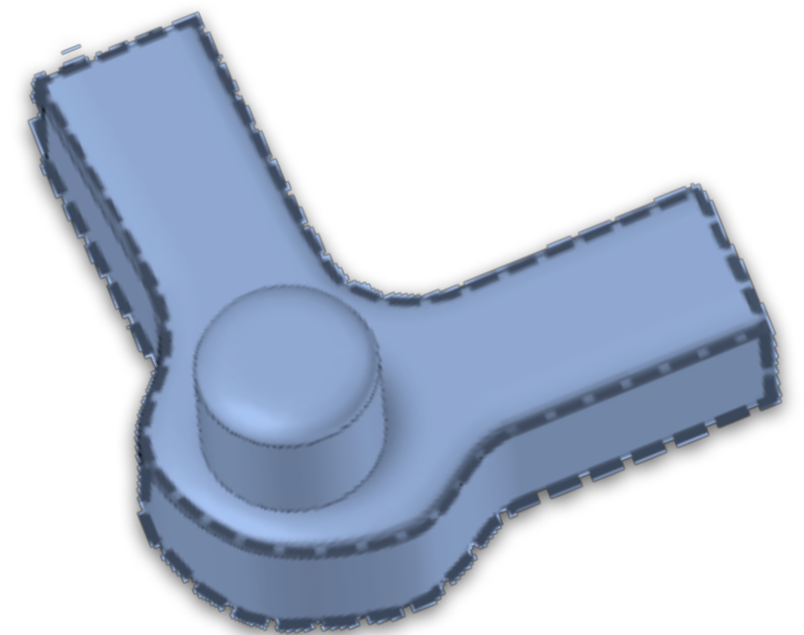
- Modeling and Detecting Parts
 - User defined parts
 - Manual segmentation
 - Fixed models
 - A priori segmentation model
 - Data-driven segmentation
 - A priori: meta-model

Parts



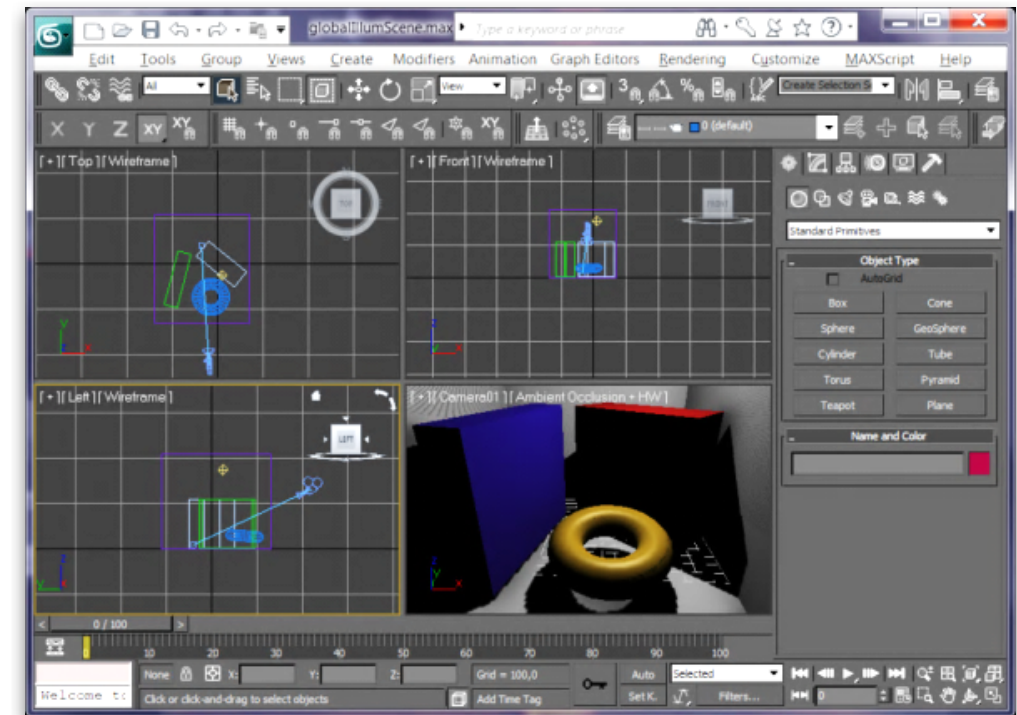
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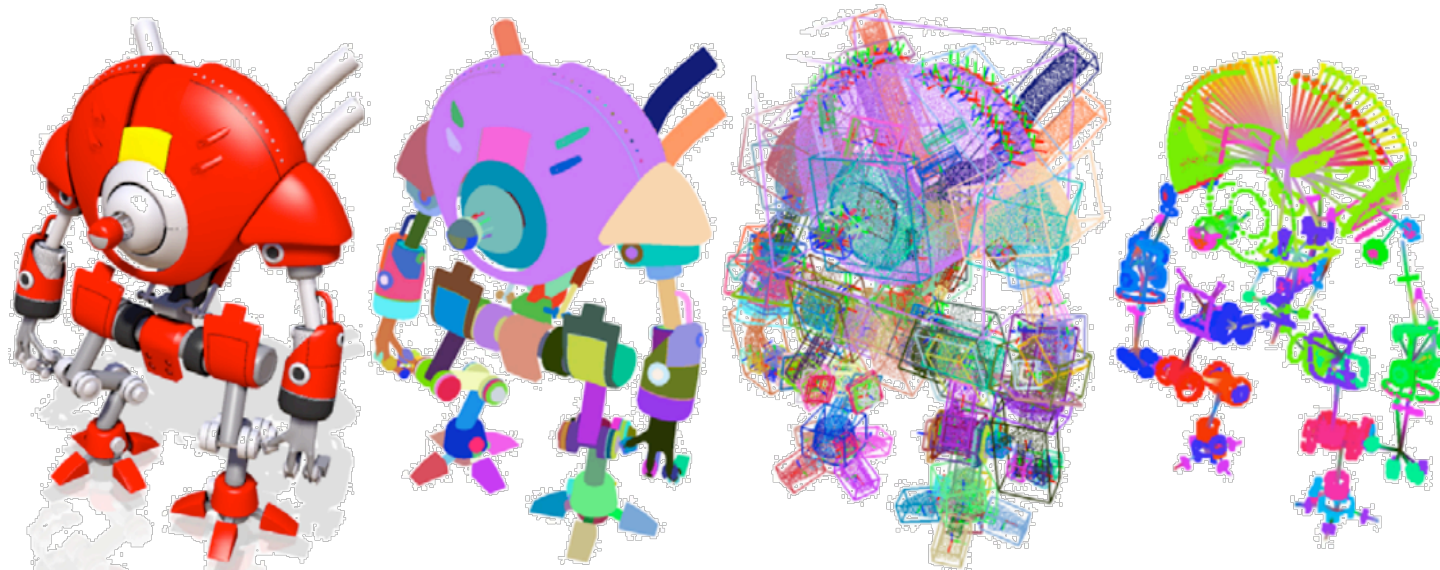


User Defined Parts

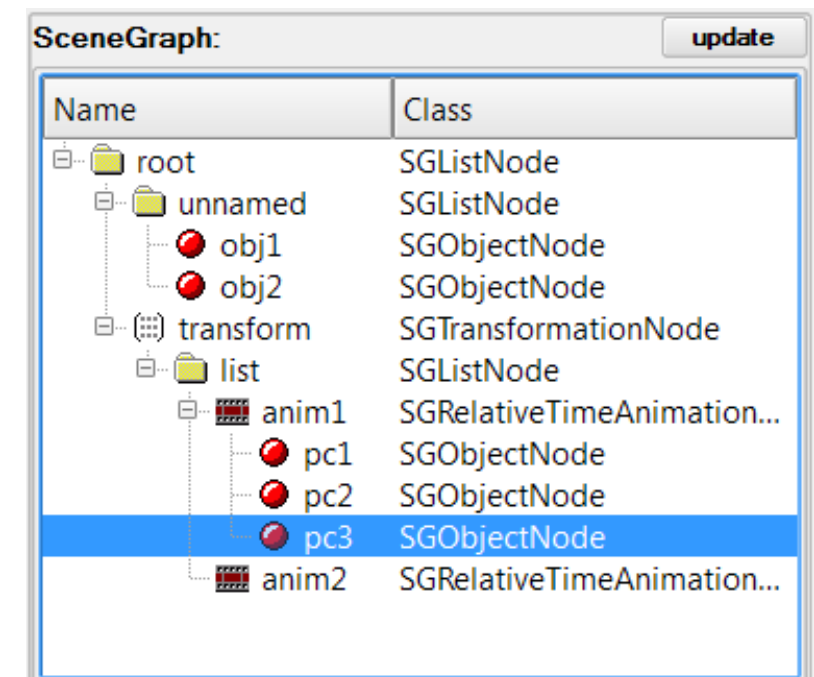
- **Traditional Modeling**
 - Scenes assembled out of primitives
 - Hierarchical organization in scene graph



[Autodesk 3DS MAX]

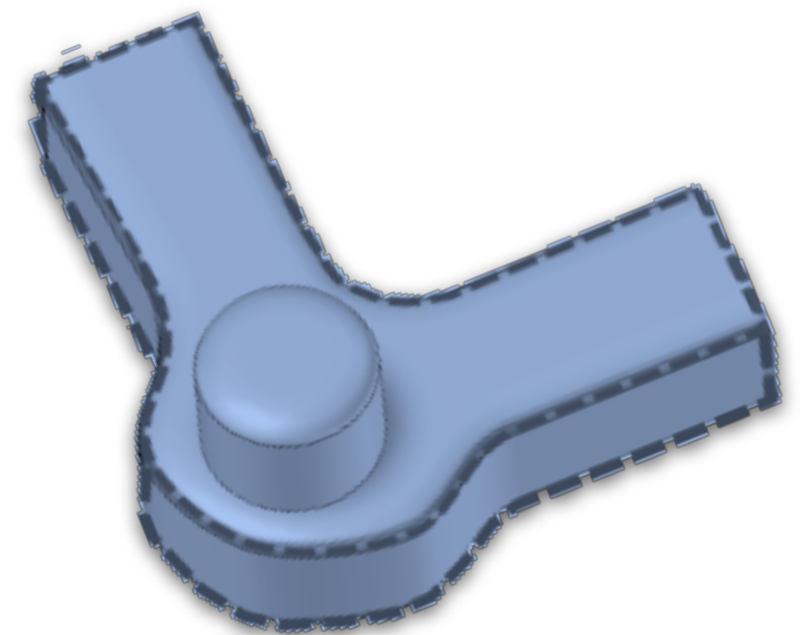


[Jain et al. EG 2012]



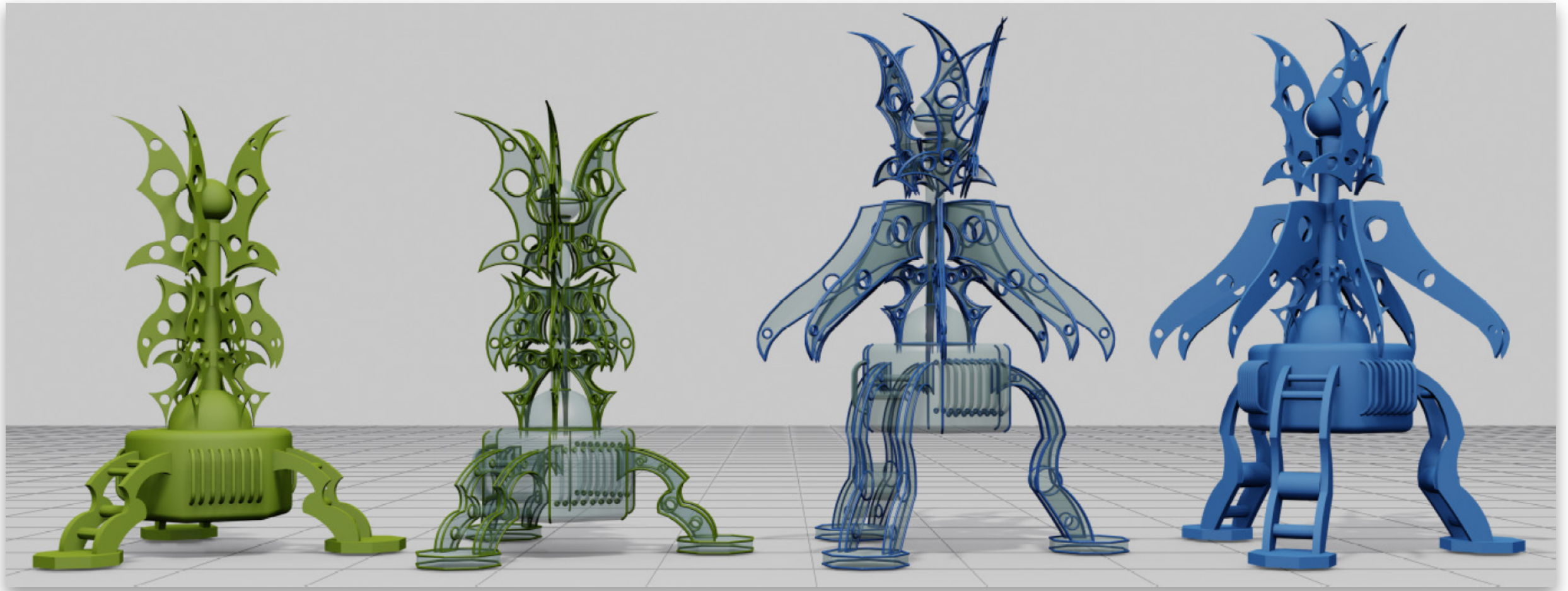
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Parts



- Fixed Models
 - Feature detection
 - Shape segmentation (local)
 - Symmetry-based segmentation (global)

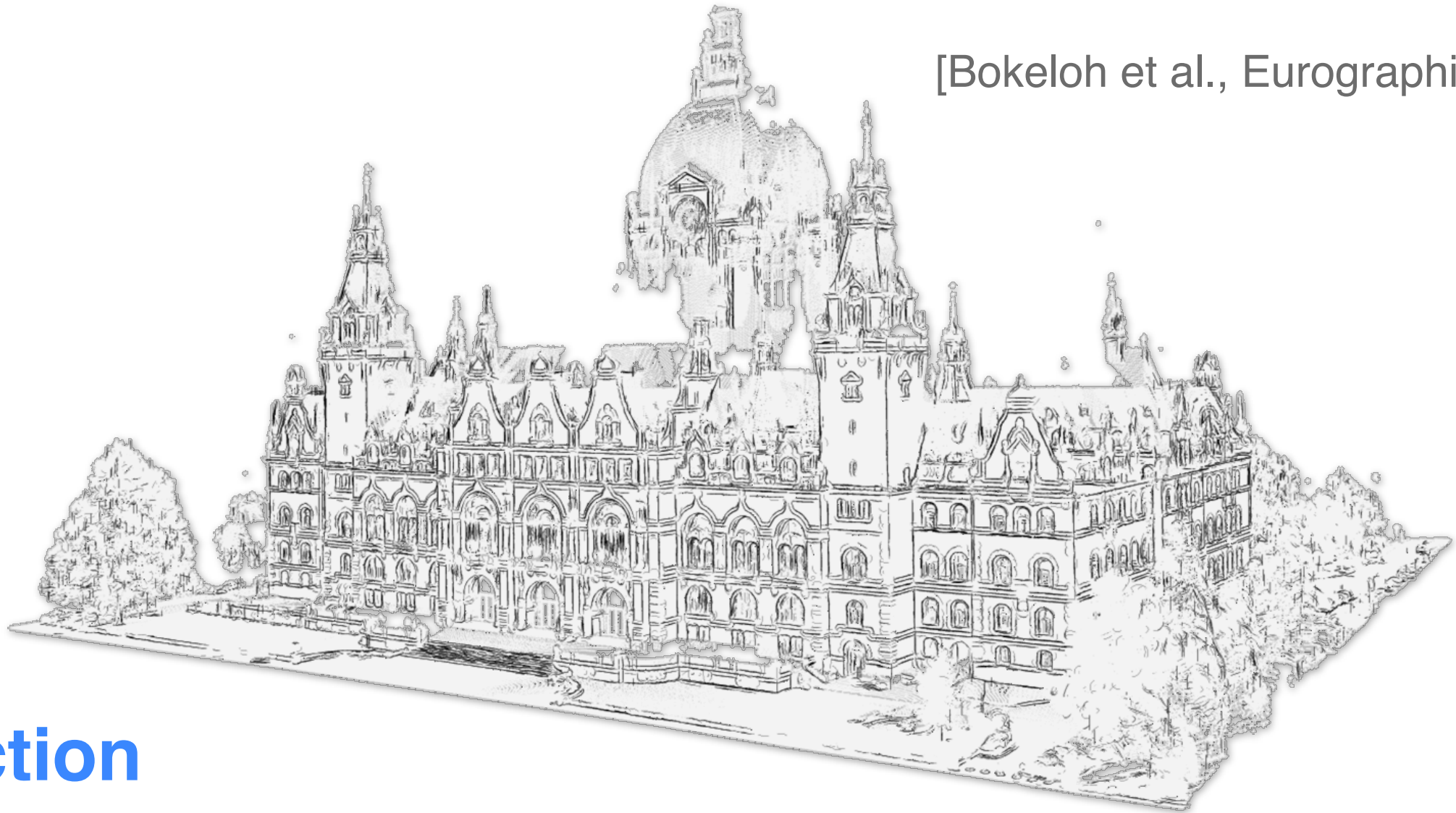
Curves as Primitives



- Example: iWires [Gal et al., Siggraph 2009]
 - Sharp creases as parts
 - Detection: based on dihedral angles

Curves from Point Sets

[Bokeloh et al., Eurographics 2009]



- **Detection**

- Local maxima of principal curvature
- Slippage analysis
- Crease edges (clean meshes), local fitting (scanner data)

Shape Segmentation

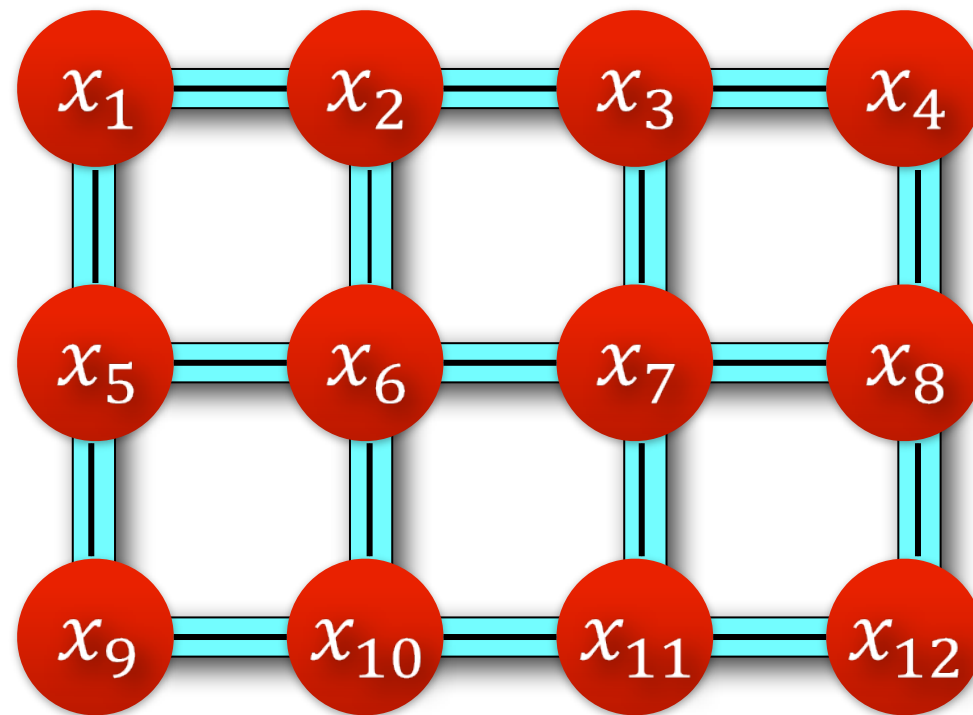
Shape Segmentation

- **Shape Segmentation**
 - Well-established field
 - Plenty of models

Shape Segmentation

- **Shape Segmentation**
 - Well-established field
 - Plenty of models
- **General Strategy**
 - **Local** evidence for part labels
 - For each primitive
 - Coherent **neighborhoods**
 - Consider pairs of adjacent primitives
 - Markov random field (**MRF**) model
 - Optimize assignment

Markovian Graphical Model



$$p_i^{(1)}(x_i)$$

Different labels for each triangle, pixel, etc.

$$p_{i,j}^{(2)}(x_i, x_j)$$

pairs of triangle, pixel, etc.

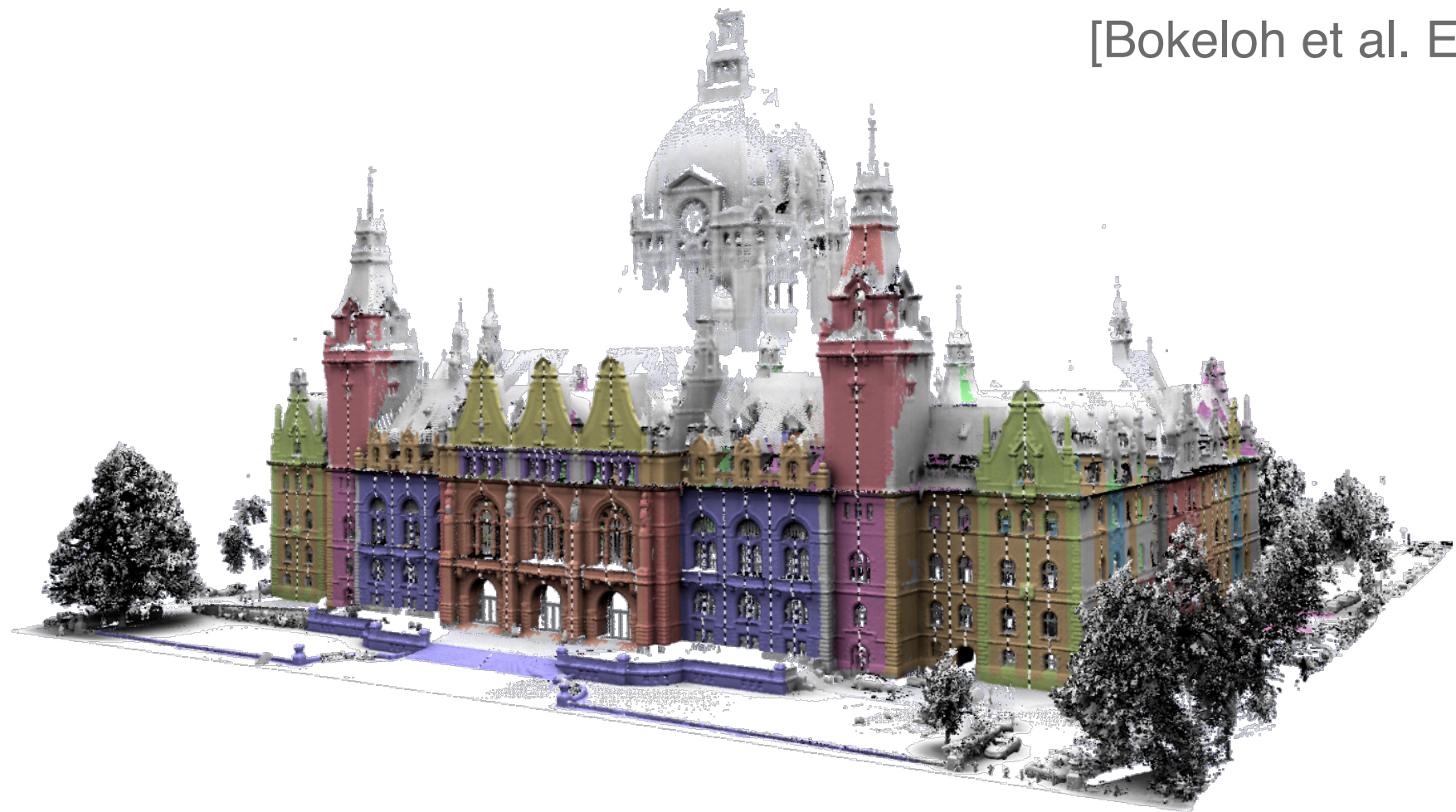
- **Pairwise Markov Random Field**

$$p(x_1, \dots, x_n) = \frac{1}{Z} \prod_{i=1}^n \underline{p_i^{(1)}(x_i)} \prod_{i,j \in E} \underline{p_{i,j}^{(2)}(x_i, x_j)}$$

Optimization: loopy belief propagation, (iterated) graph cuts

Symmetry-based Segmentation

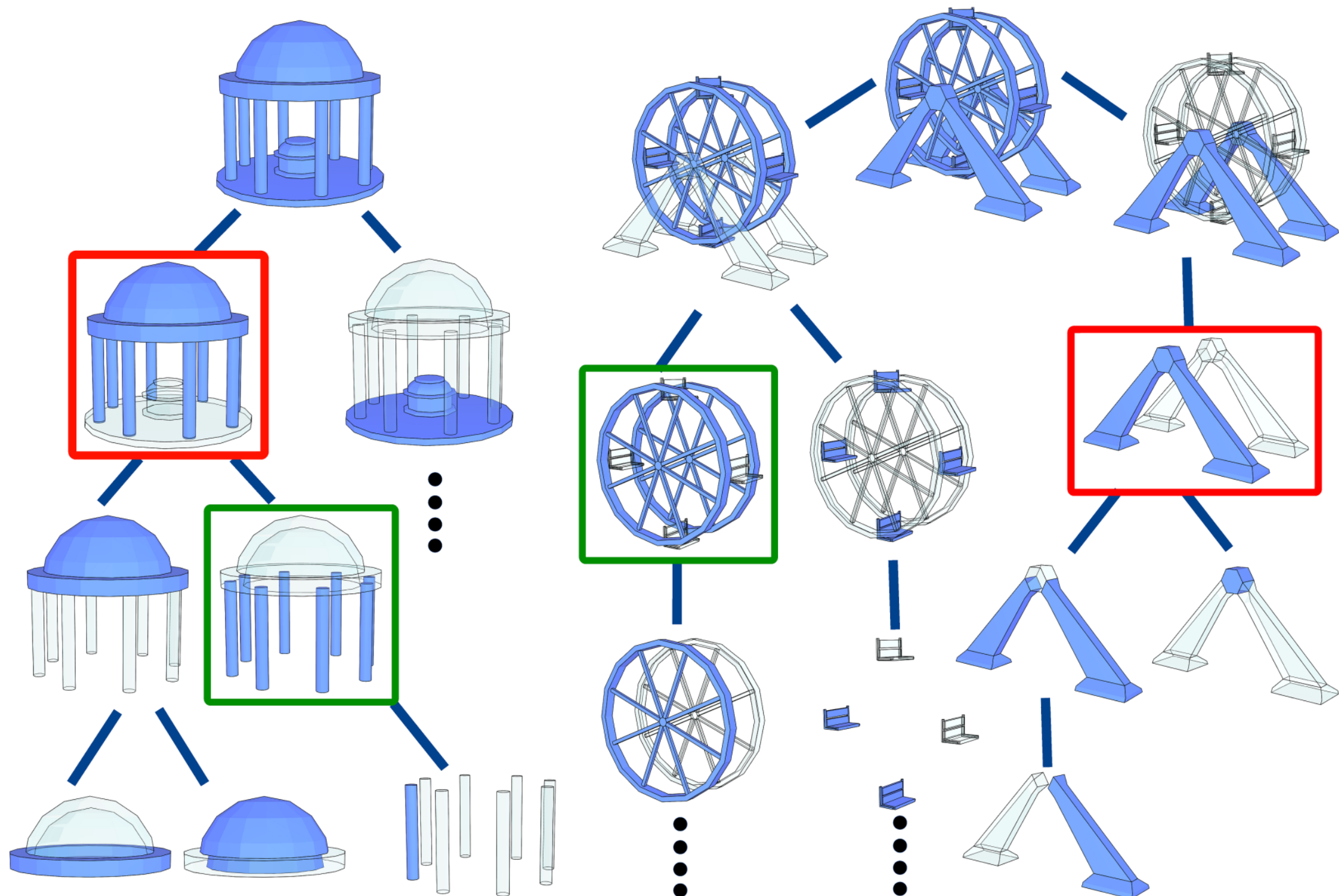
[Bokeloh et al. EG 2009]



Split Model into Symmetric Building Blocks

- Group repetitive elements
- Discover redundant instances

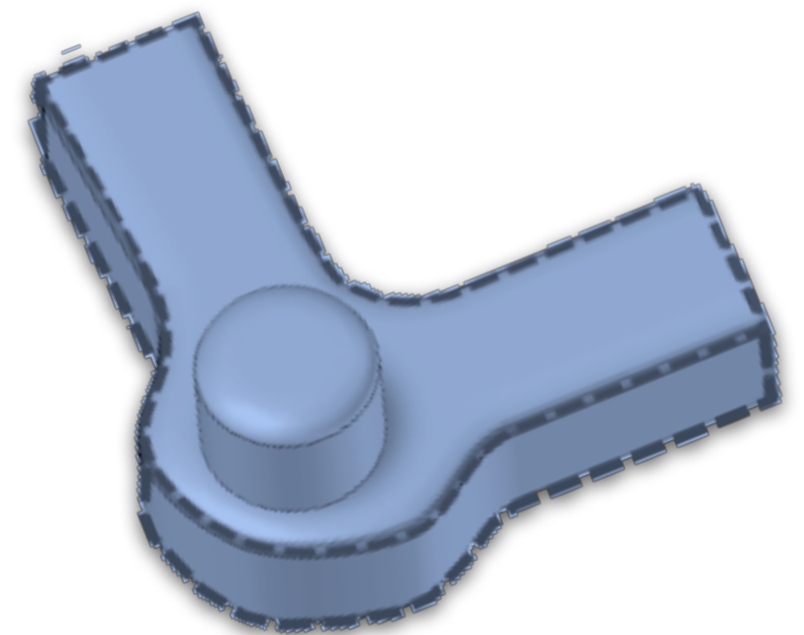
Symmetry Hierarchies



[Wang et al. EG 2011]

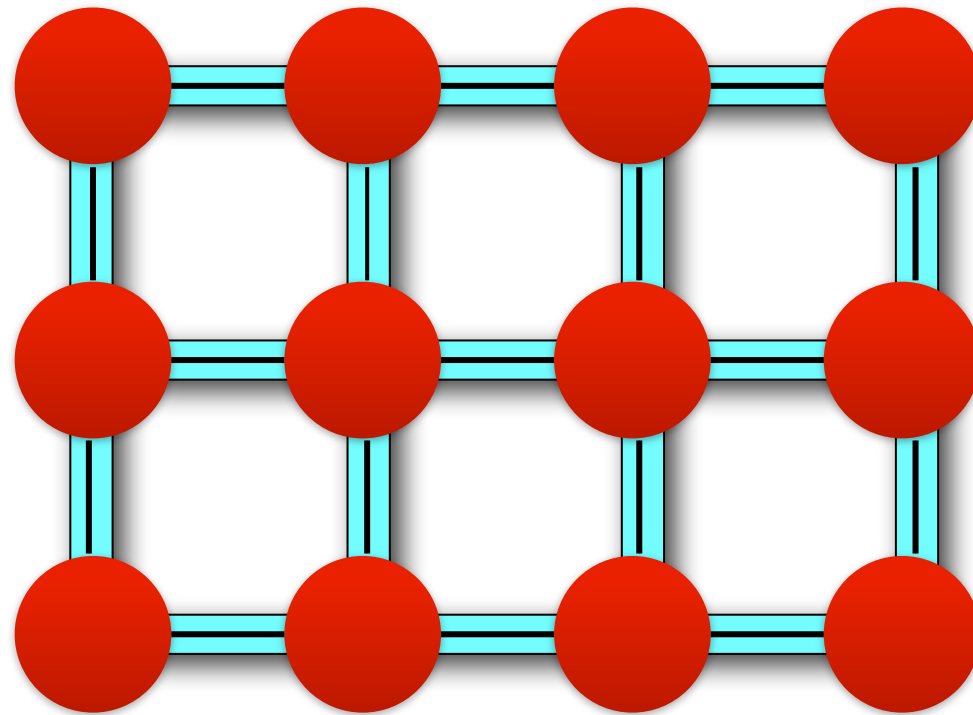
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Parts



- Approach
 - **Supervised**
 - Training data: Example Segmentations
 - Learn model parameters
 - Apply to more, unknown data after training
 - **Unsupervised**
 - No training phase
 - Clustering: Maximize coherence
 - Co-segmentation

Supervised Learning



$$p_i^{(1)}(x_i)$$

Learn: Local evidence

$$p_{i,j}^{(2)}(x_i, x_j)$$

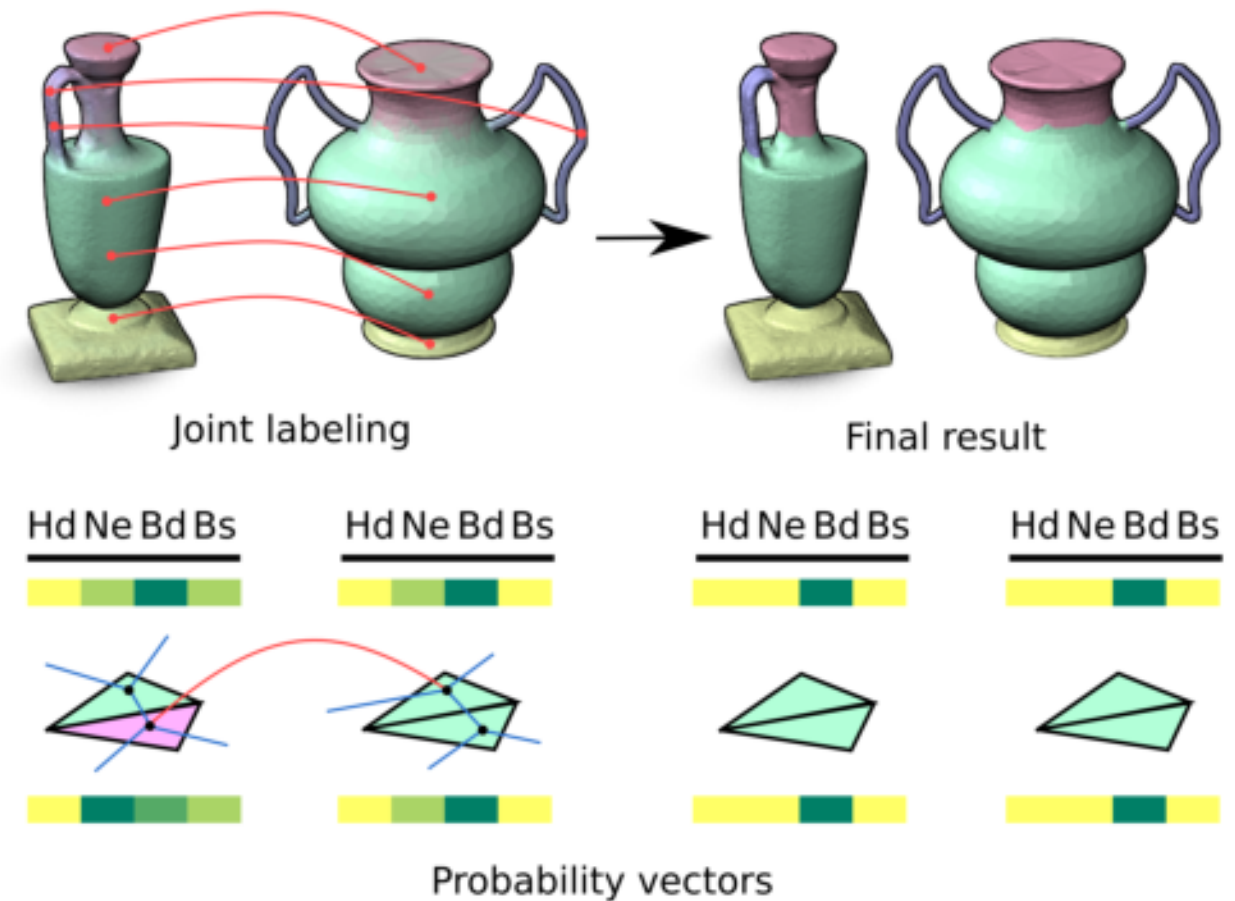
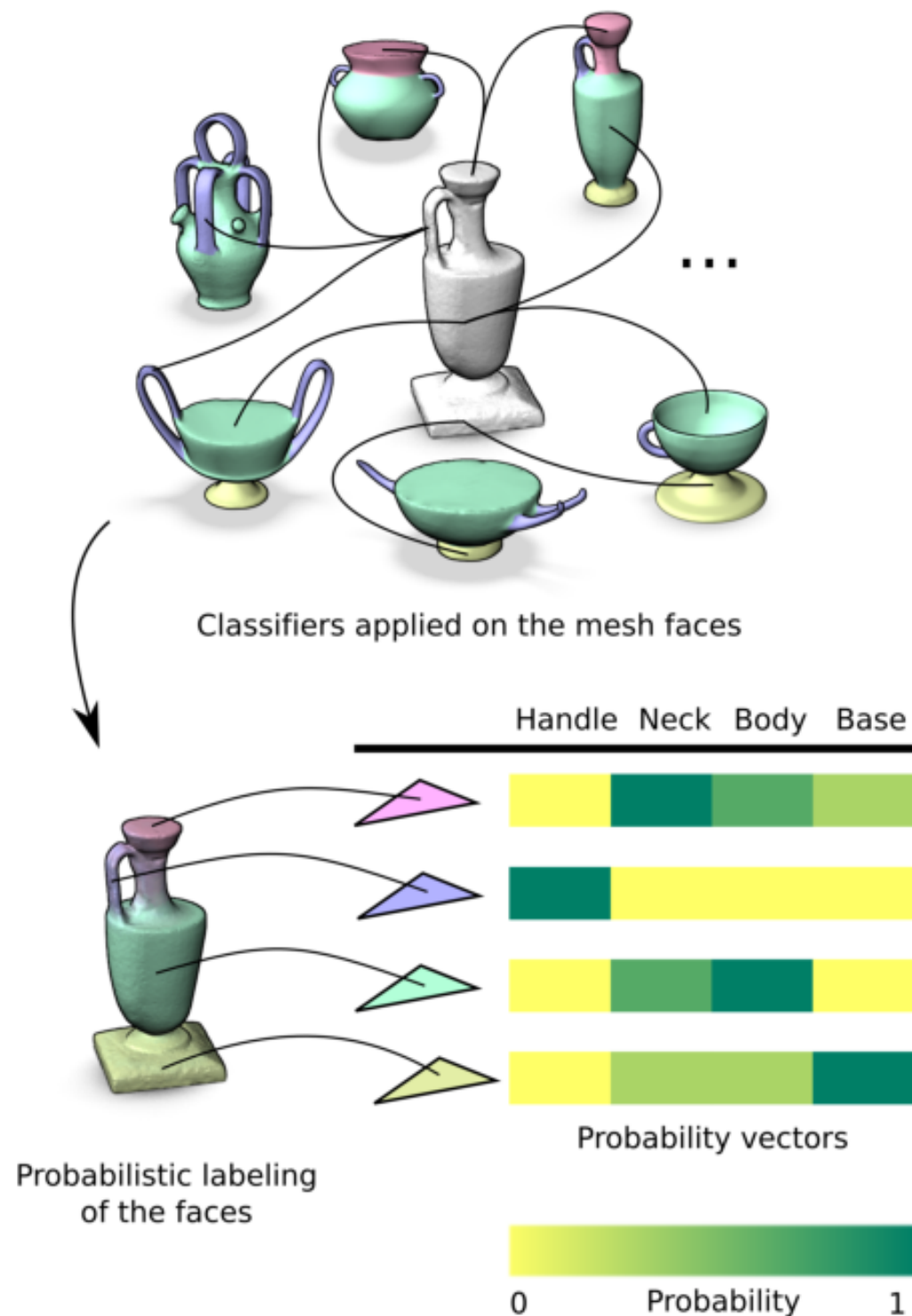
Learn: pairwise relations

- **Pairwise Markov Random Field**

$$p(x_1, \dots, x_n) = \frac{1}{Z_\theta} \prod_{i=1}^n \underline{p_i^{(1)}(x_i|\theta)} \prod_{i,j \in E} \underline{p_{i,j}^{(2)}(x_i, x_j|\theta)}$$

Optimize the same function, but for parameters θ .

Unary and Pairwise Potentials

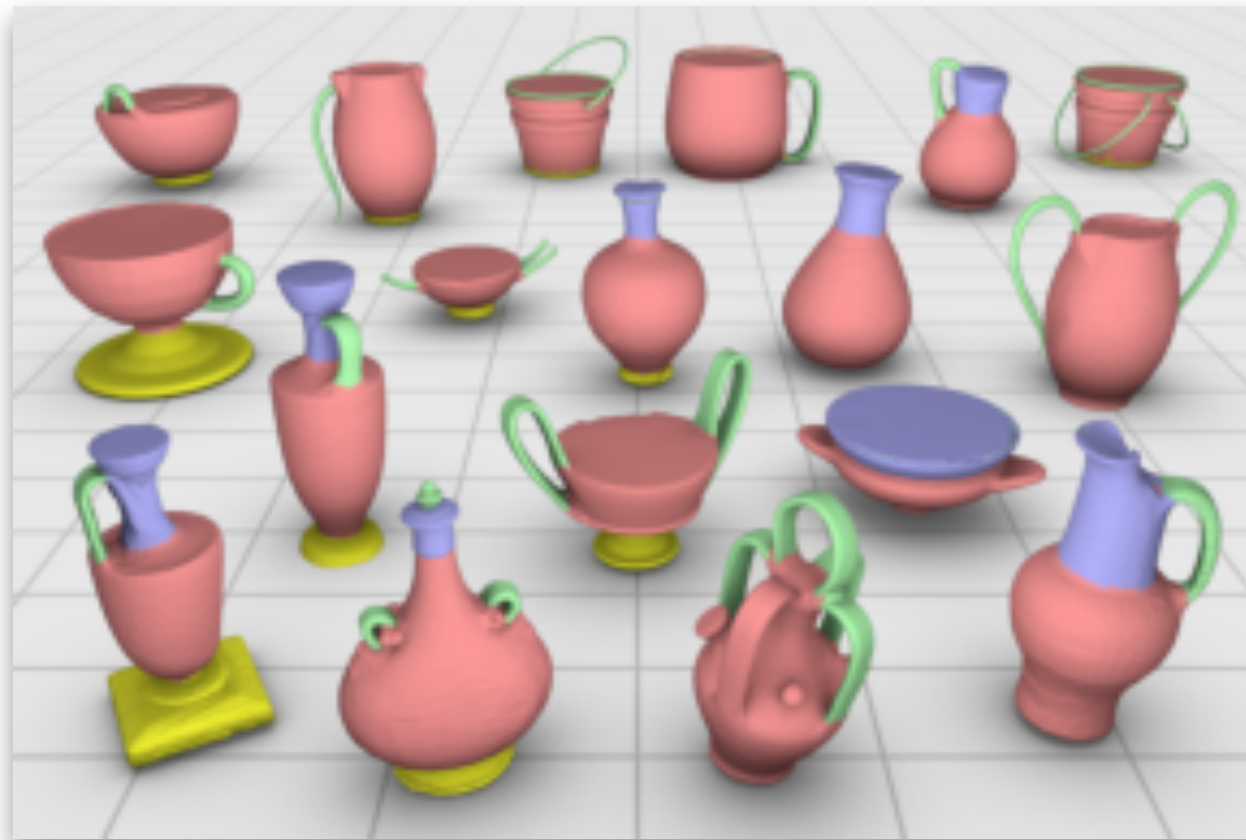


$p^{(2)}$ – pairwise

$p^{(1)}$ – unary

[van Kaik et al. EG 2011]

Unsupervised Learning



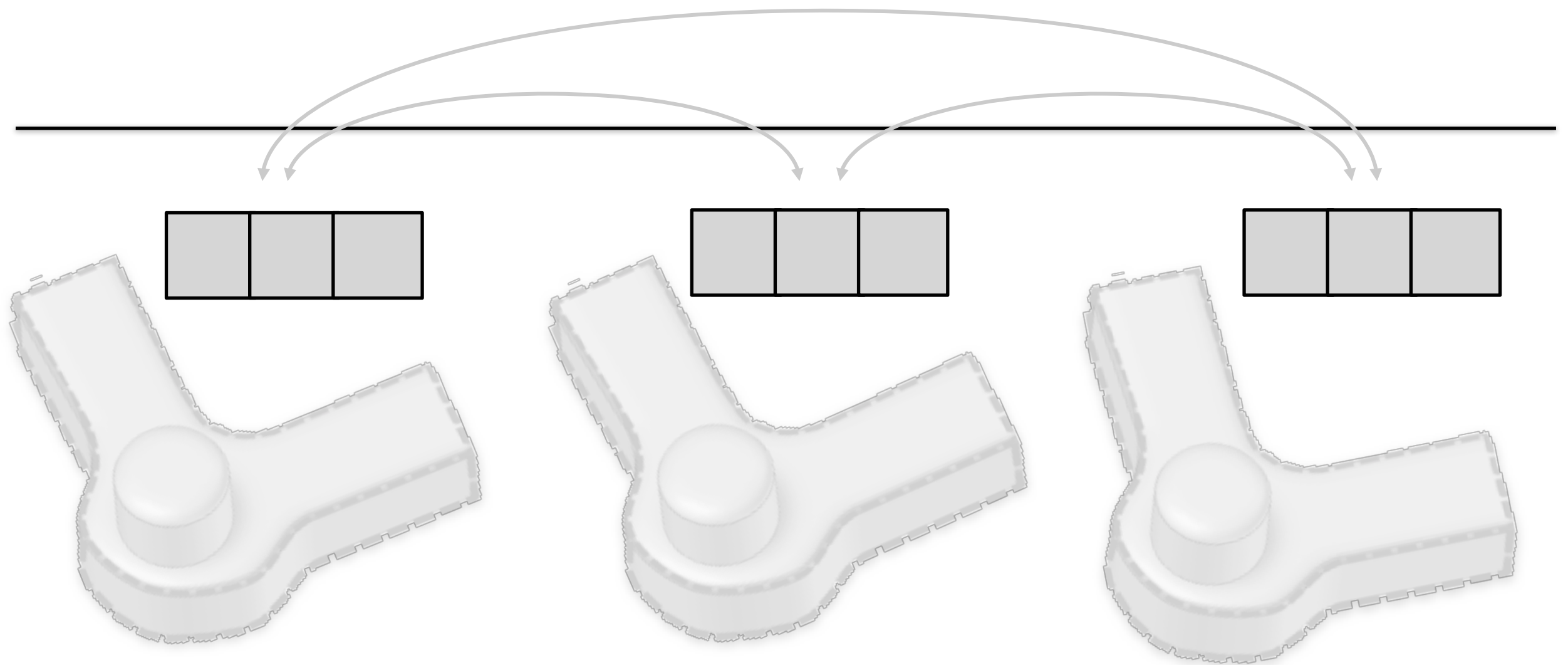
[Sidi et al. SIGA 2011]

- **Approaches**
 - Similar Markov-random field model
 - Data-term: Clustering in descriptor space
 - Pairwise term: a priori model

Parts

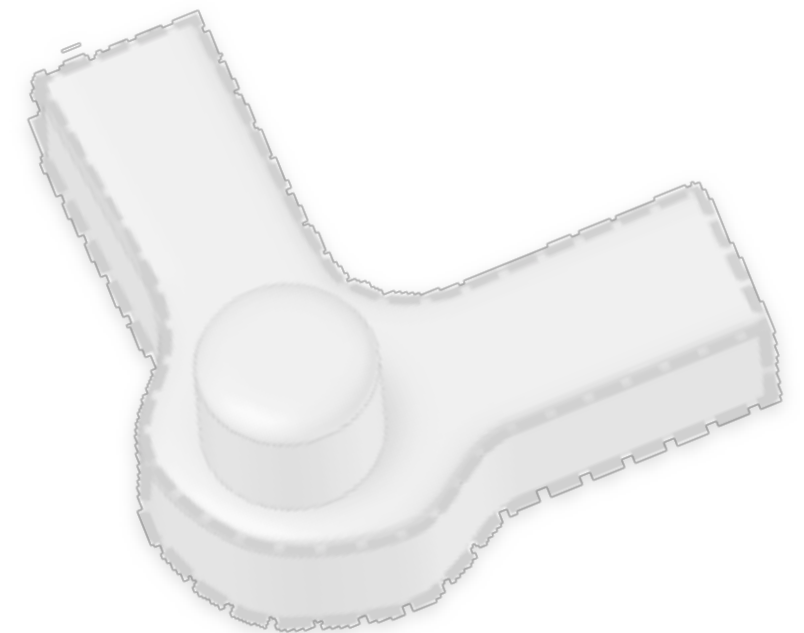
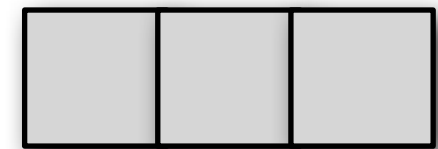
Parameters

Relations



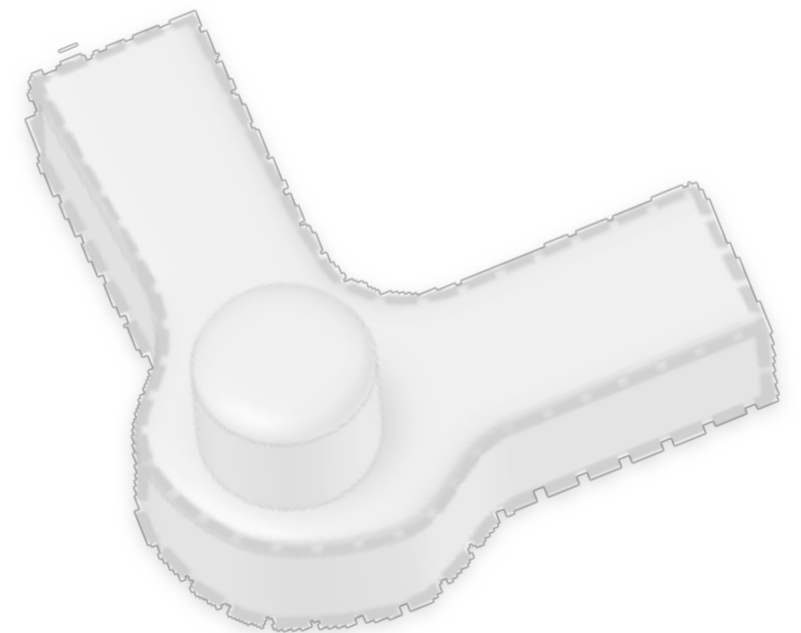
- Modeling and Detecting Parameters of Parts
 - User defined parameters
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 - Predefined variables
 - Data-driven parameters
 - Discover and learn latent variables

Parameters

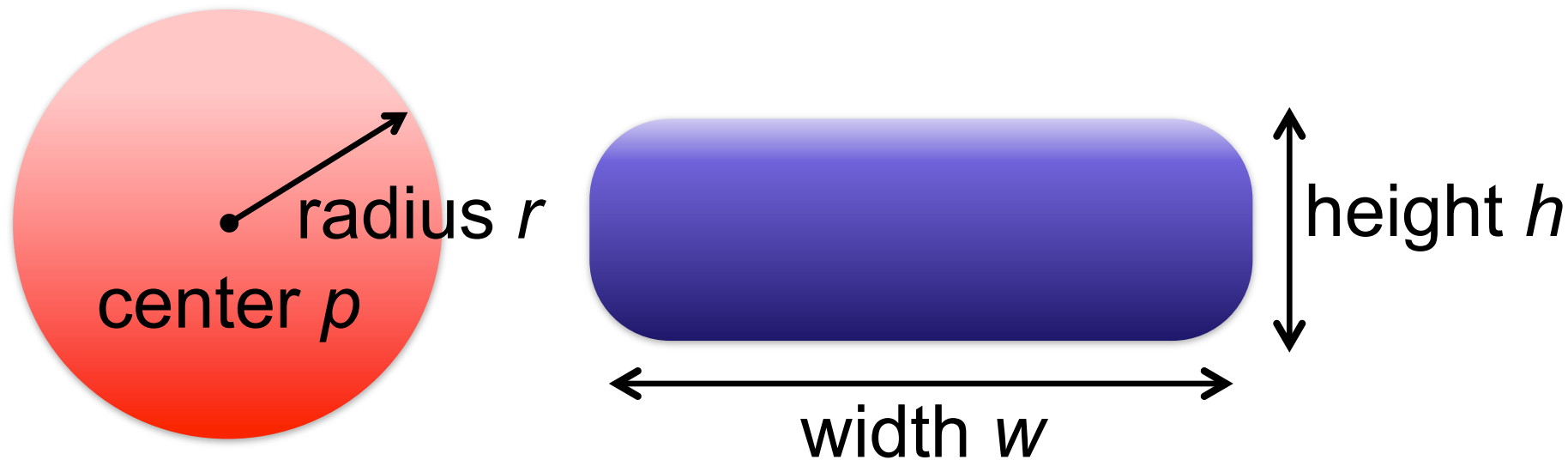


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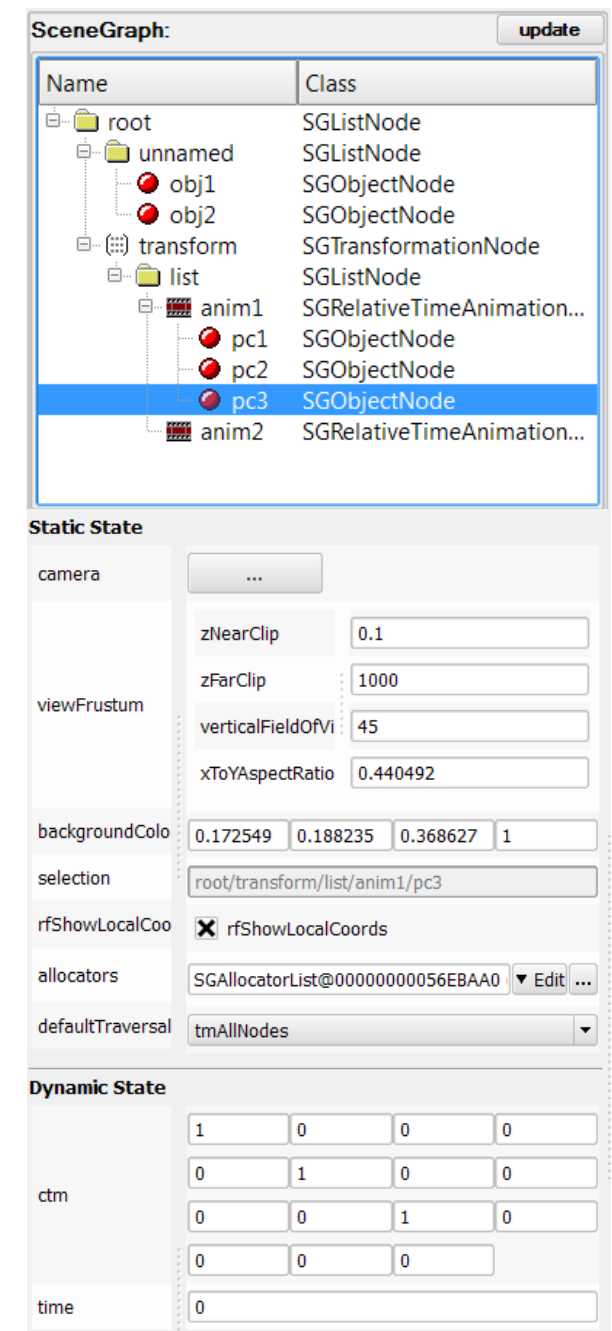
Parameters



User Defined Parameters

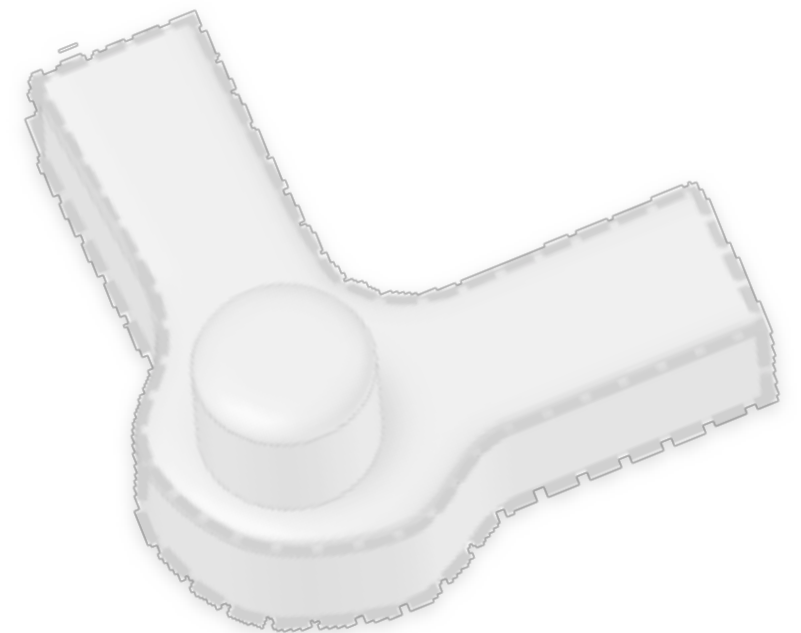


- **Traditional Modeling Systems**
 - Parameters of primitives
 - Variables in scene hierarchies
- **Procedural Modeling**
 - Hierarchical model generation
 - Scripts with local variables / arguments
e.g. [Gervautz et al. 1996]



- Modeling and Detecting Parameters of Parts
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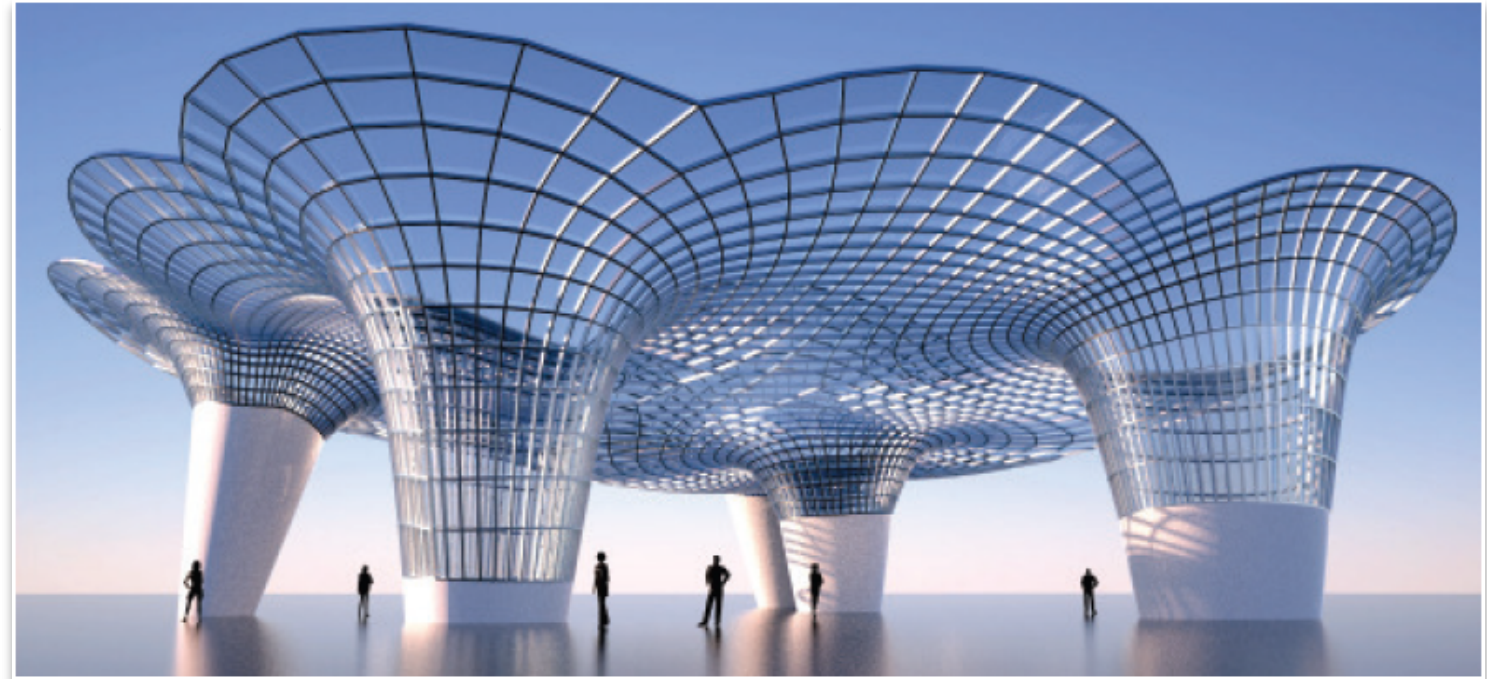
Parameters



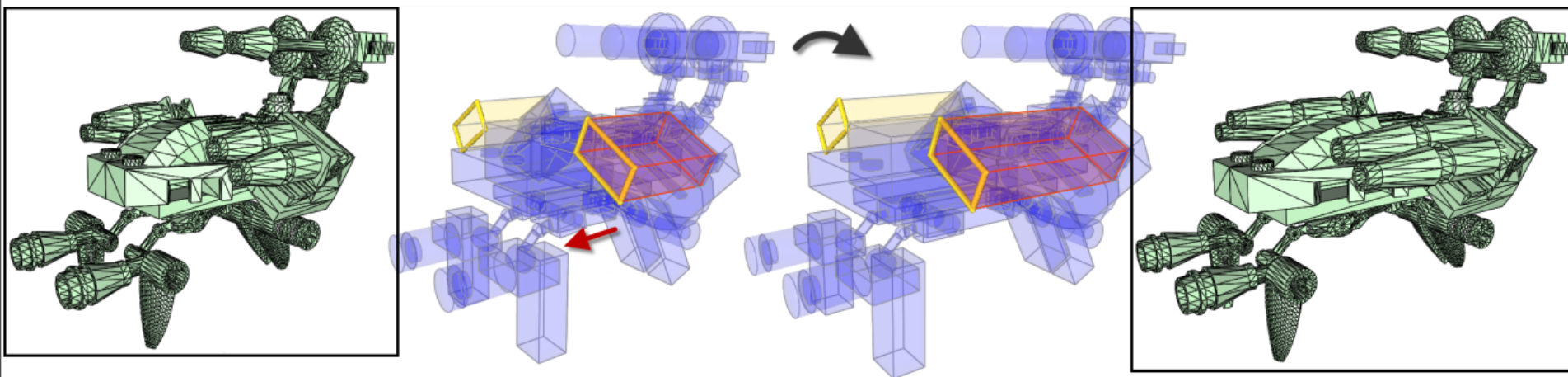
Fixed Parameter Models

• Fixed Part Parameters

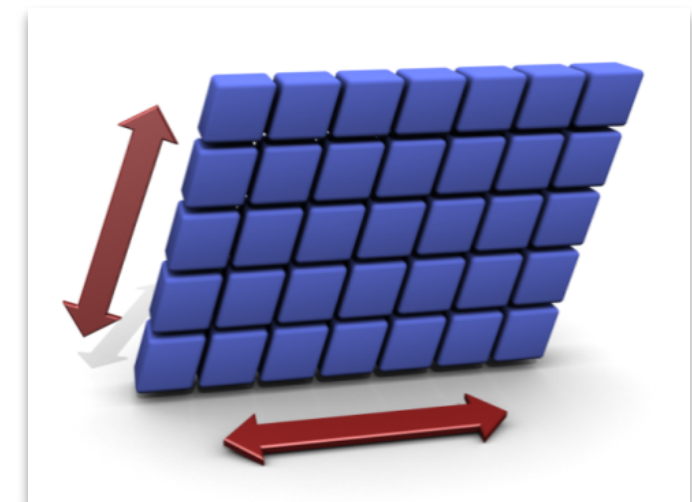
- Rigid/similarity-tr./affine mappings
- General shape spaces
 - Vertices move in \mathbb{R}^{3n}
- Constraint manifolds
 - Vertices move on smooth manifold $\mathcal{M} \subseteq \mathbb{R}^{3n}$
- Instantiation
- Controllers & Proxies



[Yang et al. SIGA 2011]



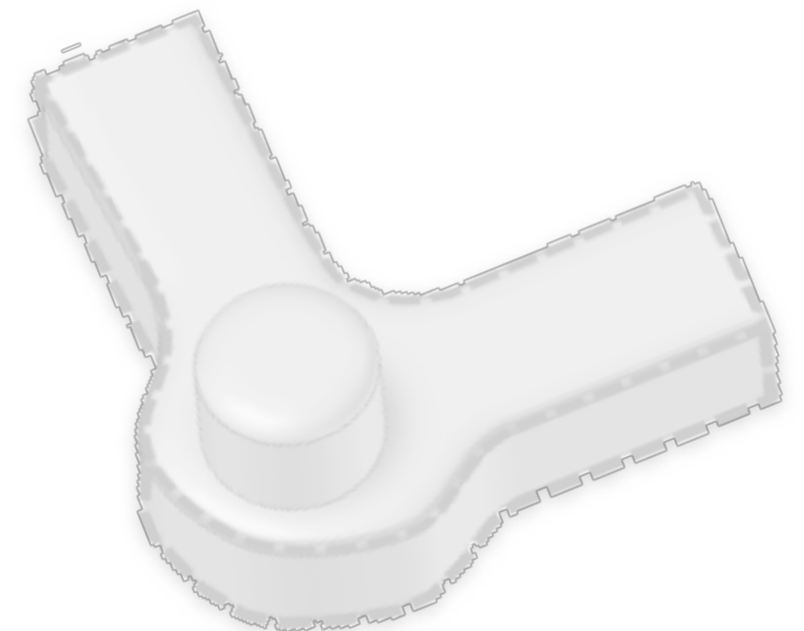
[Zheng et al. EG 2011]



[Bokeloh et al. SG 2012]

- Modeling and Detecting Parameters of Parts
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 - Manual model setup
 - Fixed models
 - Predefined variables
 - Data-driven parameters
 - Discover and learn latent variables

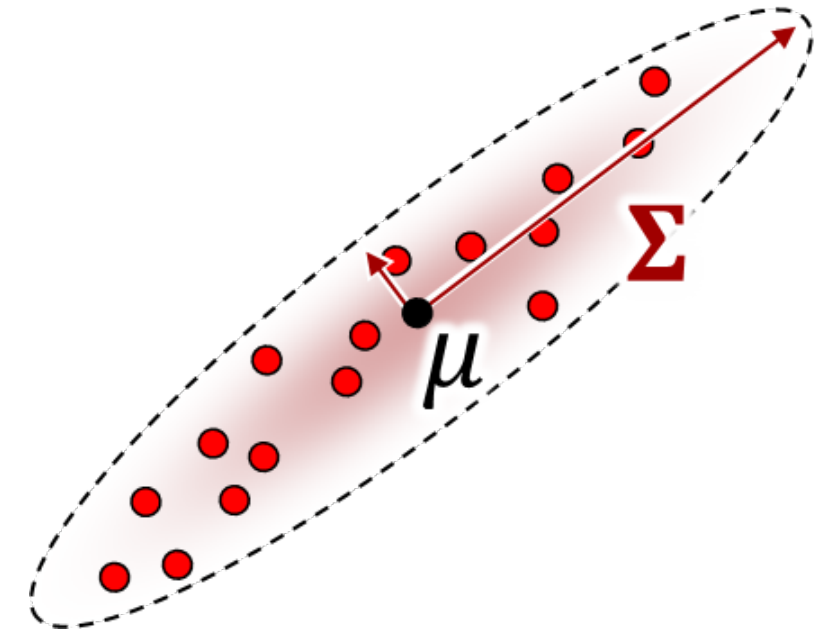
Parameters



Learning Parameters

- **Learning Parameters from Data**

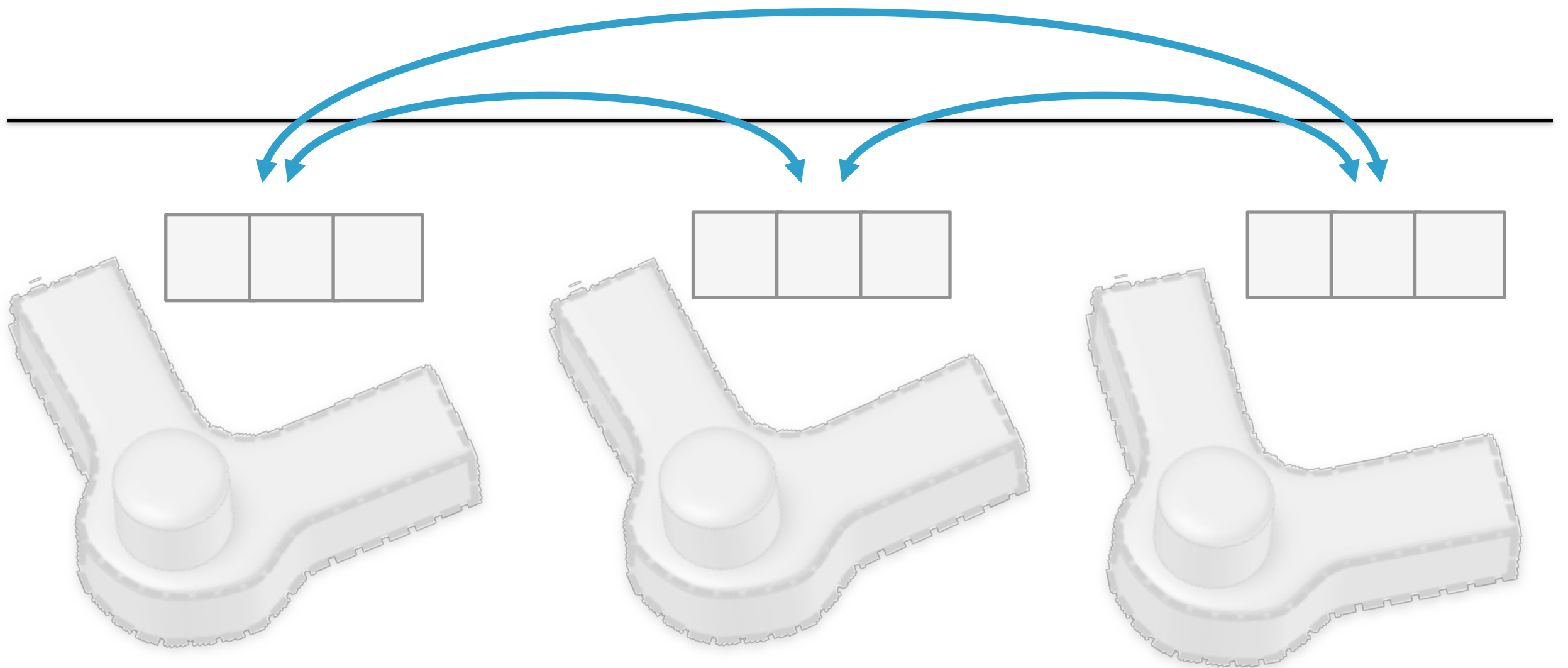
- No prescribed variables / mappings
- Discover latent variables



- **Common Approaches**

- Principal component analysis
 - “Morphable Models” [Blanz et al. 1999, Allan et al. 2003,...]
 - Kernel-PCA / spectral embedding for nonlinear models
- Independent component analysis
- In general: latent variable models
(e.g., latent variable Gaussian processes)

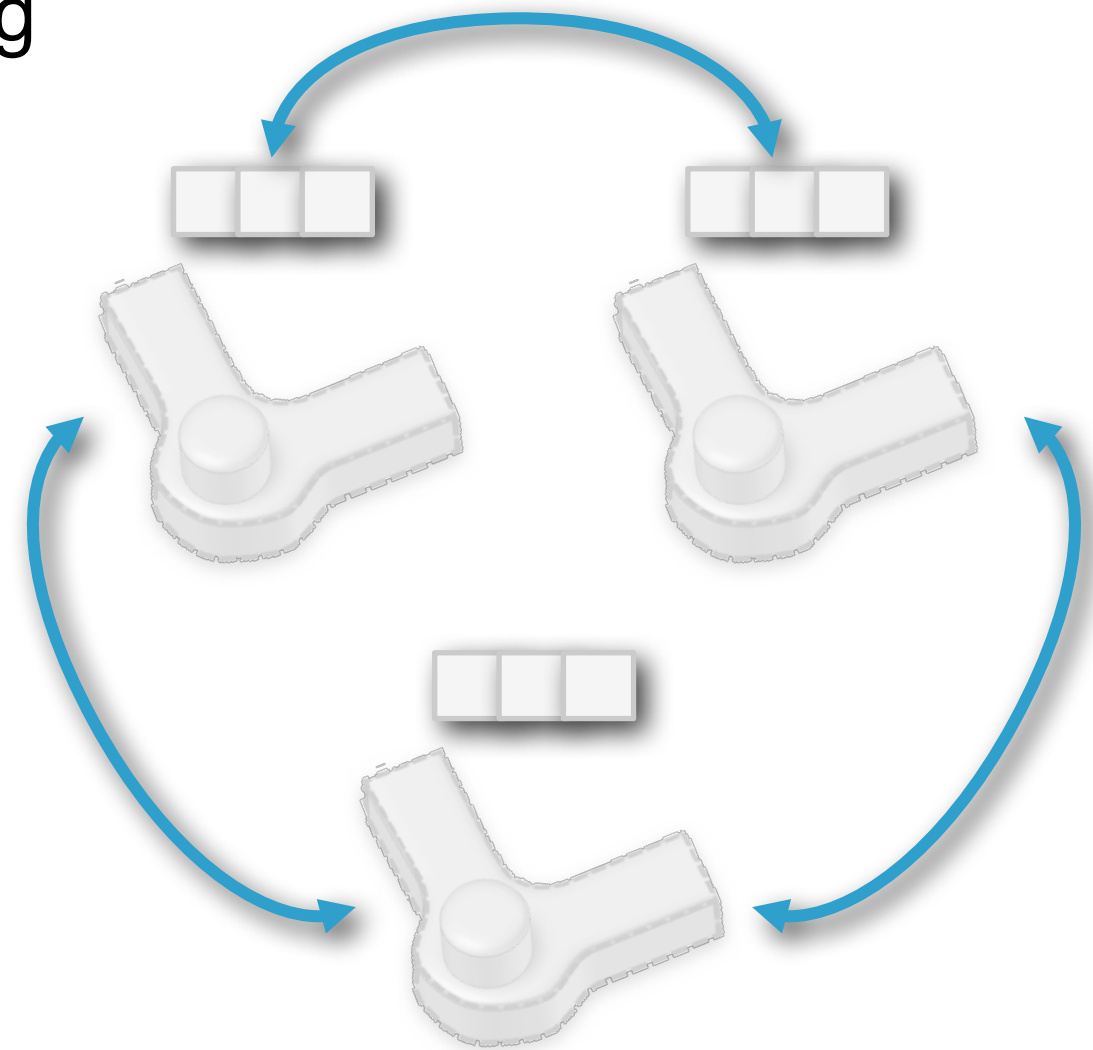
Parts Parameters Relations



- Modeling and Detection of Relations

- User defined relations
 - Traditional constrained modeling
- Fixed models
 - Detect relations from predefined classes
- Data-driven relations
 - Discover new types of invariants from data

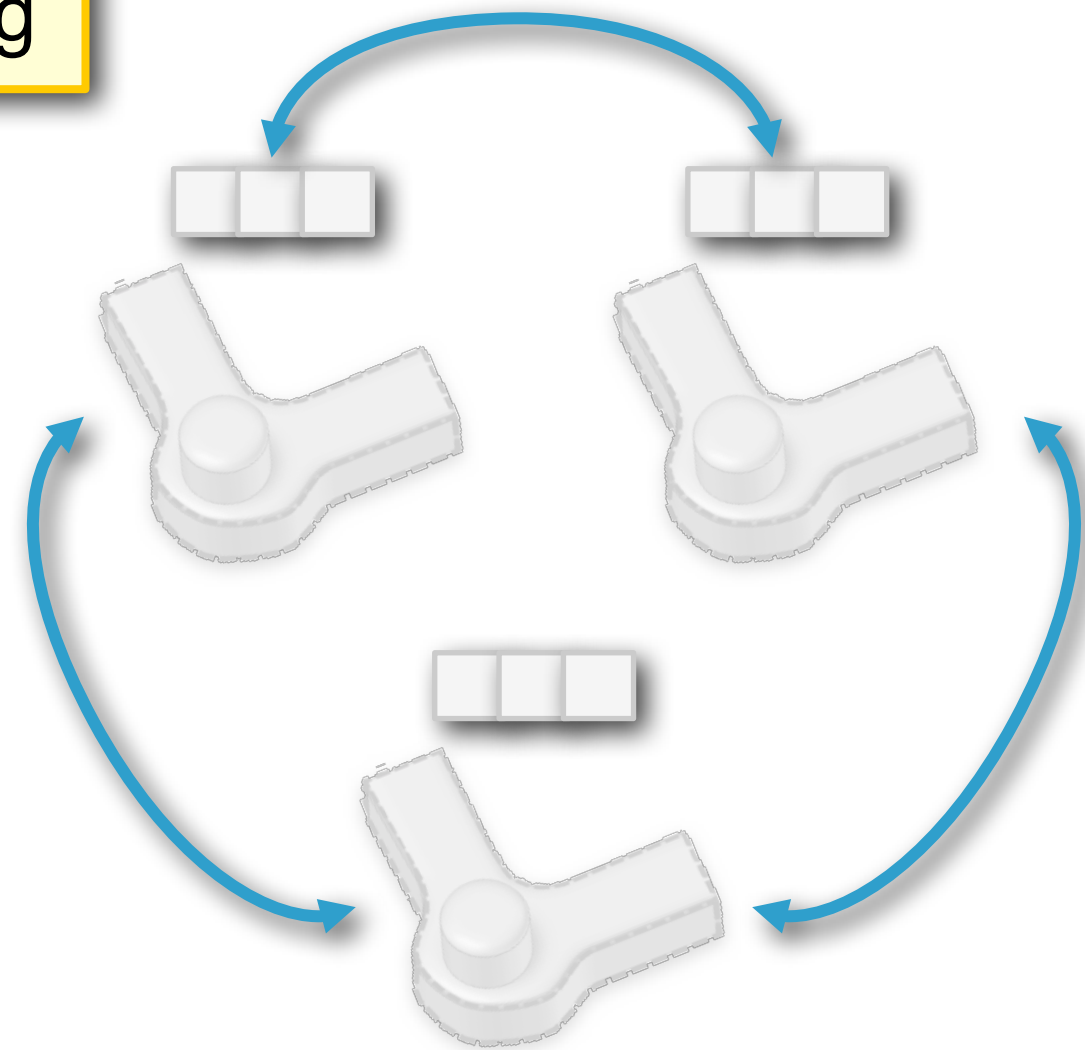
Relations



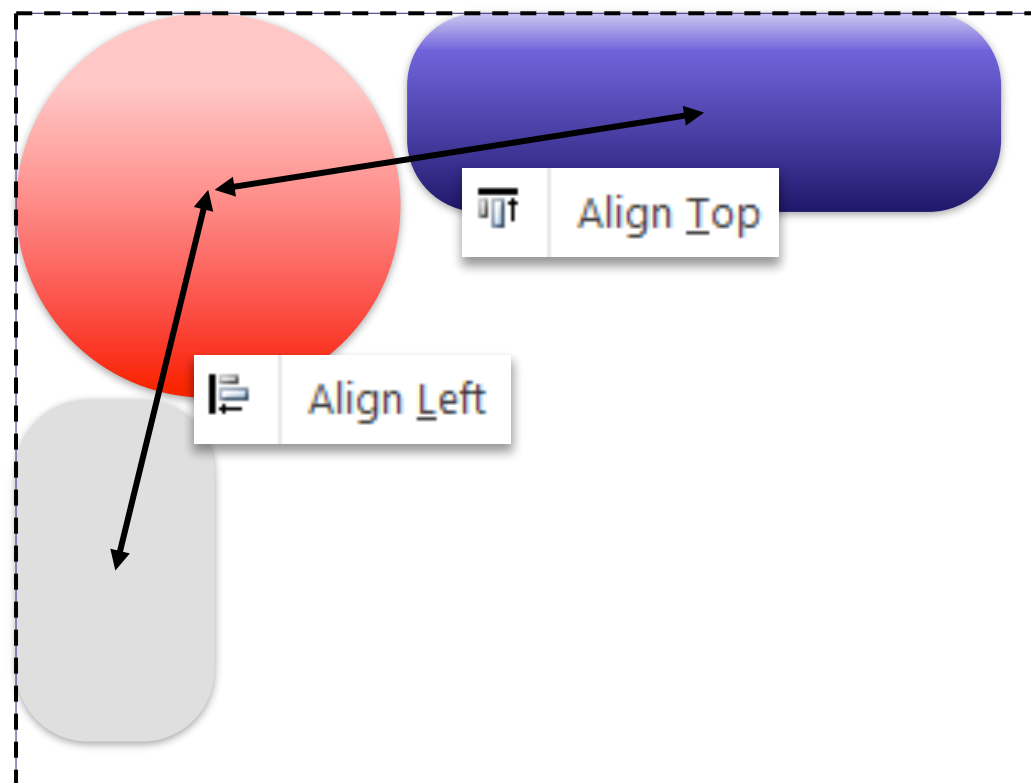
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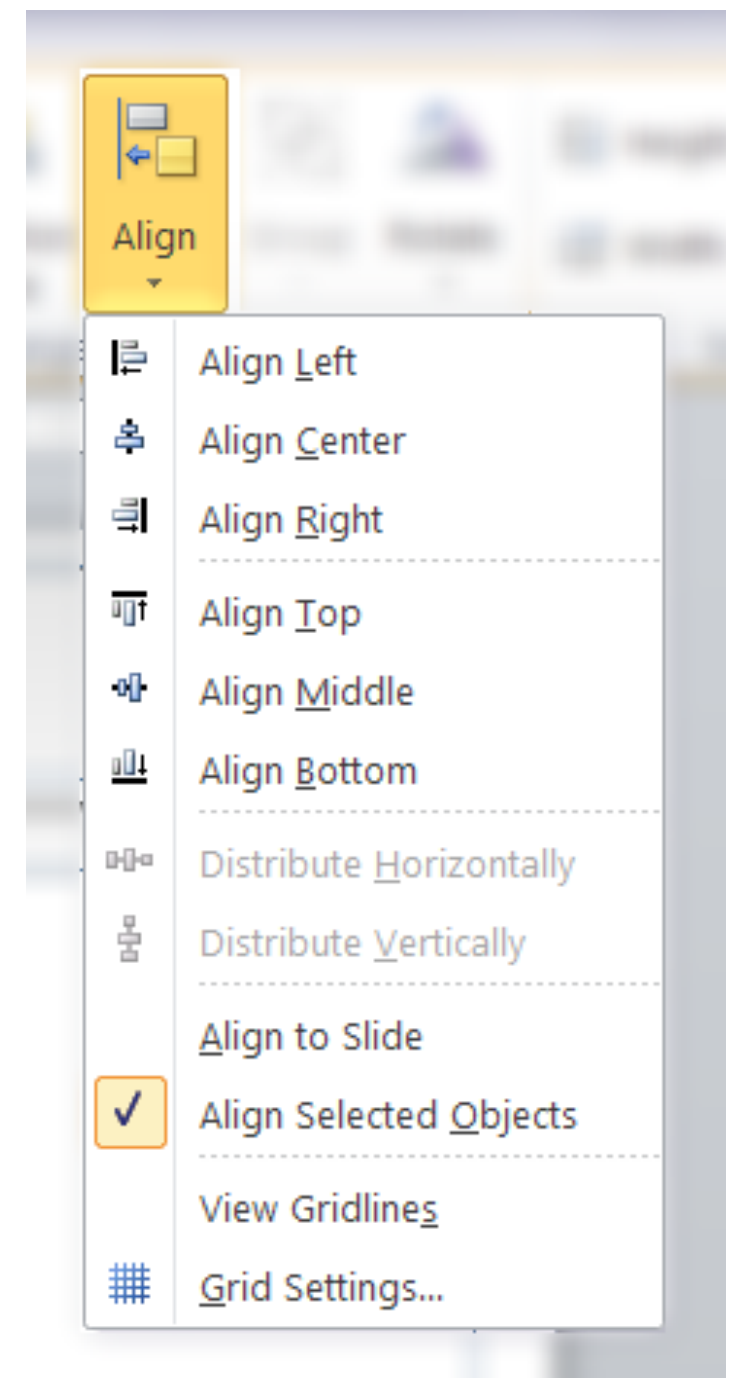
Relations



Manual Relations



- **Constraints-Based Modeling**
 - Specify desired constraints
 - Part parameters
 - Derived properties
 - Constraints-solver (hard/soft)



[MS Powerpoint 2010]

- Modeling and Detection of Relations

- User defined relations

- Traditional constrained modeling

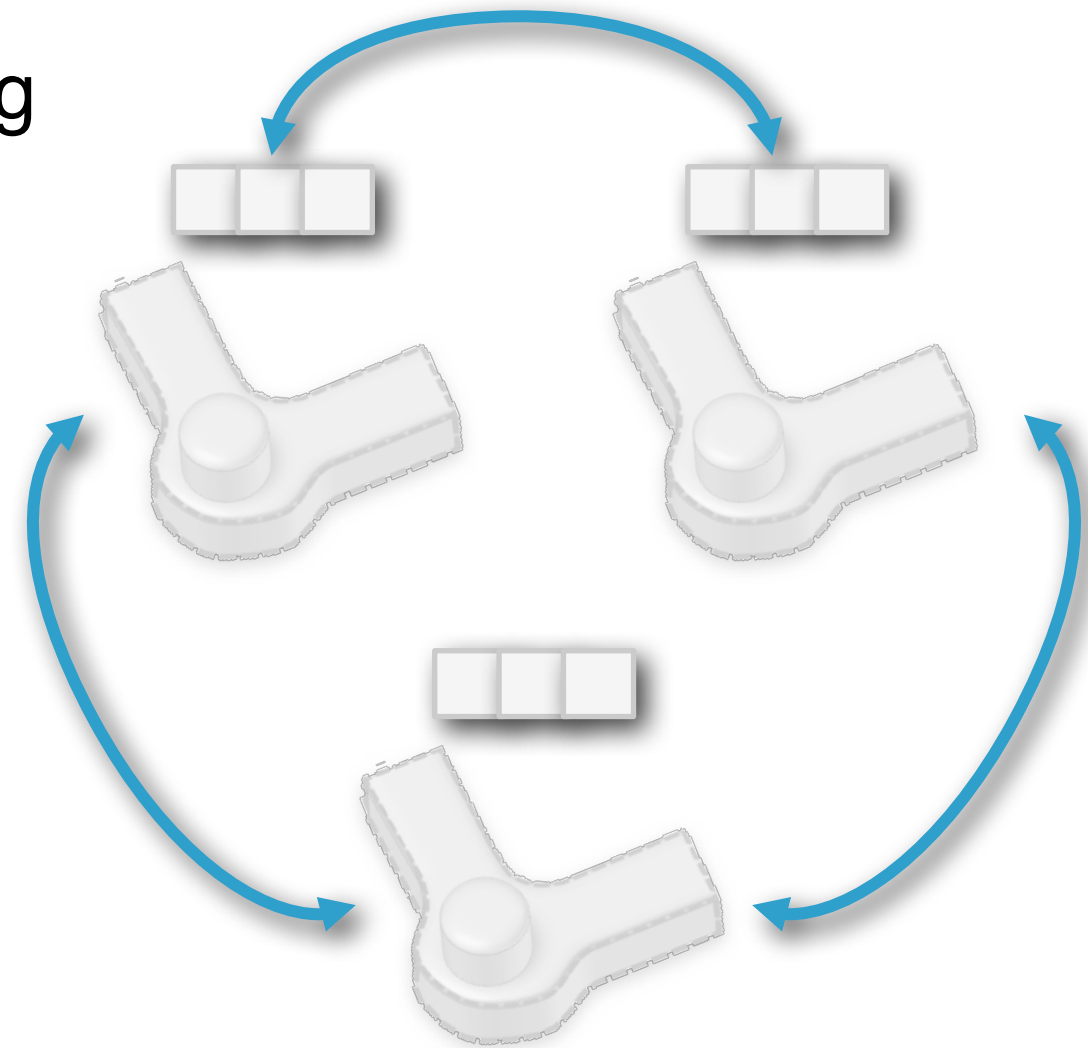
- Fixed models

- Detect relations from predefined classes

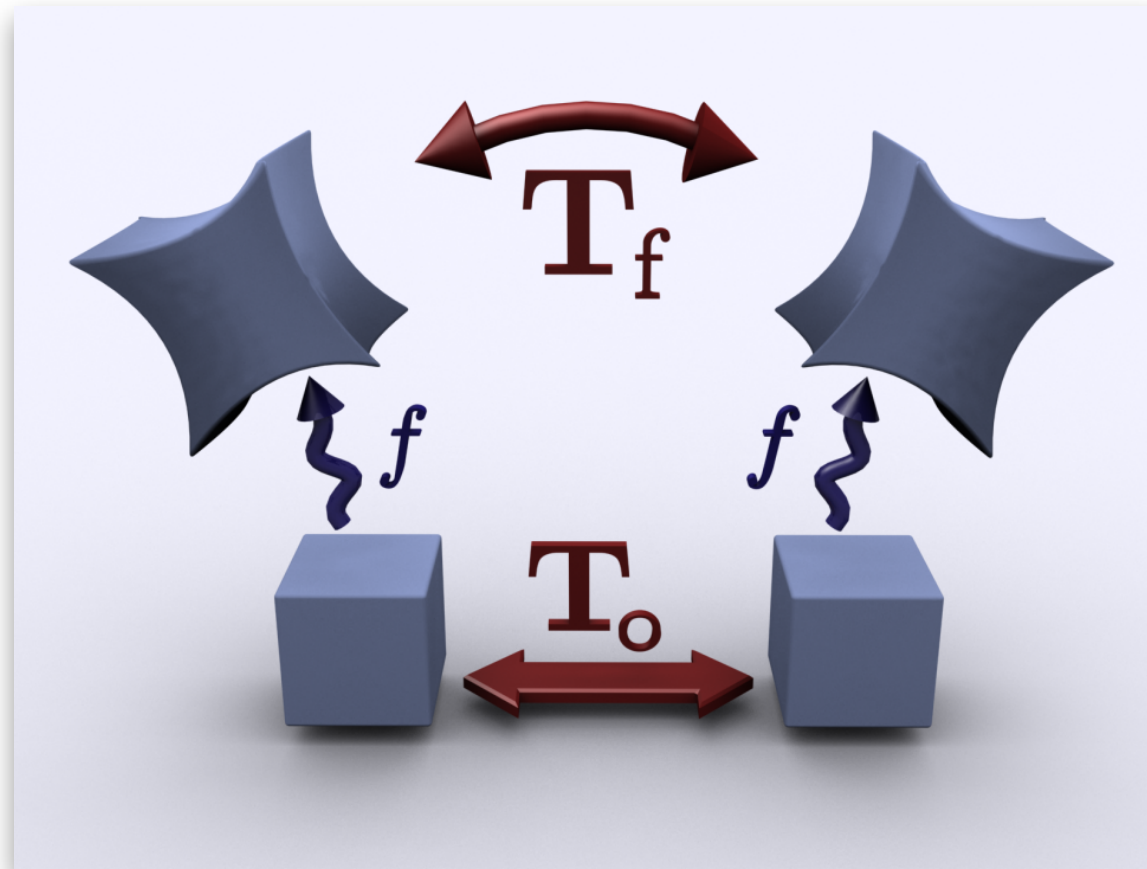
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Relations

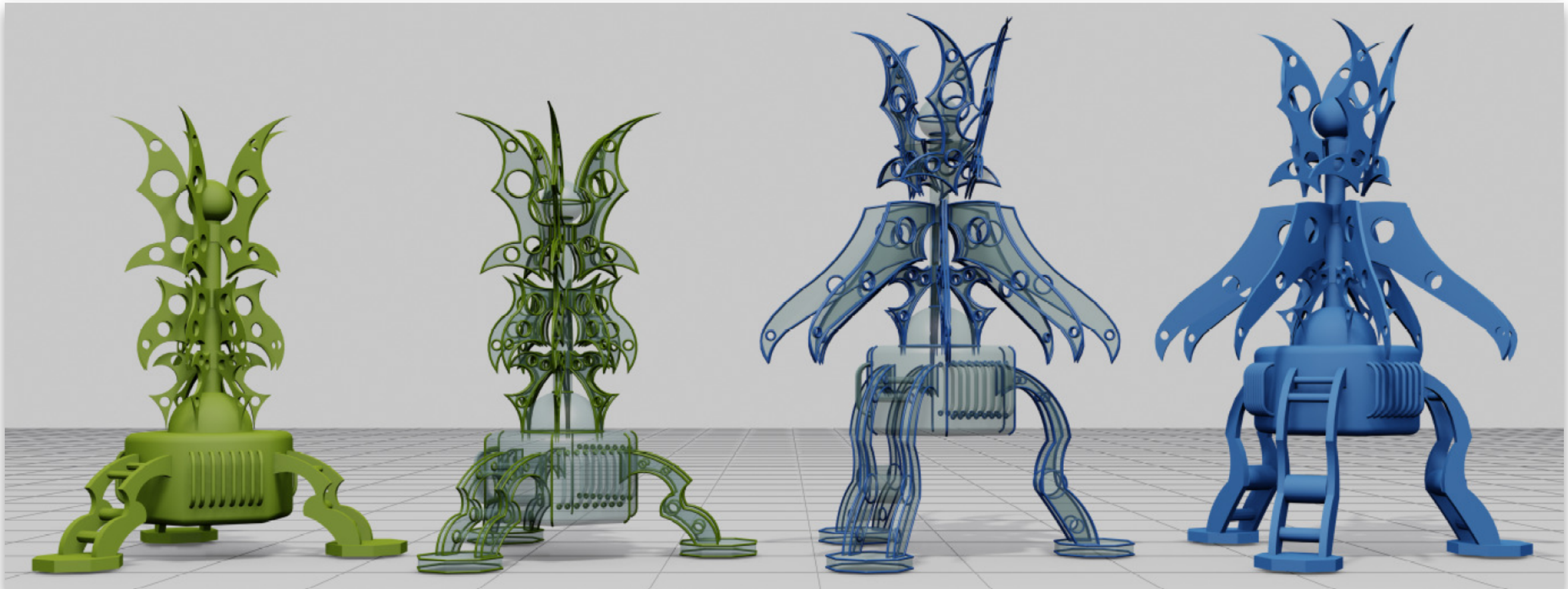


Predefined Classes of Relations



- Symmetry and Euclidean Invariants
 - **Detect symmetries**
 - Also: partial Euclidean invariants (parallelity, distances, angles, etc.)
 - **Build constraints** (soft/hard)

Predefined Classes of Relations



- Example System: iWires

[Gal et al. SG 2009]

- Detection:

- Feature-based approach
 - Line features (“wires”)

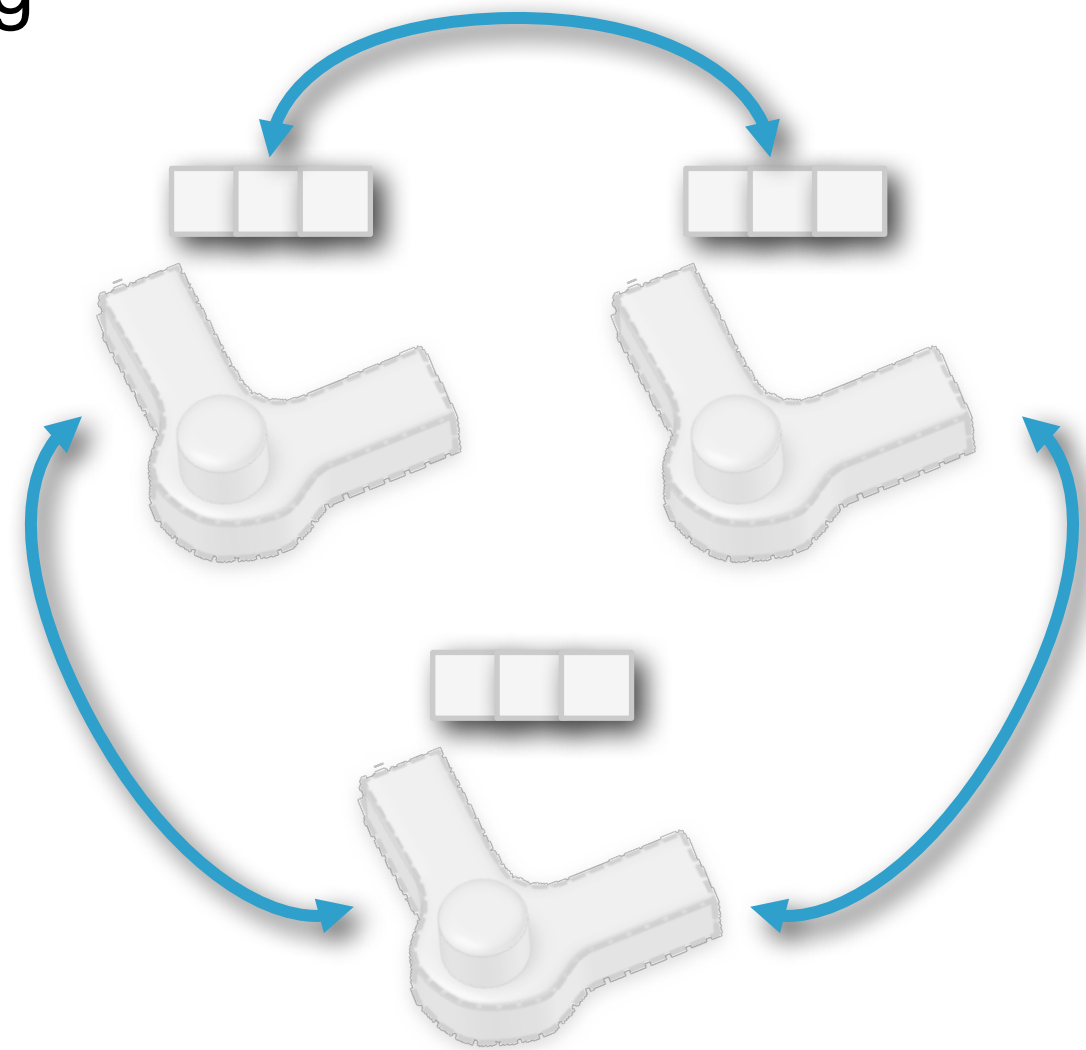
Physical Constraints

- Physics
 - **Stability**
 - Stable standing under gravity
 - Ability to withstand forces in use
 - **Functionality**
 - Transmission of forces, movements (rotational, translational)
 - Movability
 - **Assembly**
 - Parts can be put together
 - Accessibility (service)
 - etc.

- Modeling and Detection of Relations

- User defined relations
 - Traditional constrained modeling
- Fixed models
 - Detect relations from predefined classes
- Data-driven relations
 - Discover new types of invariants from data

Relations



Learning Constraints

- **Constraints from Data**
 - Relatively new, unexplored area
- **Latent parameter models**
 - Dimensionality reduction (PCA), manifold learning (kernel-PCA, spectral embeddings)
[Ovsjanikov et al. 2011]
- **Shape assemblies**
 - Learning scene layout [Fisher et al. 2010-2012]
 - Learning how to assemble shapes
[Kalogerakis et al. 2012]