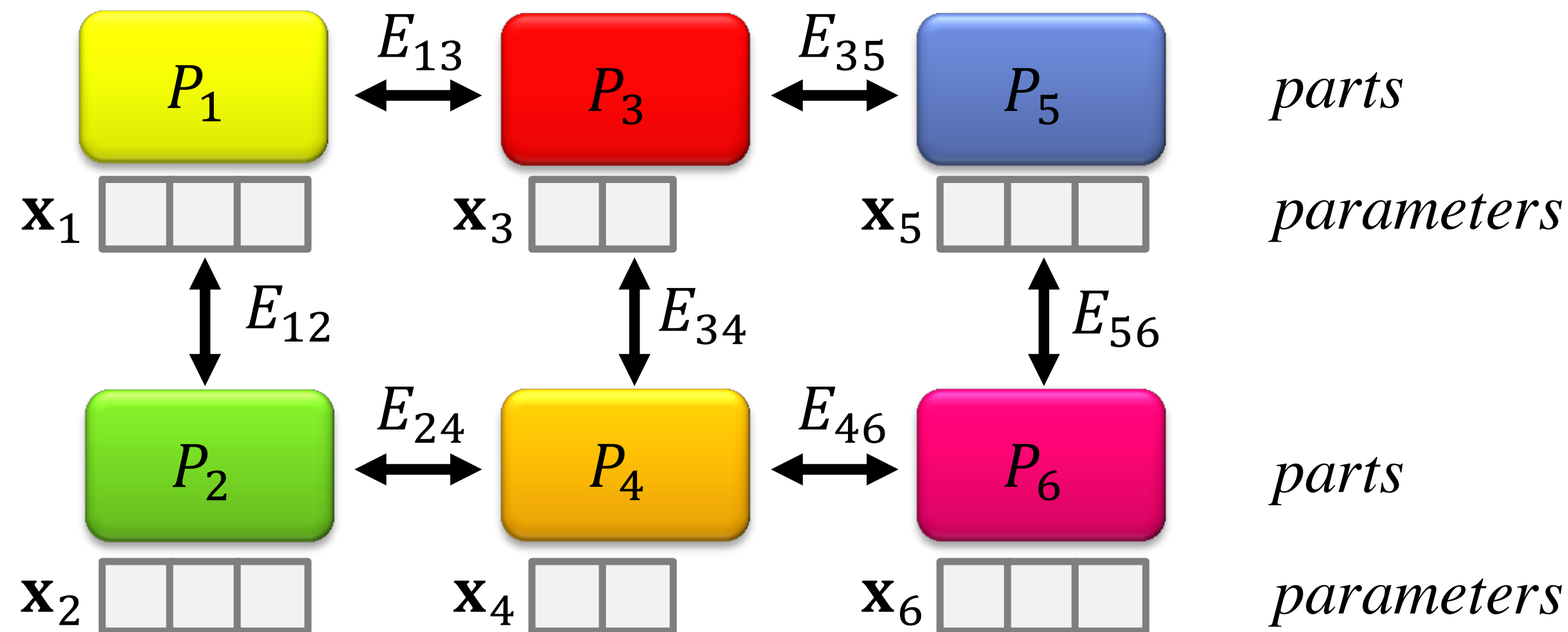


Structure-Aware Shape Processing



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Qi-Xing Huang



Course Organizers

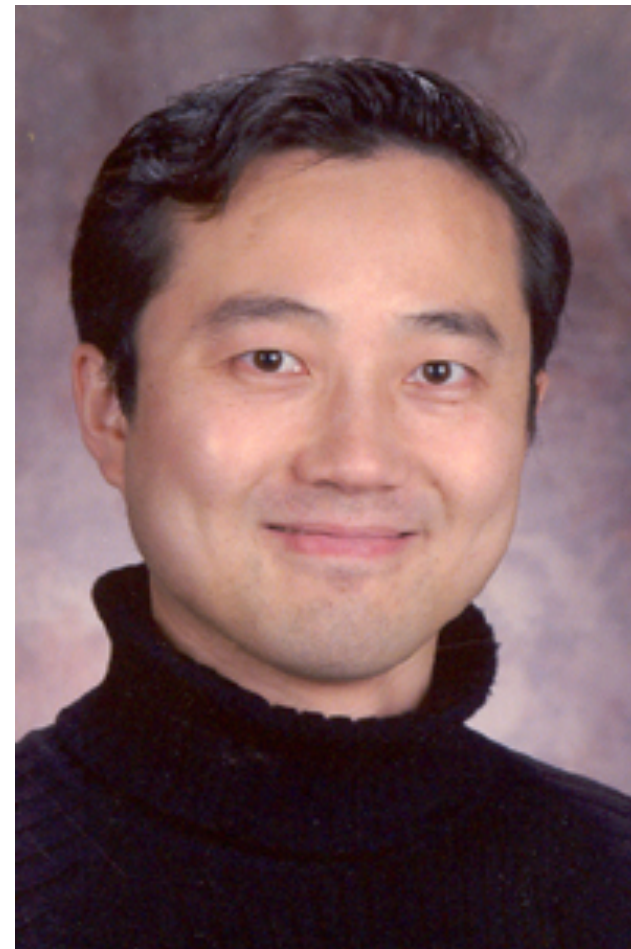
People



Niloy J. Mitra



Michael Wand



Hao Zhang



Daniel Cohen-Or



Vladimir Kim



Qi-Xing Huang

- **Introduction to Geometric ‘Structure’**
- **Extracting Structures**
 - Analysis of Individual Models
 - Analysis of Shape Collections (co-analysis)
 - Encoding Structural Hierarchy
- **Manipulating Structures**
 - Modeling as Structural Variations
 - Structure-guided Design
 - Organization and Exploration of Shape Collections
- **Future Directions**



Introduction

*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

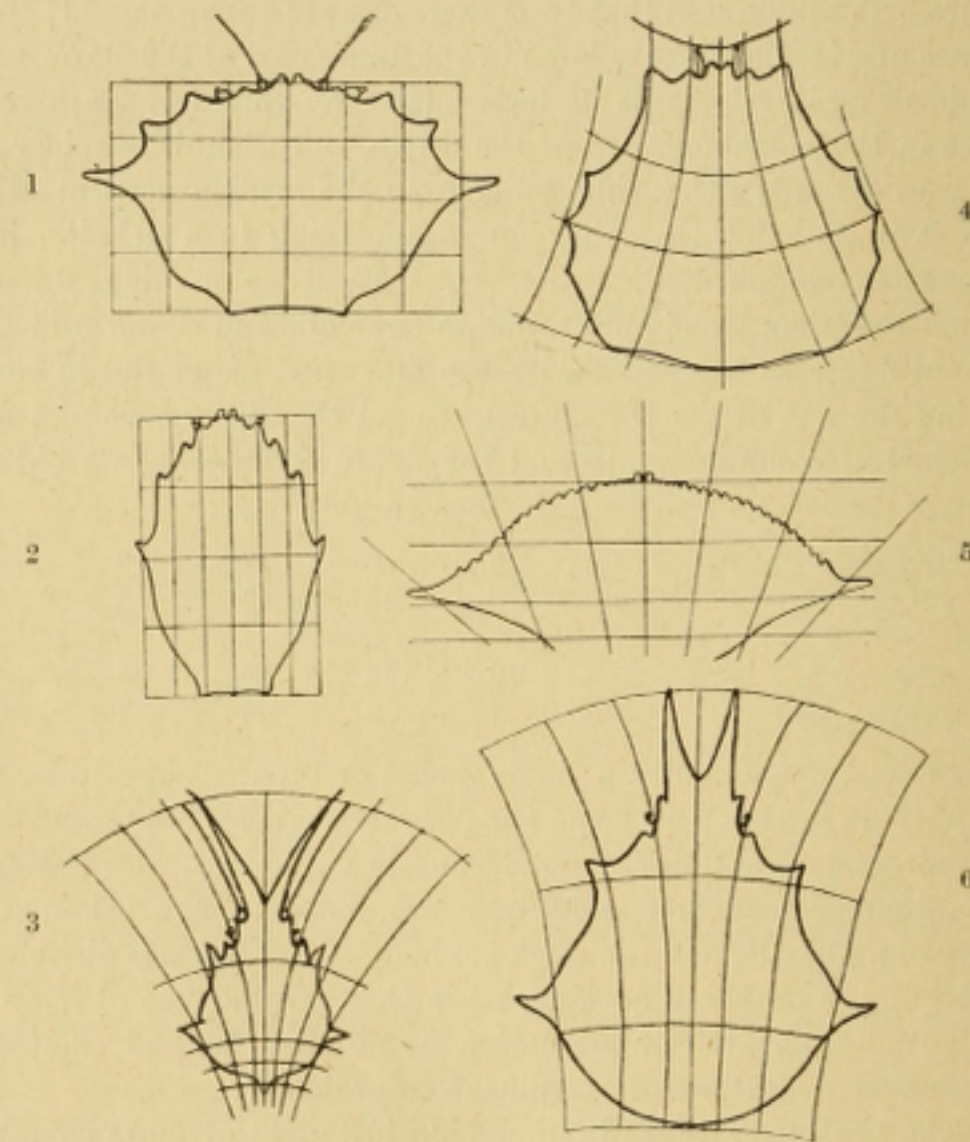


Fig. 369. Carapaces of various crabs. 1, *Geryon*; 2, *Corystes*; 3, *Scyramathia*; 4, *Paralomis*; 5, *Lupa*; 6, *Chorinus*.

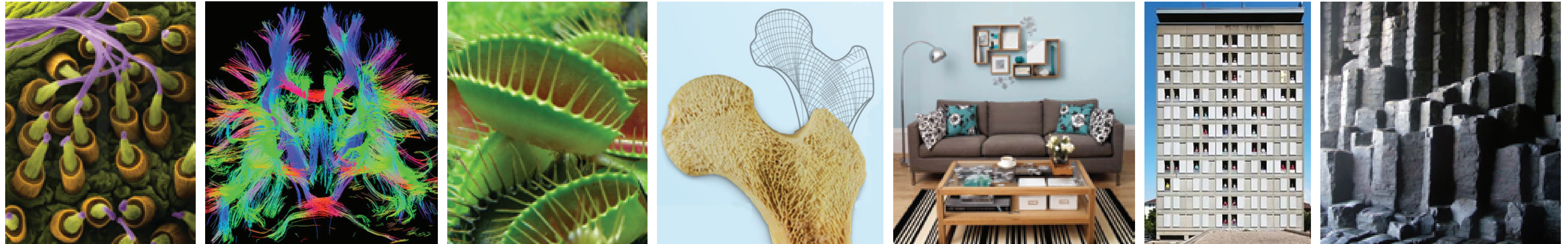
number and situation of the marginal spines, though these are in other cases subject to independent variability.

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.

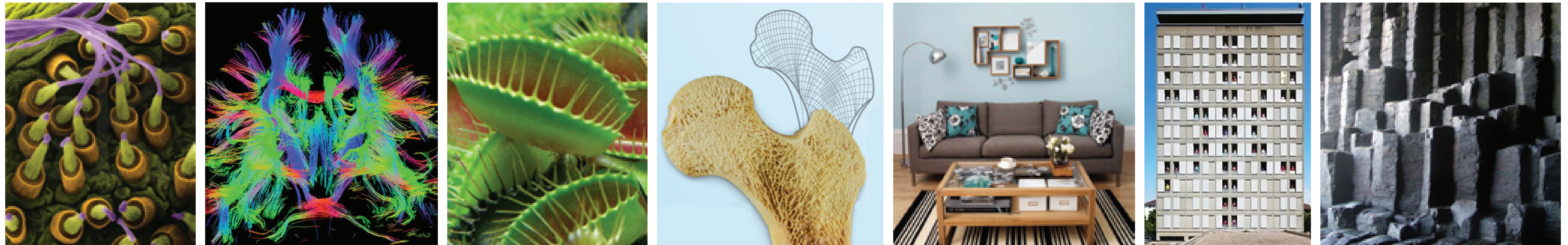
Chapter XVI [Thompson 1892]

Structure in Shapes

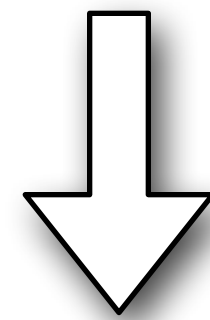


structures in nature

Structure in Acquired Geometry

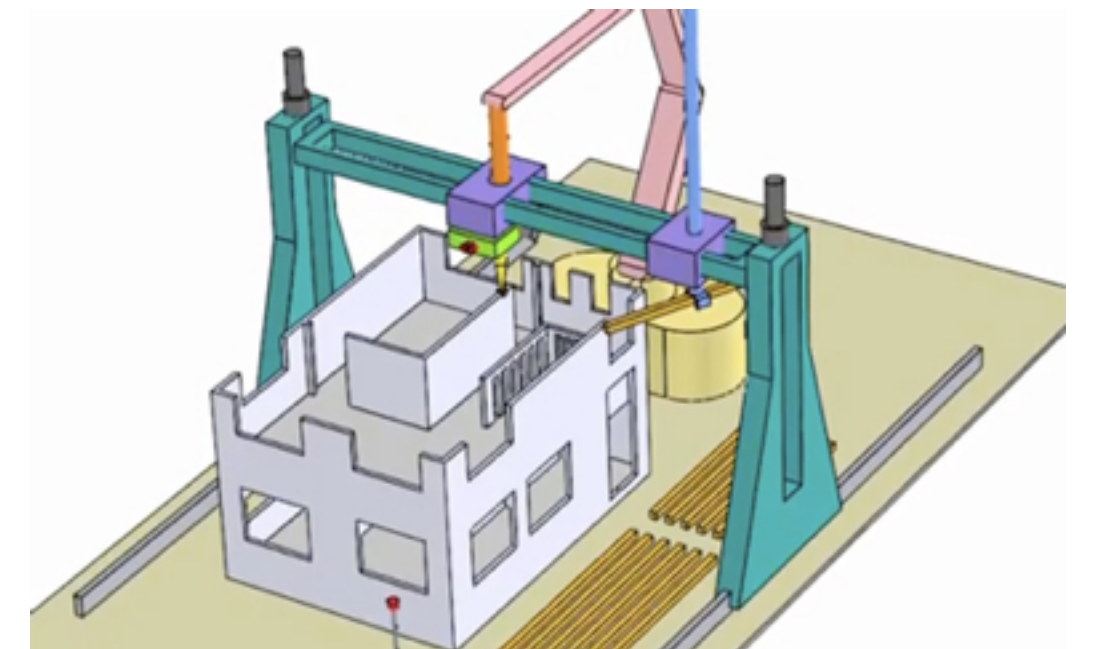
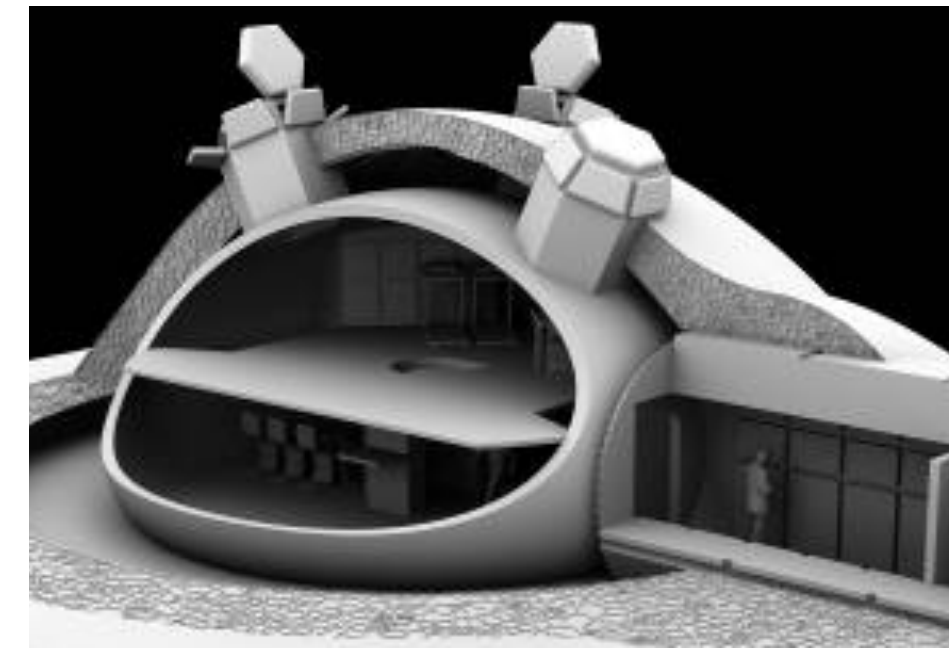
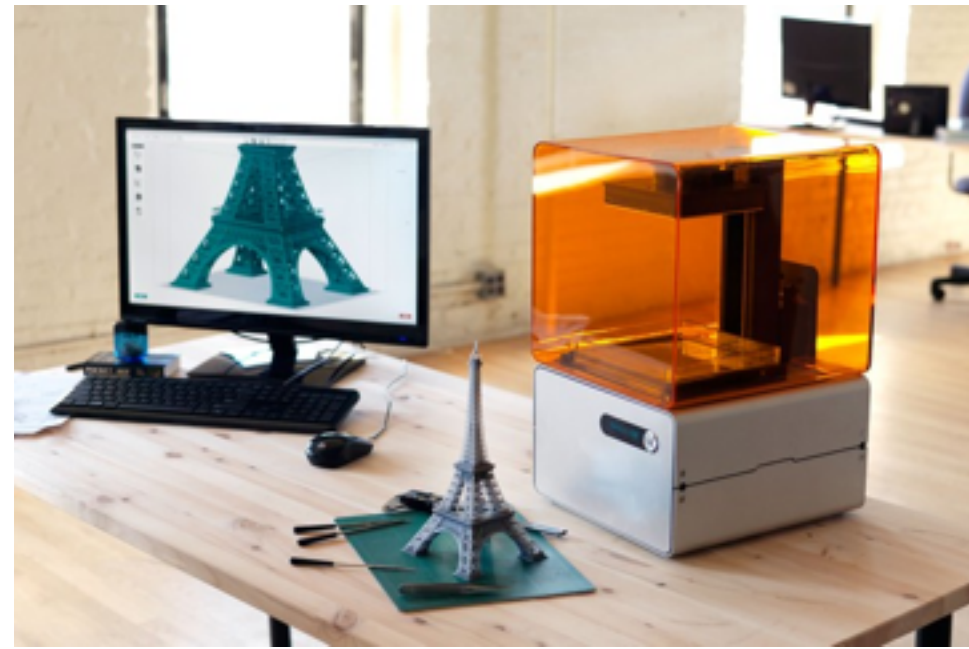
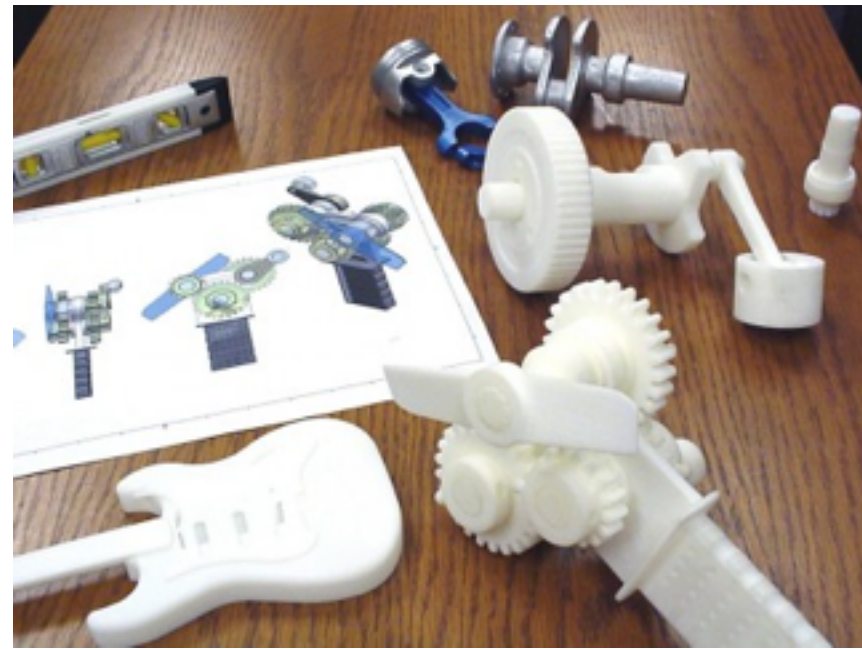


structures in nature

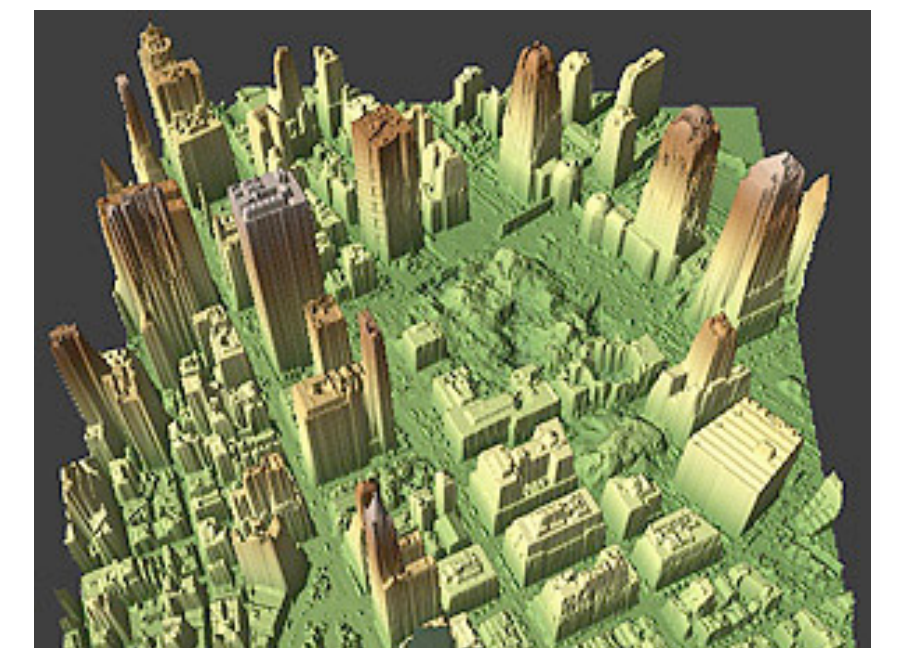
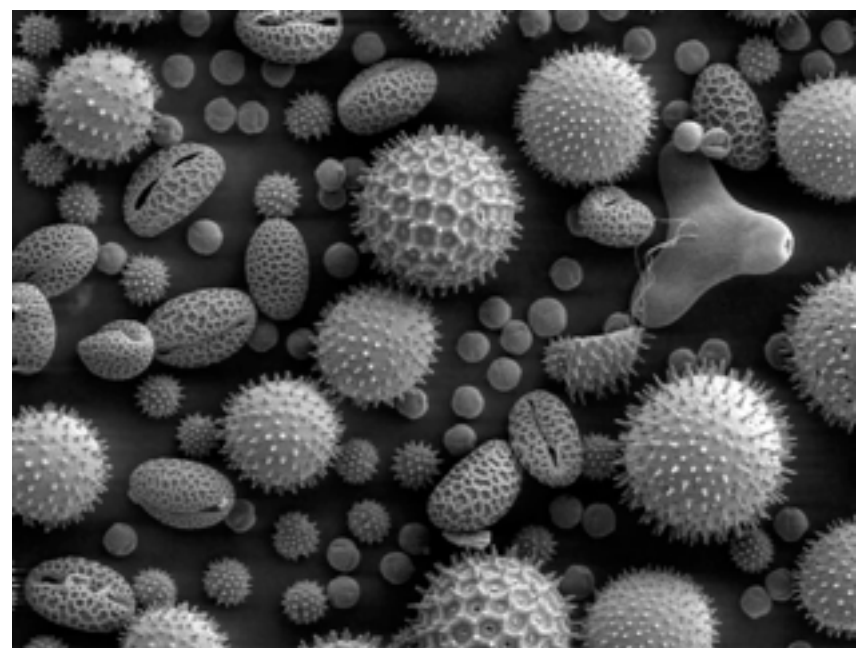
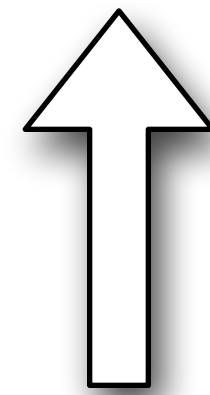


‘structures’ as captured

Structure in Synthesized Geometry

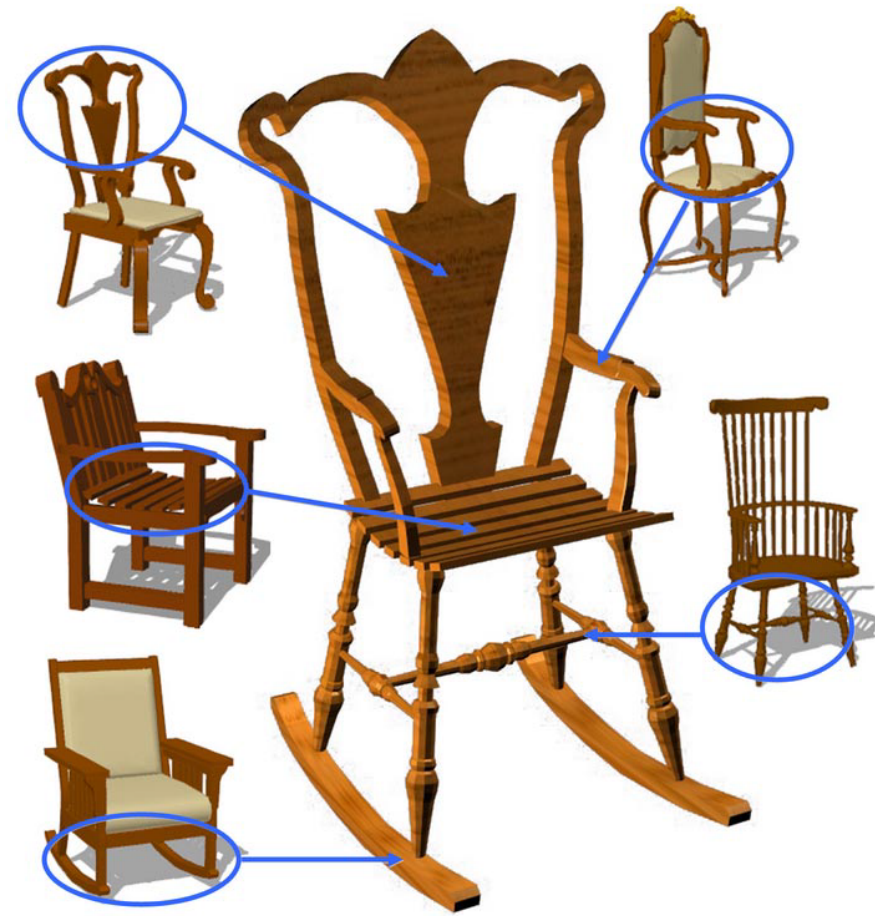


back to the physical world

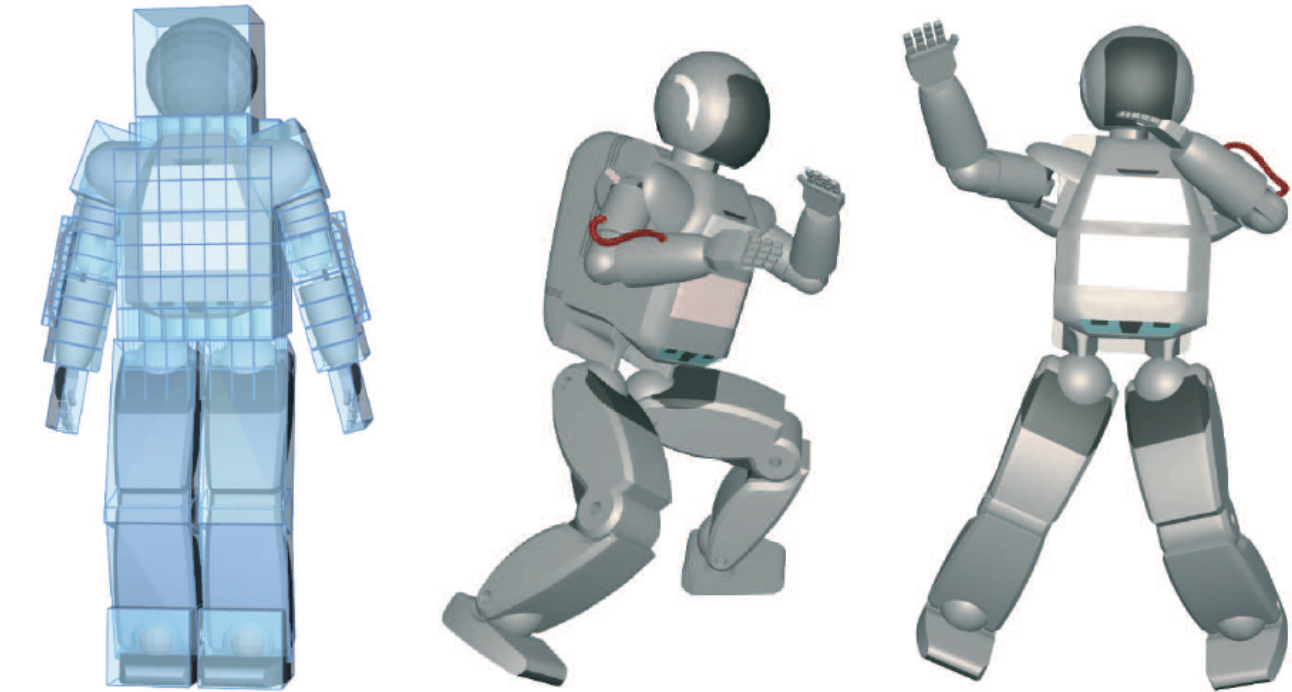


‘structures’ as captured

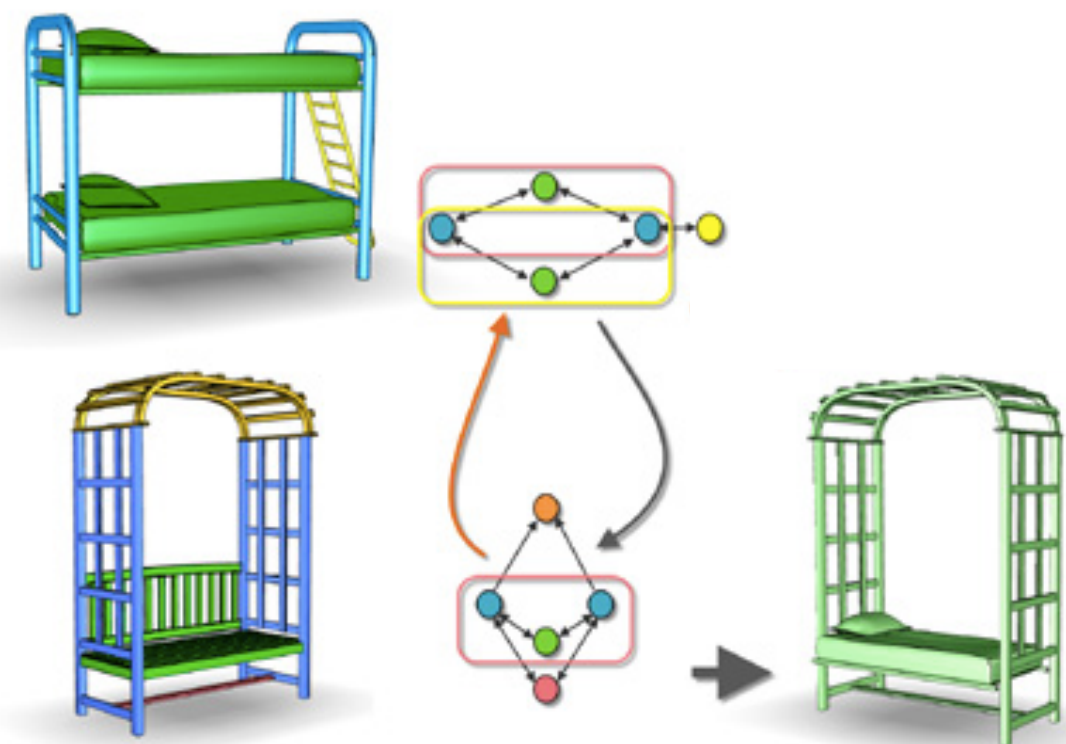
Shape Synthesis



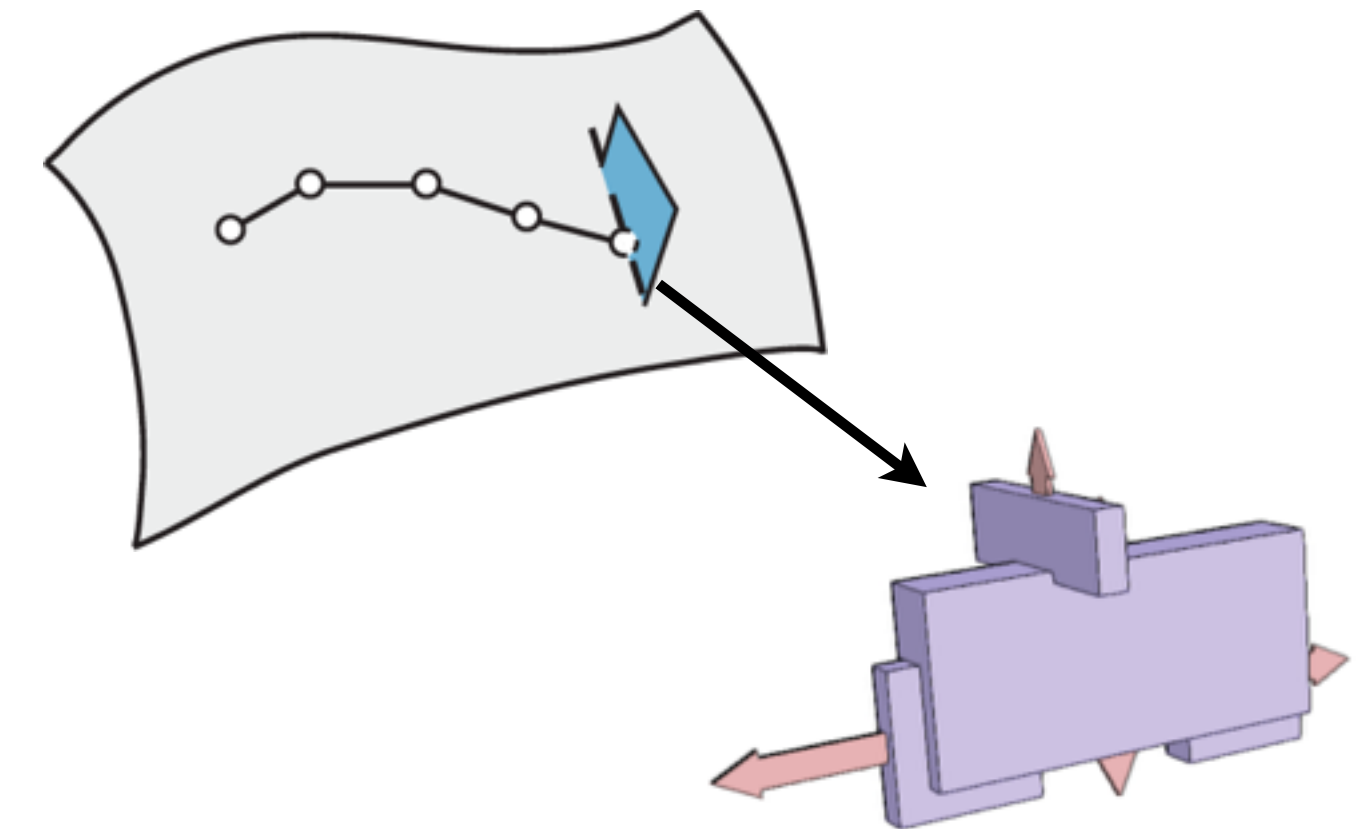
[Funkhouser et al. 04]



[Xu et al. 09]



[Zheng et al. 13]



[Ovsjanikov et al. 11]

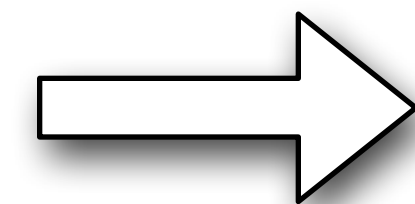
and much much more ...

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

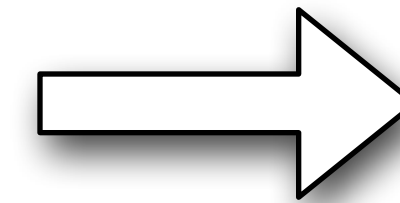
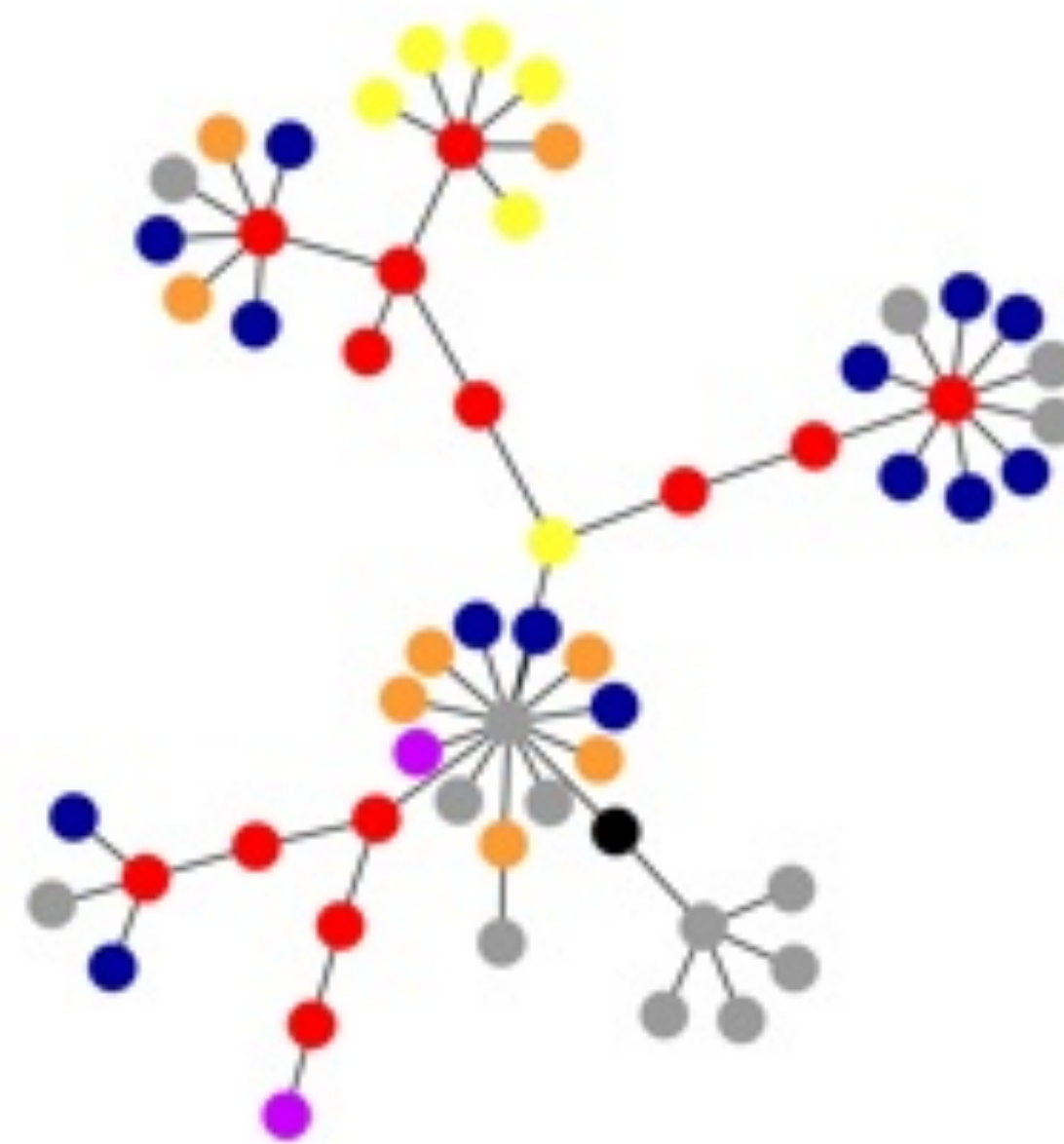
structure of individual shapes and shape collections

Structure-aware Shape Processing

encoding structure



analysis



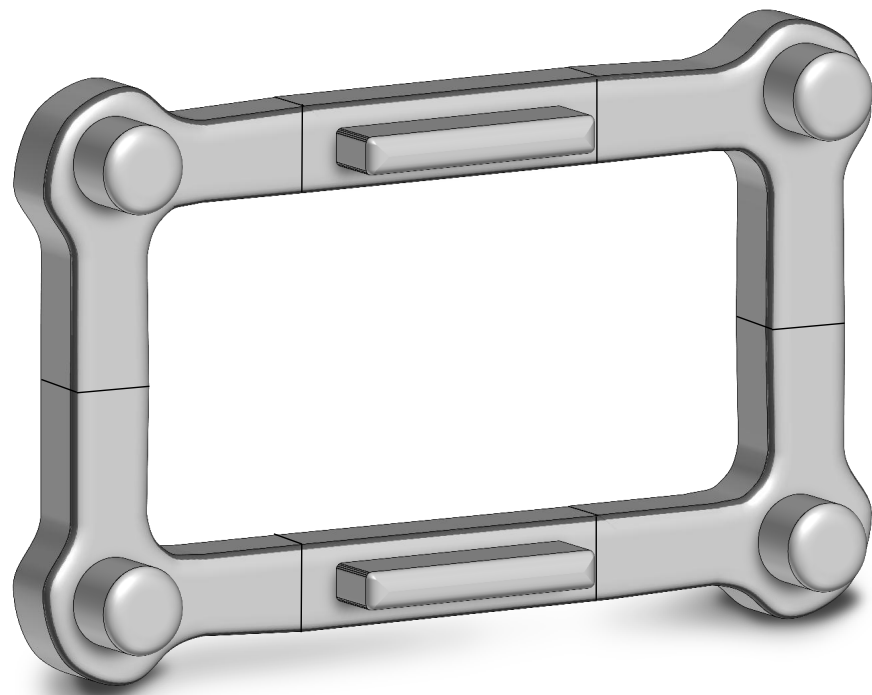
manipulation



What are the **parts**?

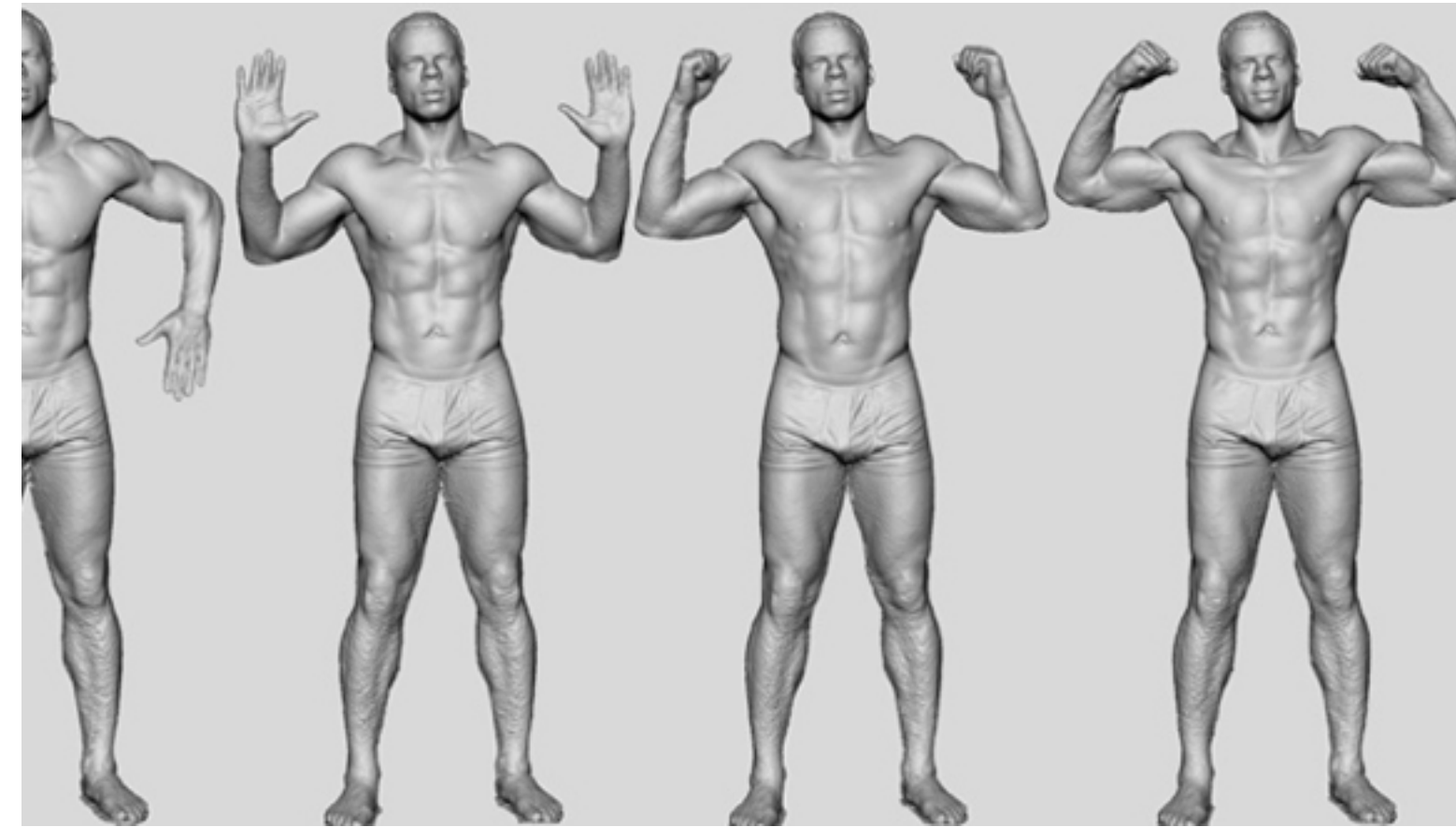
How do the parts **relate** in/across models?

How do the parts **vary** across the models?



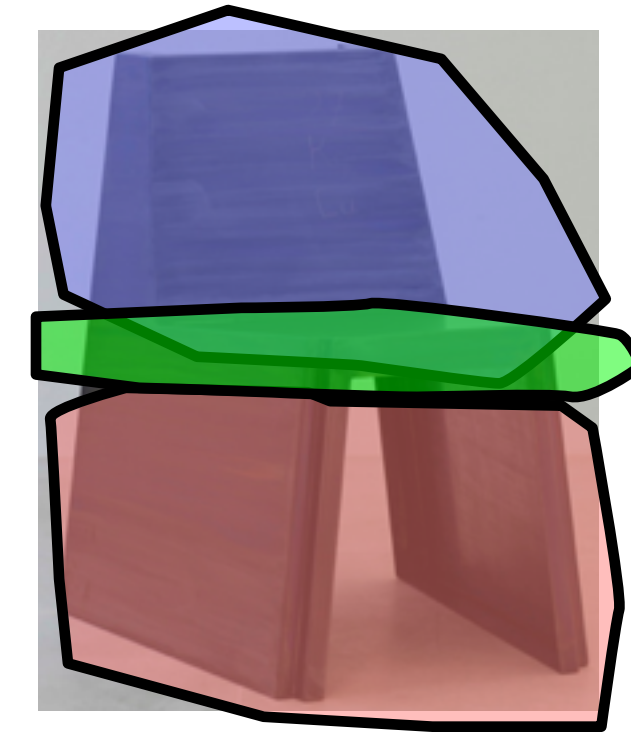
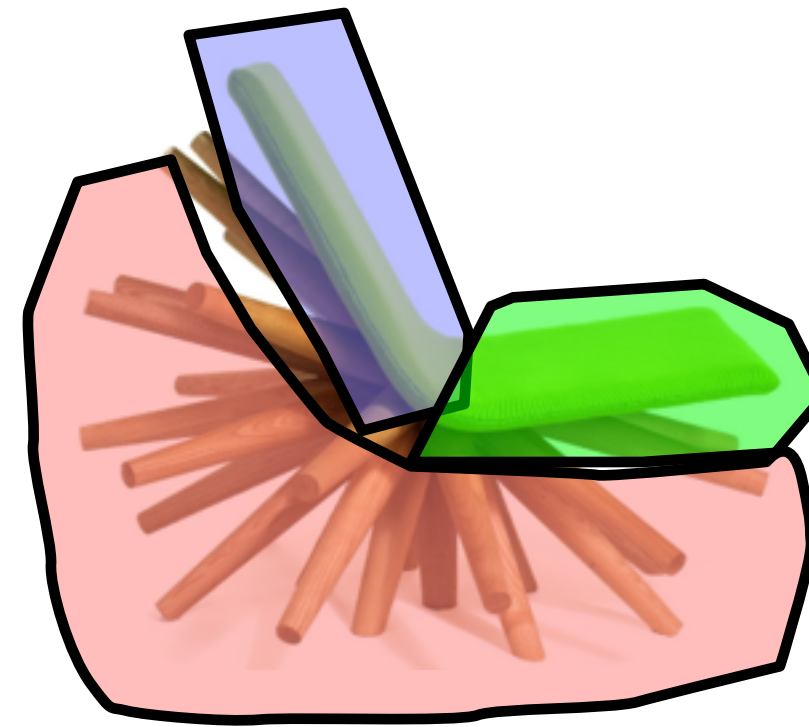
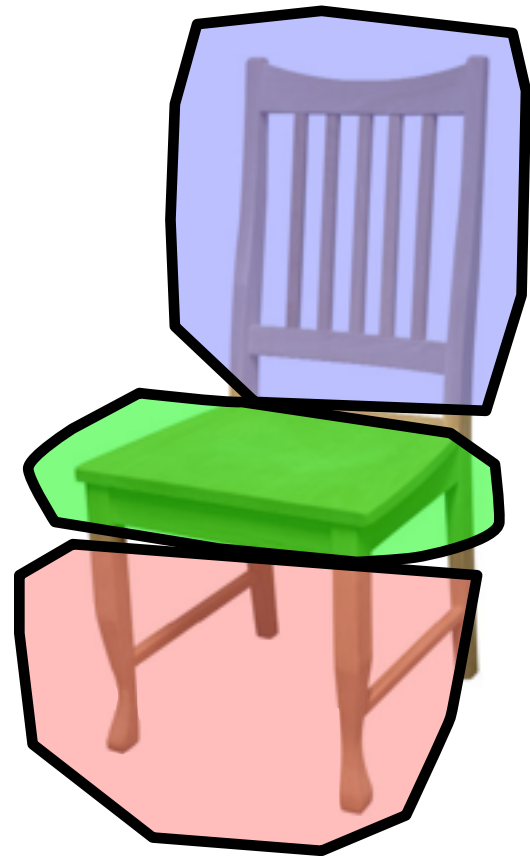
(a) a piece of geometry \mathcal{S}

New Sources of Data

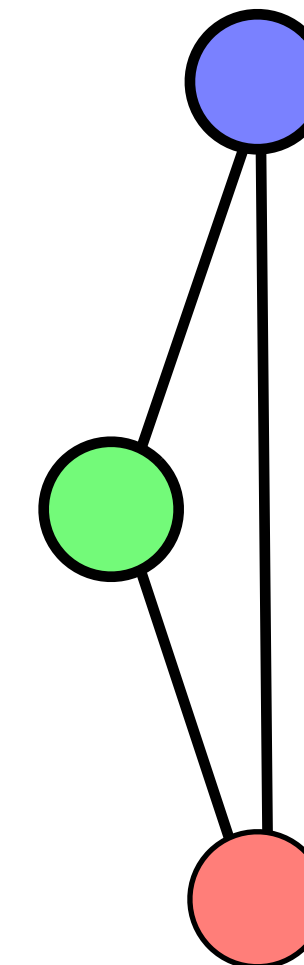
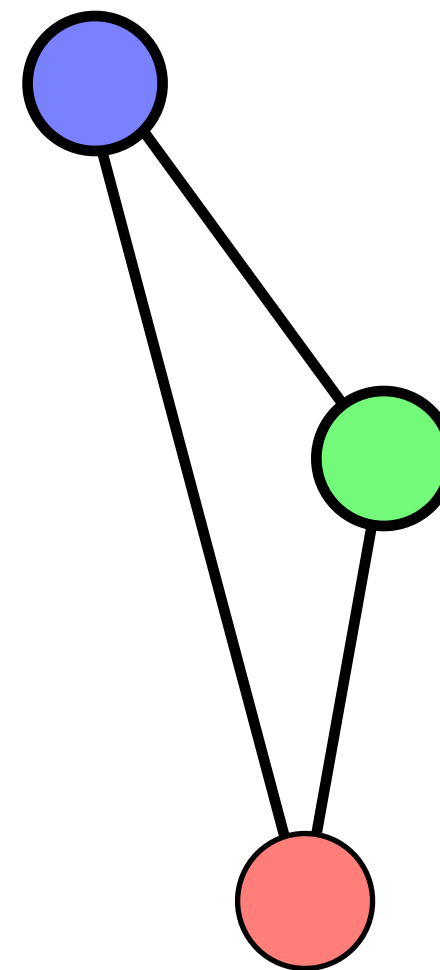
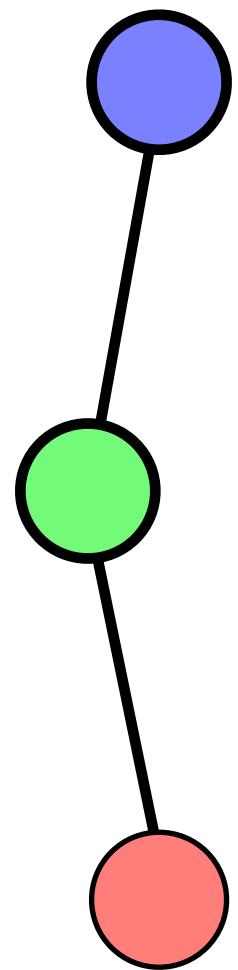


network of parts

Why Structures?

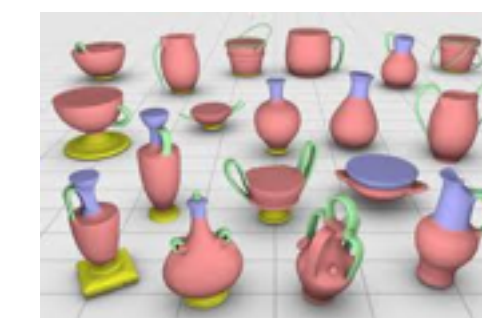
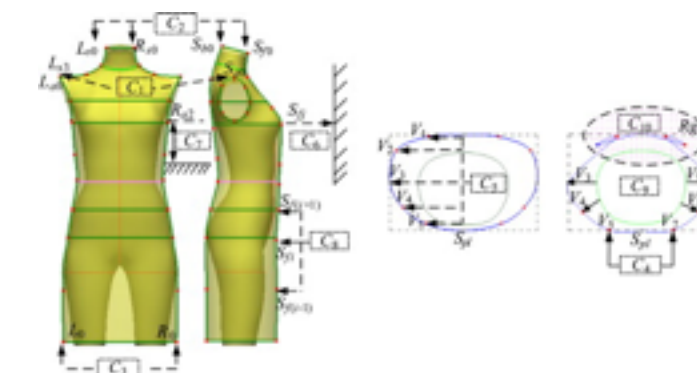


relation graph + variations ~ captures semantics?



Historical Perspective

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



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

- User annotated
- Template fitting
- Learning
 - supervised learning
(e.g., classifiers on labeled parts)
 - unsupervised learning
(e.g., spectral clustering)

Extracting Part Parameters

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

Extracting Relations

- User specified relations
(e.g., constrained-modeling)
- Relations are specified apriori
(e.g., manually authored, physical laws)
- Discovered from data
(e.g., learned across abstracted geometry)
 - supervised
 - unsupervised

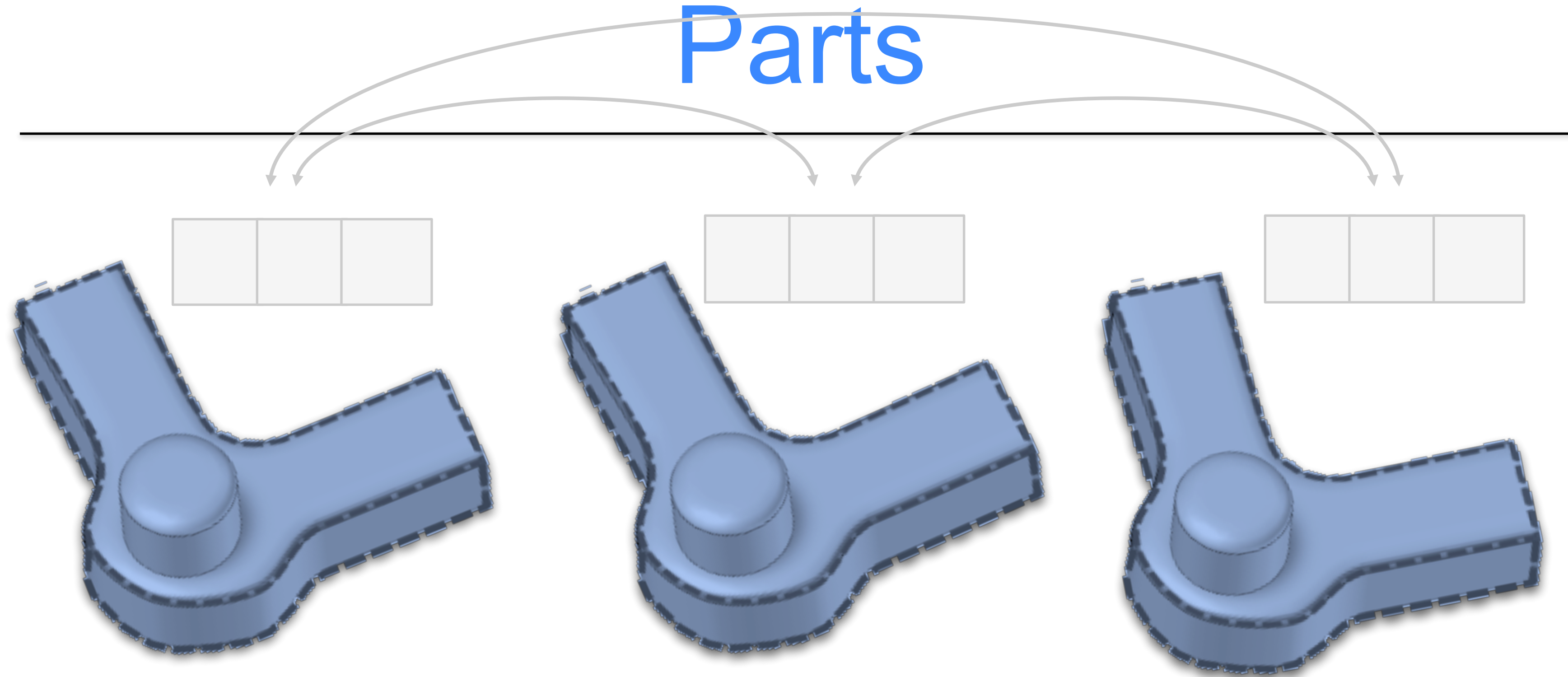
Mathematical Tools

Background Tools

- Principal component analysis (PCA)
- Shape features (extrinsic vs. intrinsic)
- Basic geometry processing (e.g., mesh stitching)

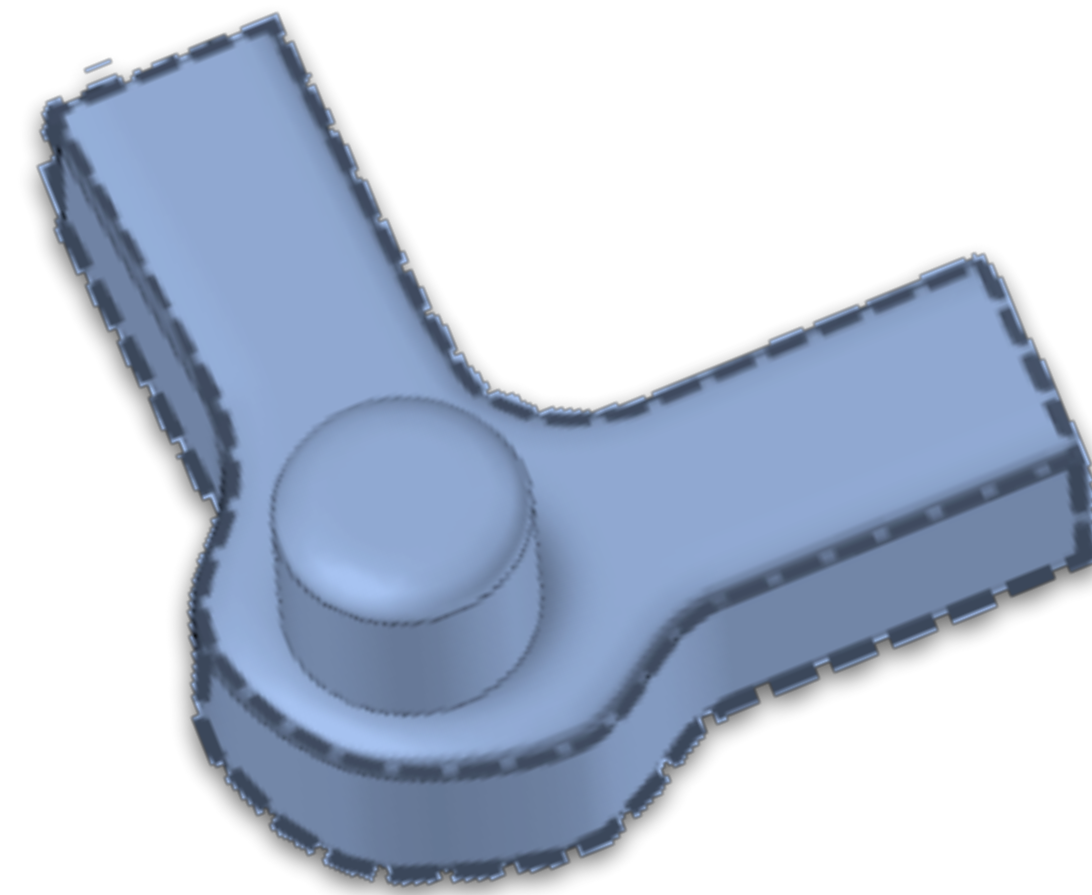


Parts



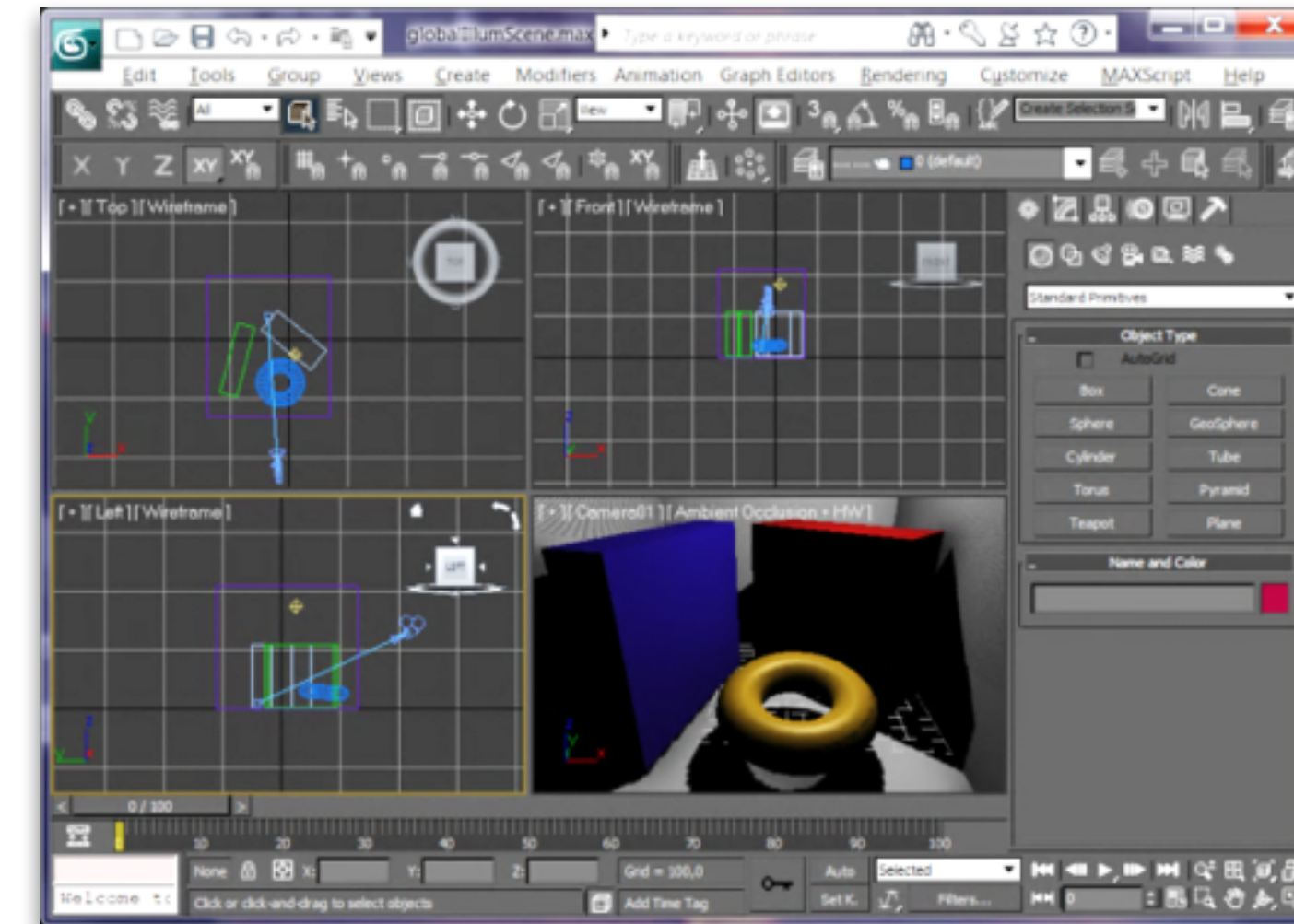
- Modeling and Detecting Parts
 - User defined parts
 - Manual segmentation
 - Fixed models
 - A priori segmentation model
 - Data-driven segmentation
 - A priori: meta-model

Parts

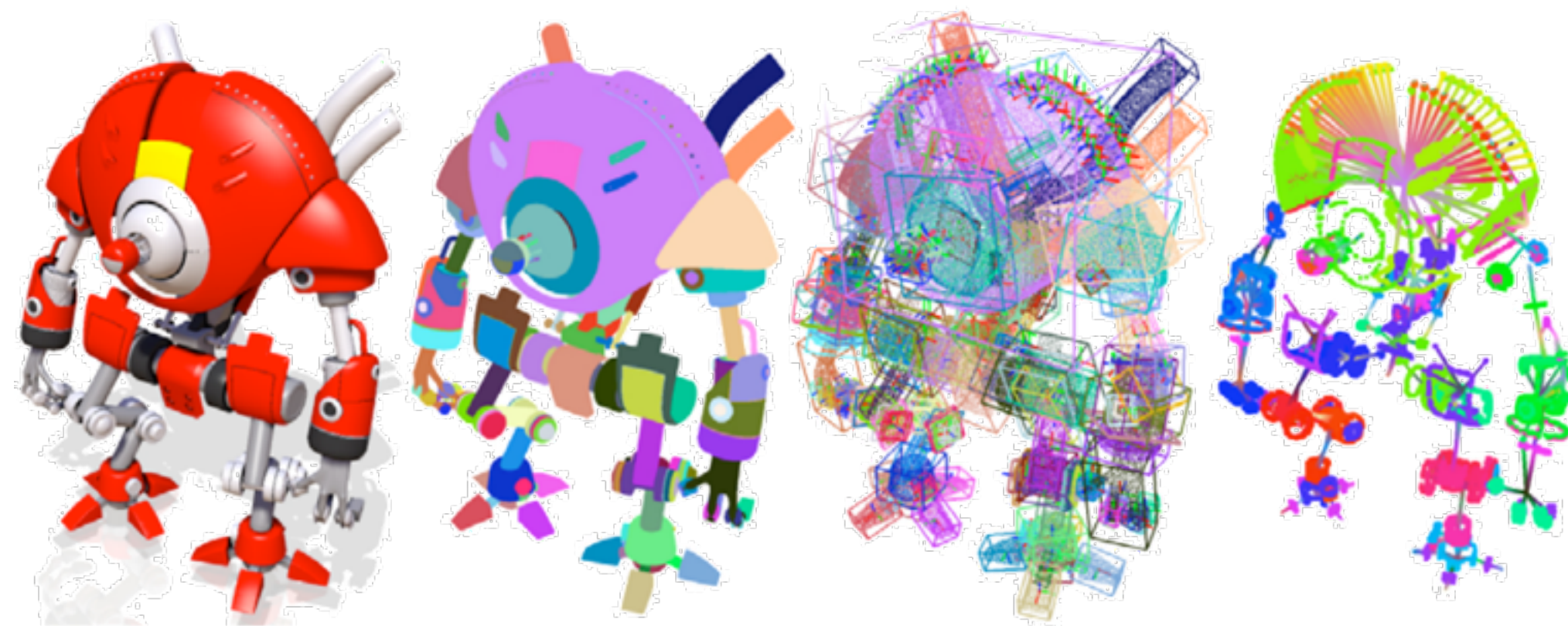


User Defined Parts

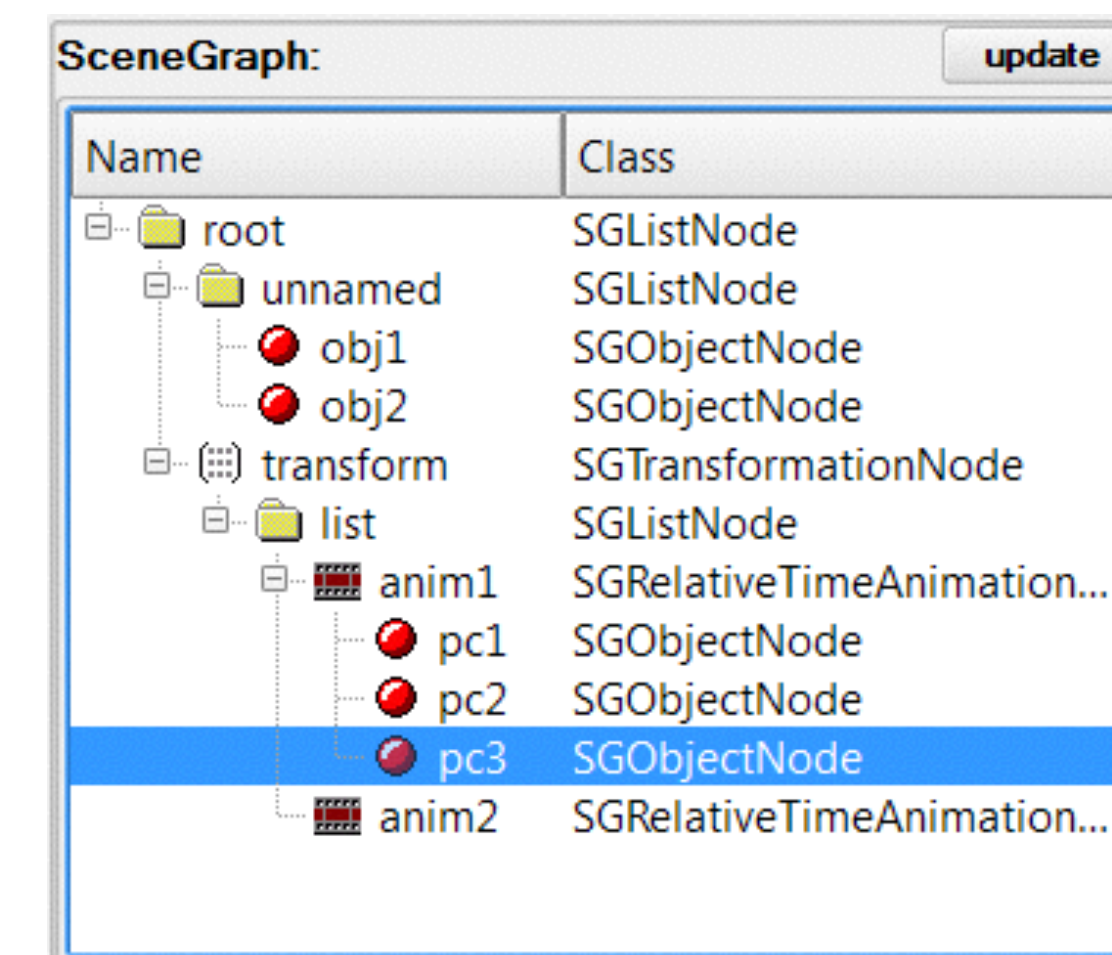
- **Traditional Modeling**
 - Scenes assembled out of primitives
 - Hierarchical organization in scene graph



[Autodesk 3DS MAX]

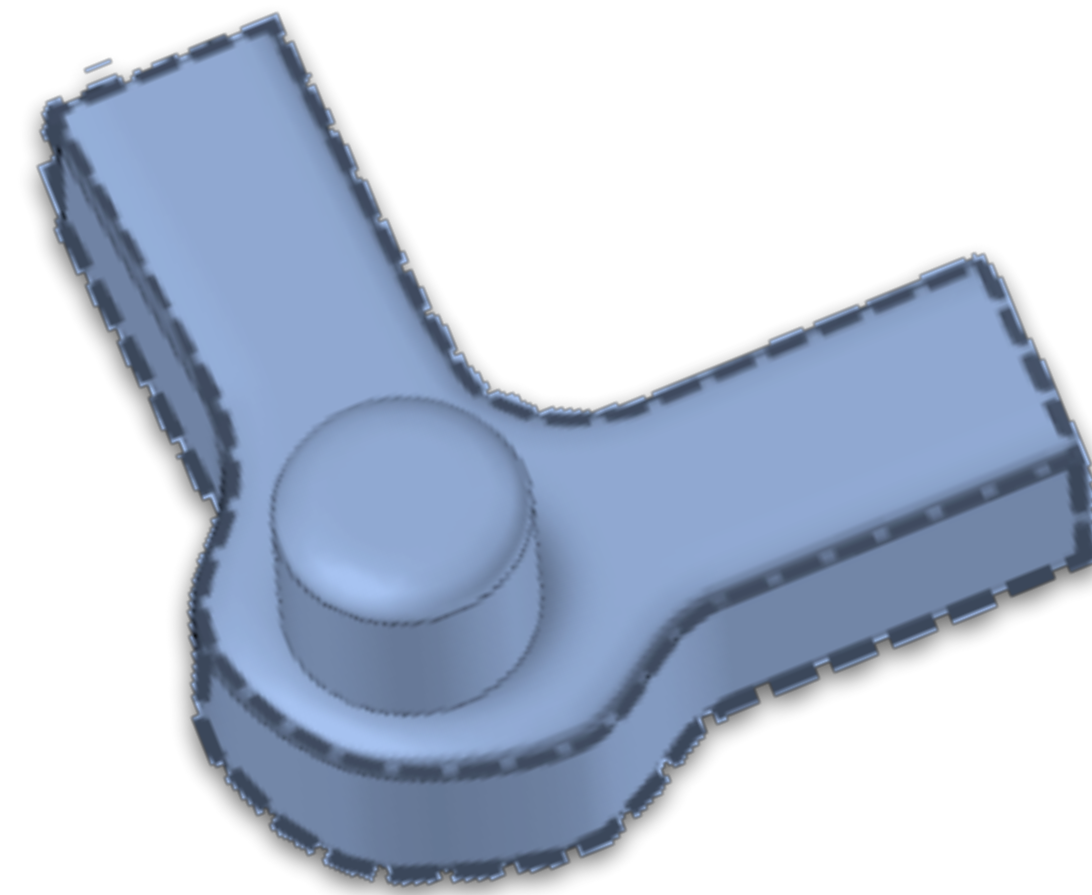


[Jain et al. EG 2012]



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

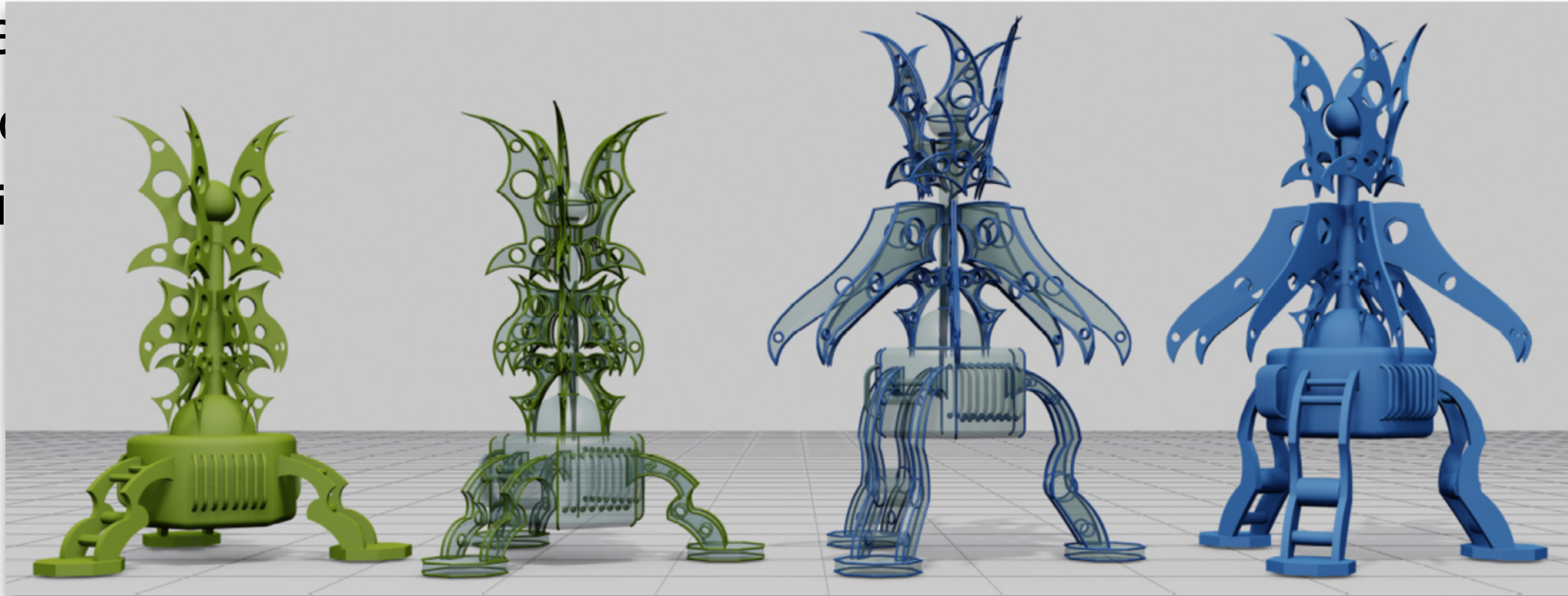
Parts



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

Curves as Primitives

- Example
 - Sharp c
 - Detecti

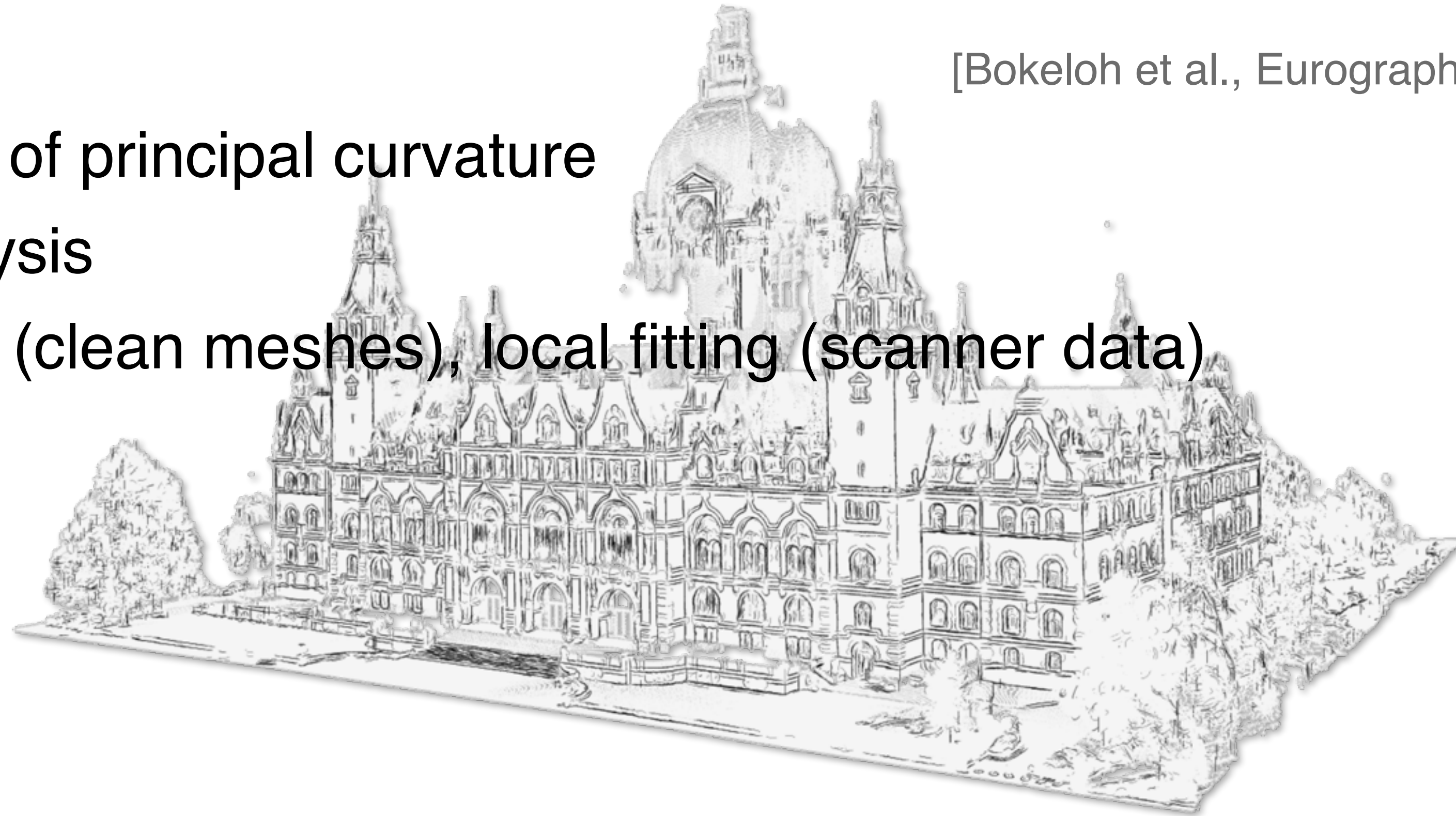


Curves from Point Sets

- **Detection**

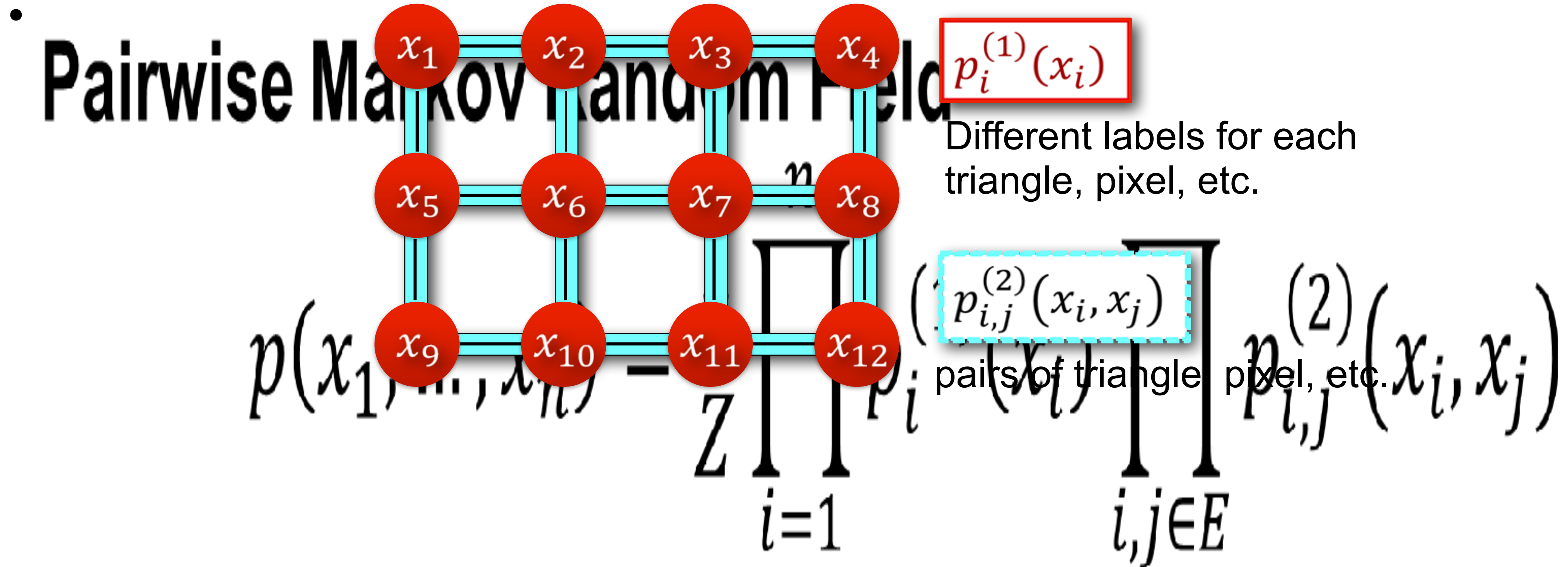
[Bokeloh et al., Eurographics 2009]

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



- **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



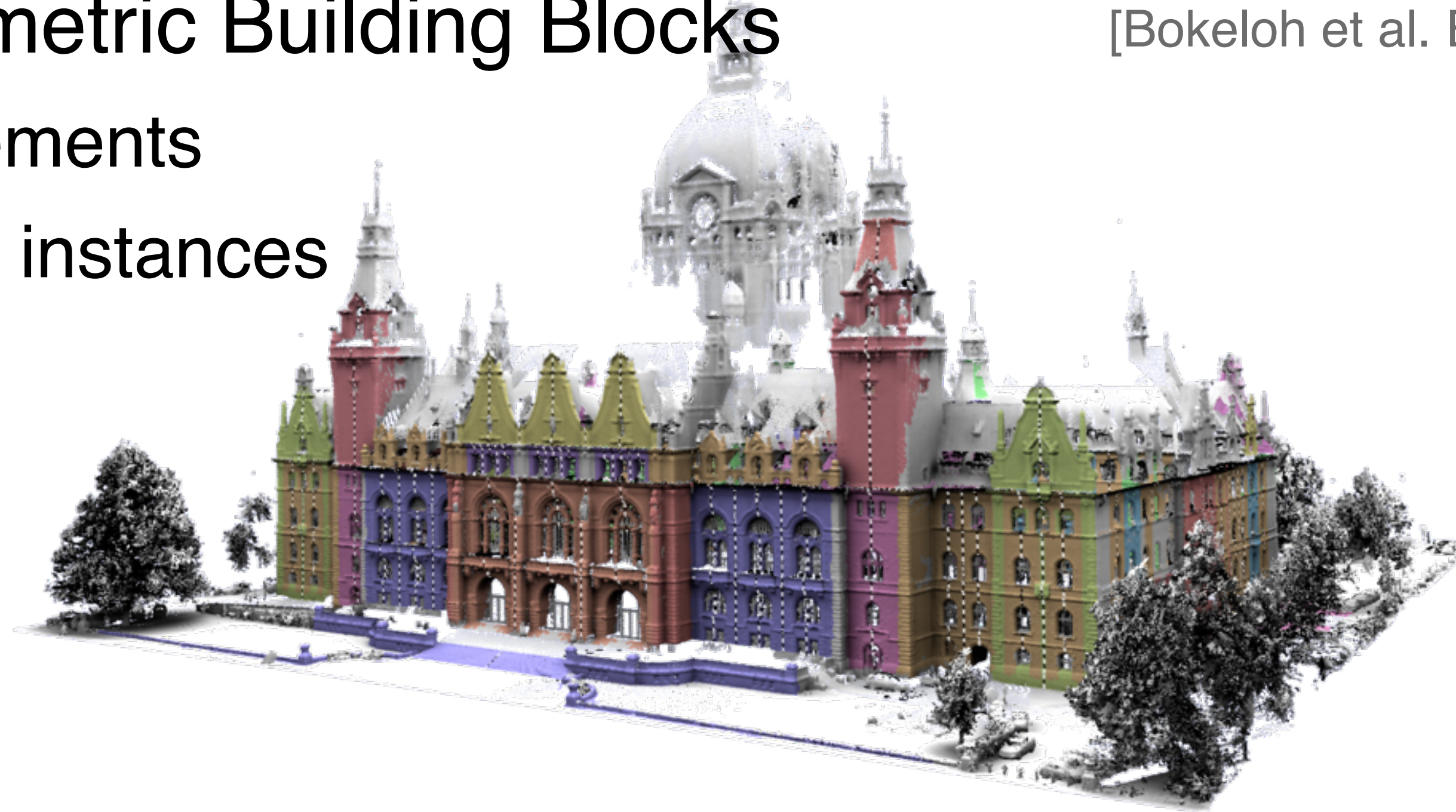
Optimization: loopy belief propagation, (iterated) graph cuts

Symmetry-based Segmentation

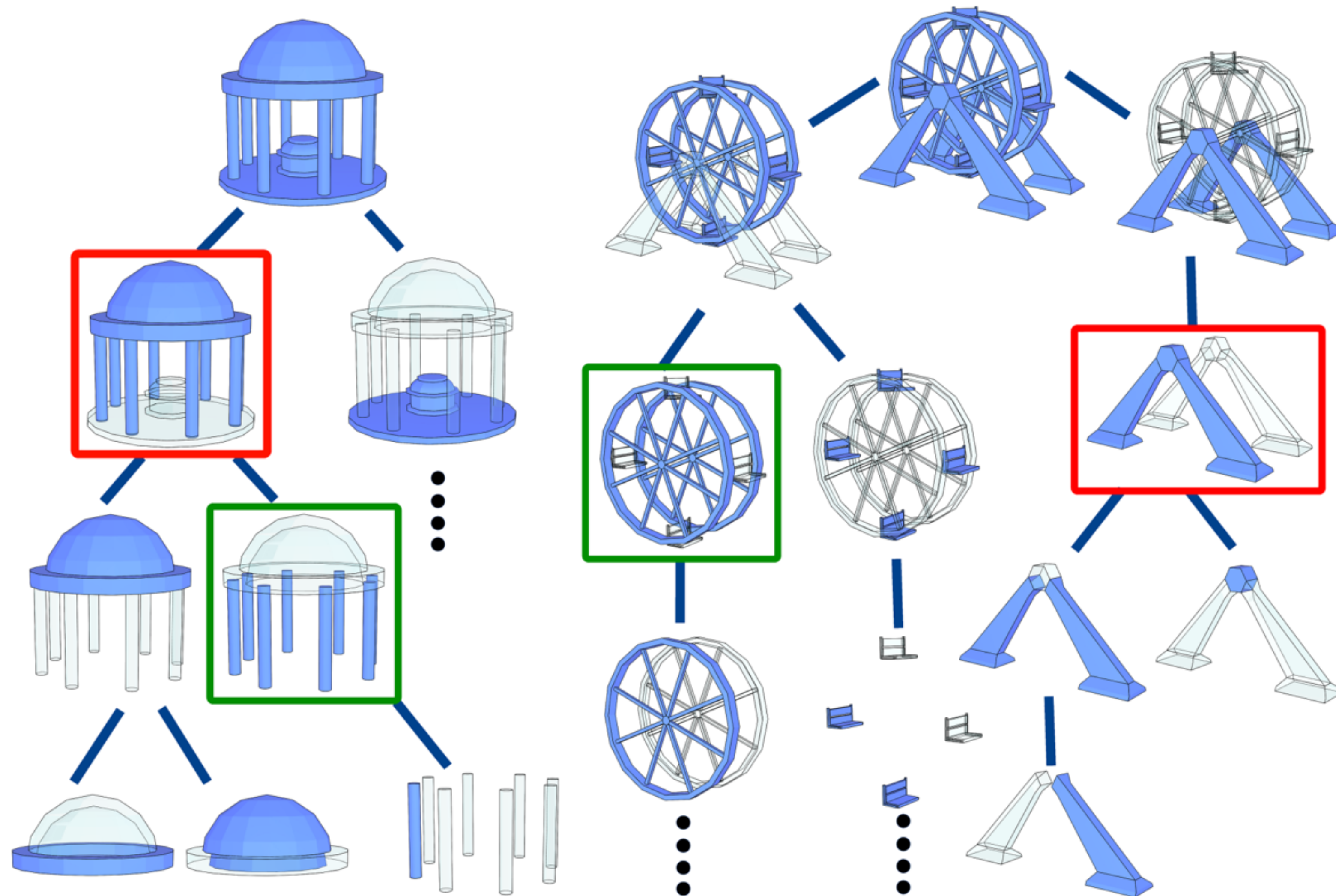
Split Model into Symmetric Building Blocks

[Bokeloh et al. EG 2009]

- Group repetitive elements
- Discover redundant instances



Symmetry Hierarchies

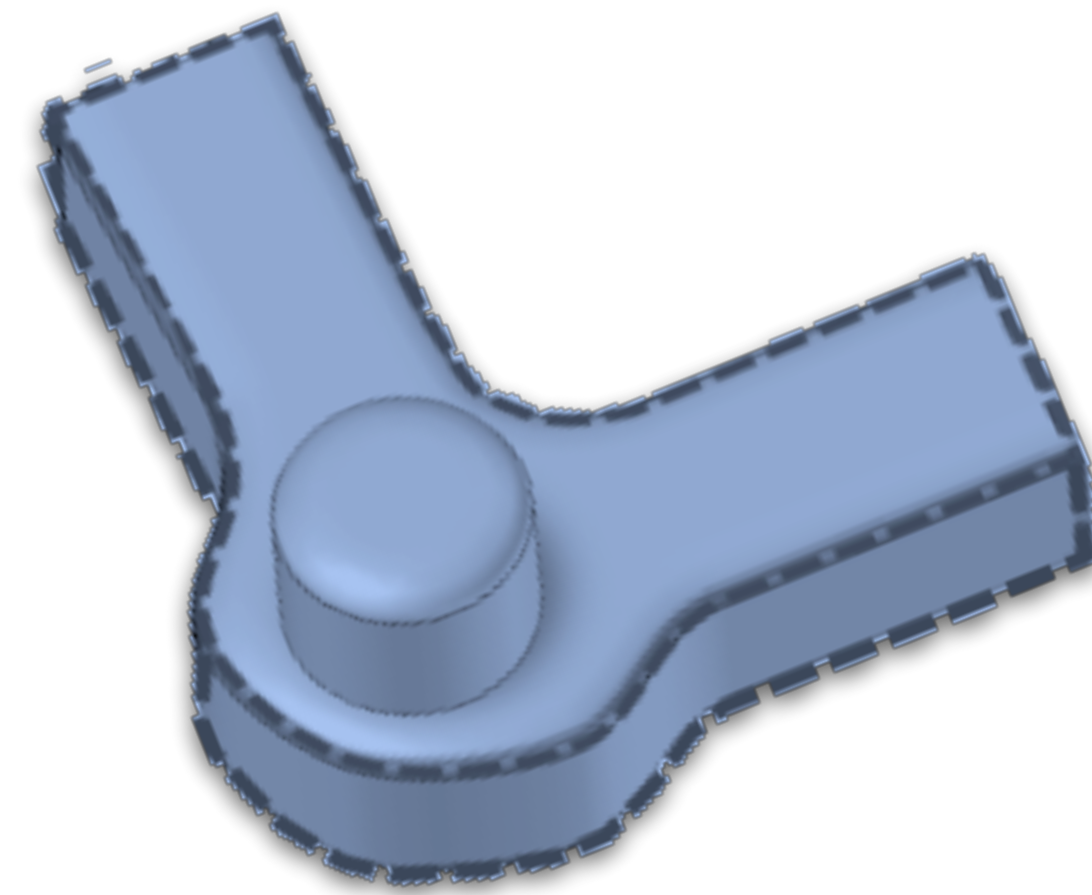


[Wang et al. EG 2011]

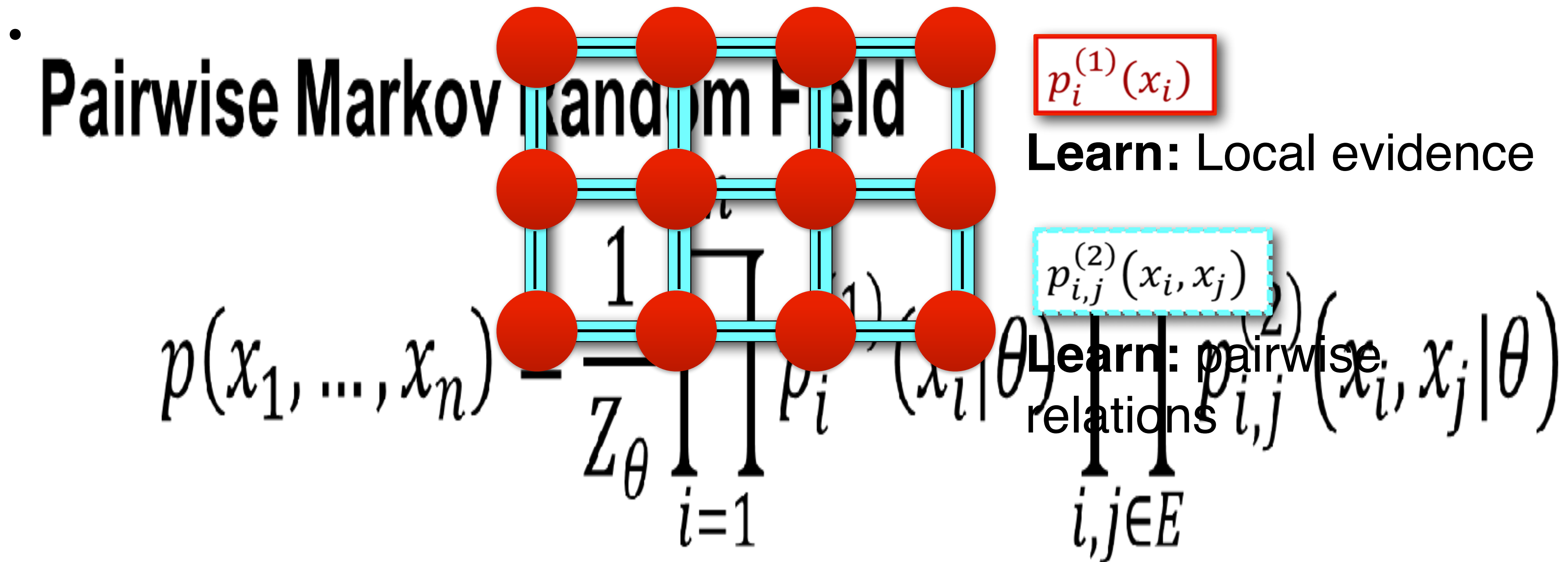
- Modeling and Detecting Parts
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 - Data-driven segmentation
 - A priori: meta-model



Parts

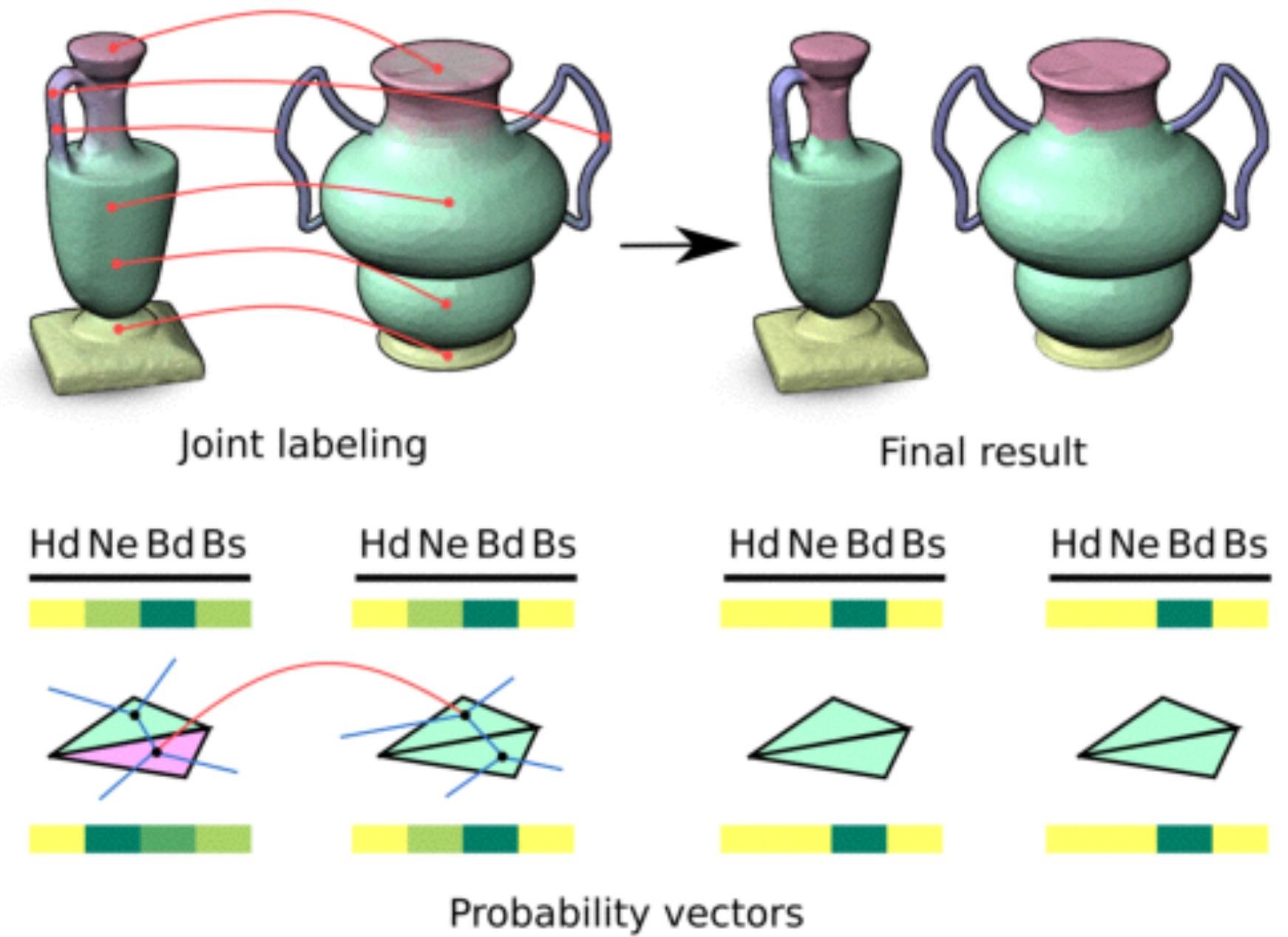
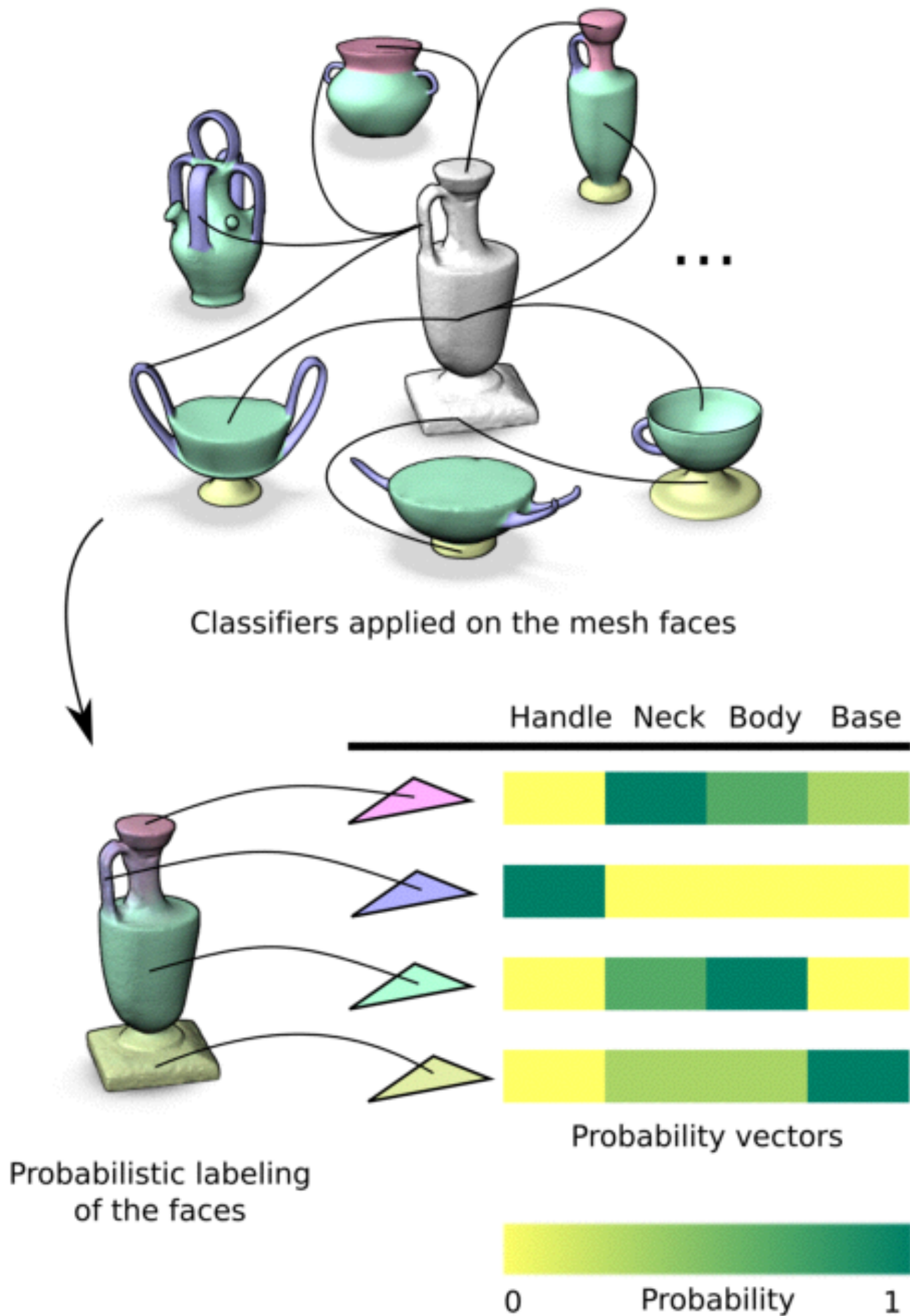


- Approach
 - **Supervised**
 - Training data: Example Segmentations
 - Learn model parameters
 - Apply to more, unknown data after training
 - **Unsupervised**
 - No training phase
 - Clustering: Maximize coherence
 - Co-segmentation



Optimize the same function, but for parameters θ .

Unary and Pairwise Potentials



$p^{(2)}$ – pairwise

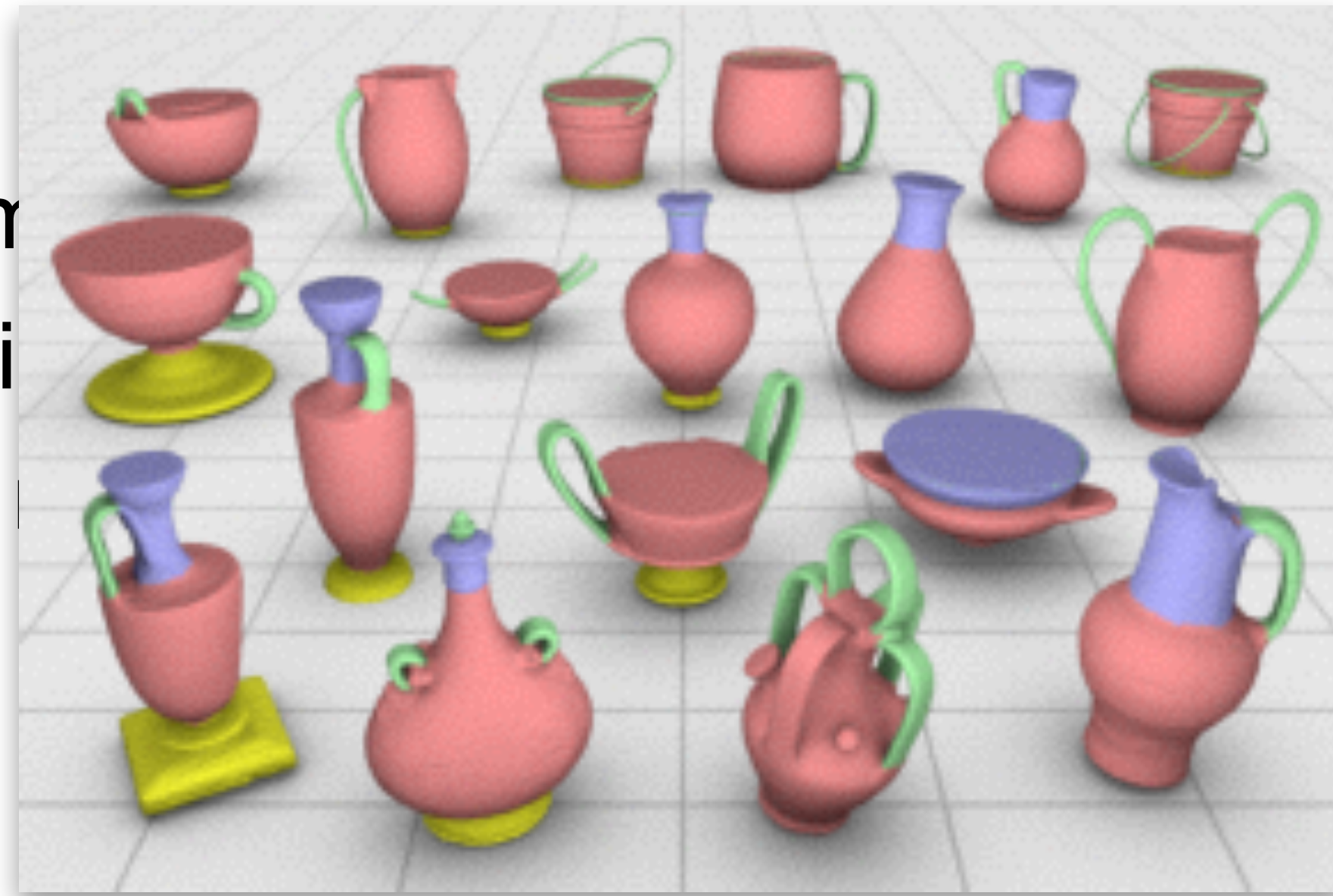
$p^{(1)}$ – unary

[van Kaik et al. EG 2011]

Unsupervised Learning

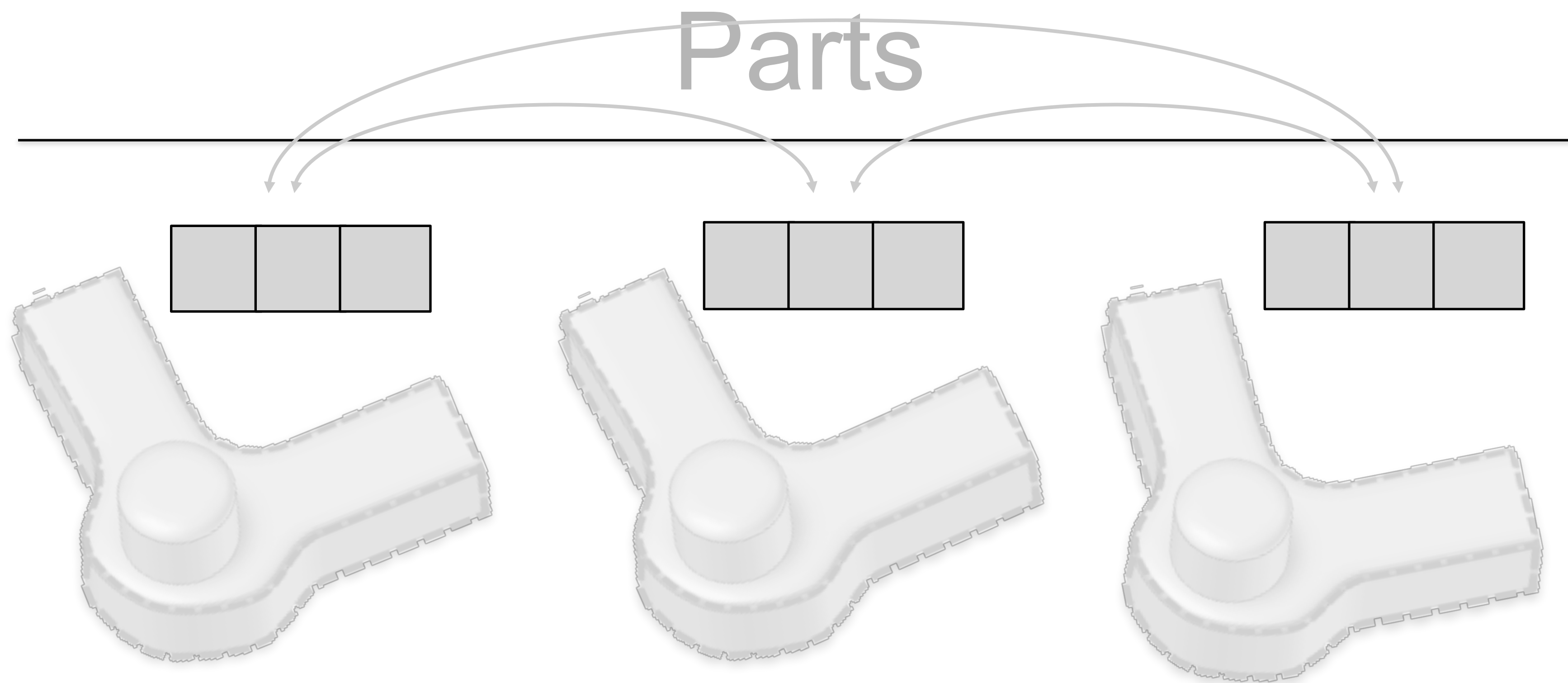
- **Approaches**

- Similar Markov-random
- Data-term: Clustering i
- Pairwise term: a priori



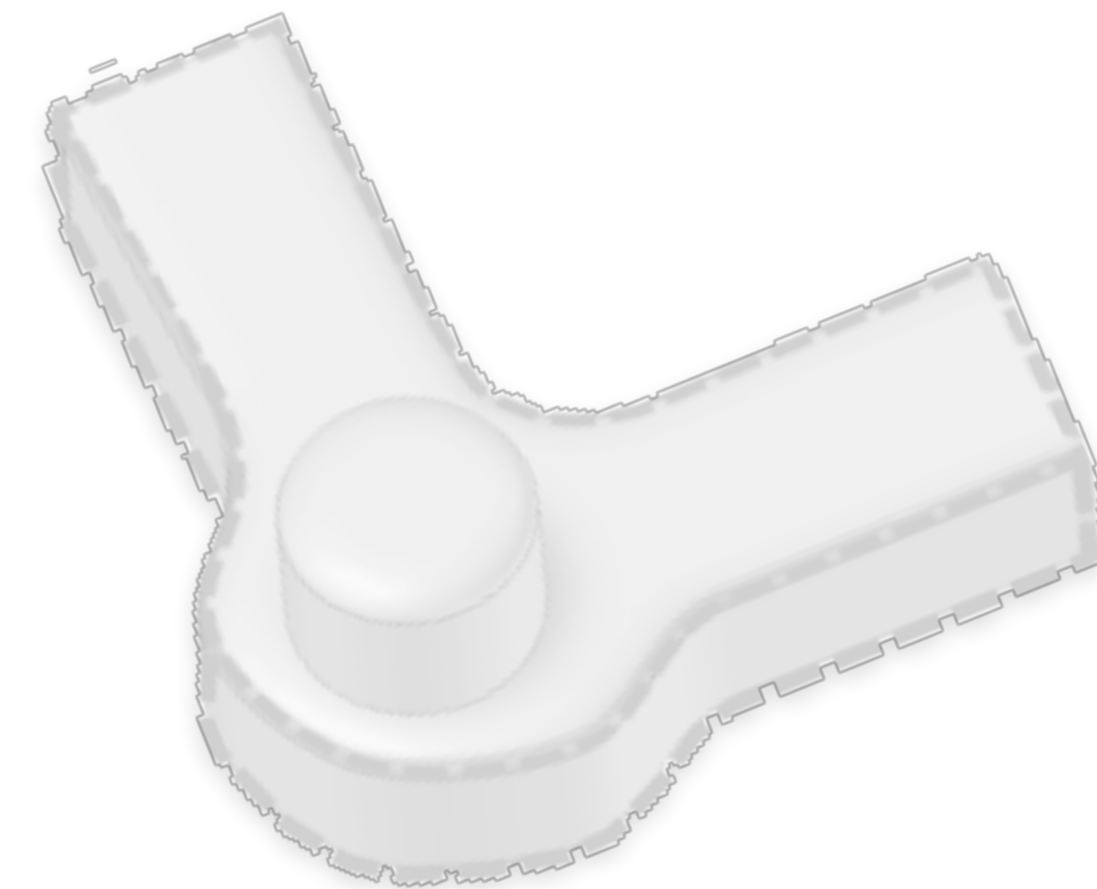
[Sidi et al. SIGA 2011]

Parts



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

Parameters



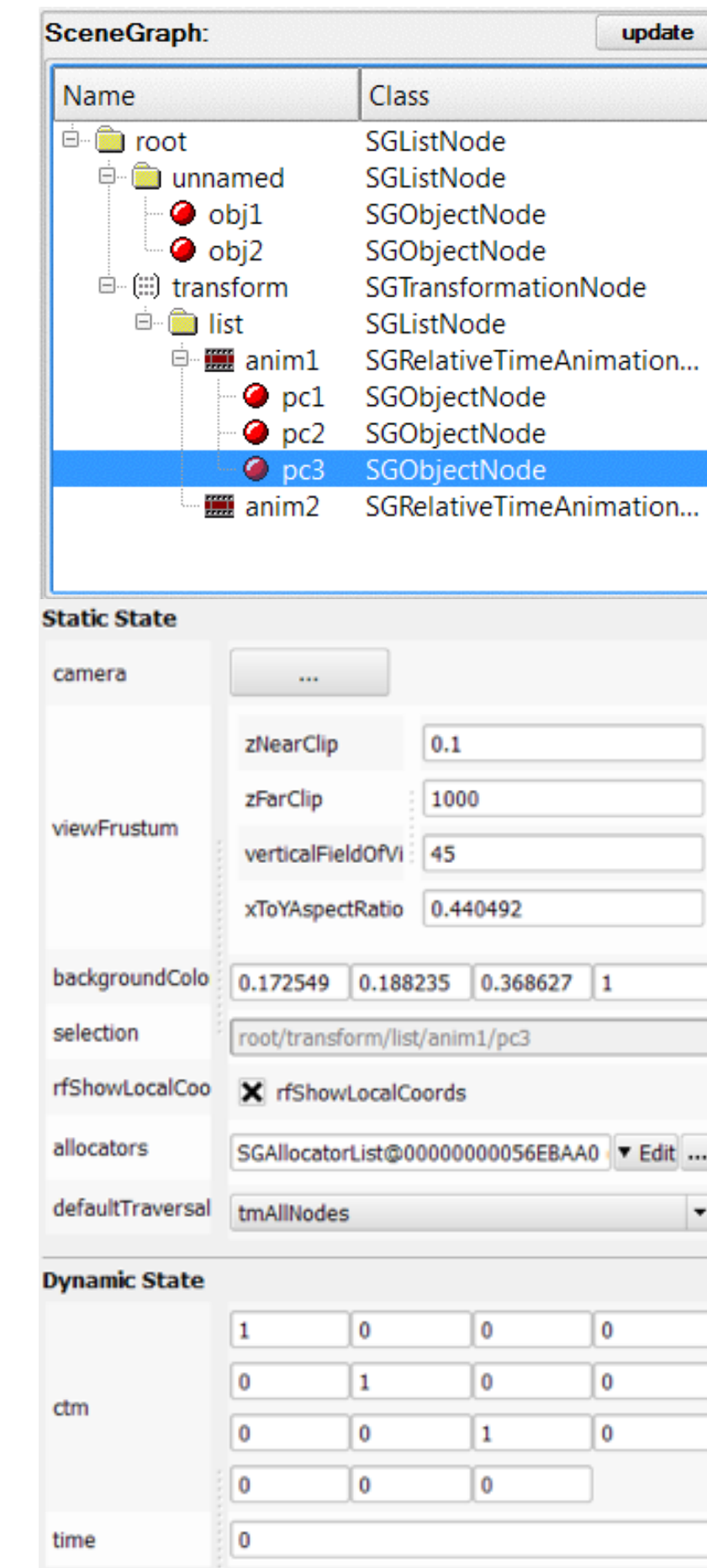
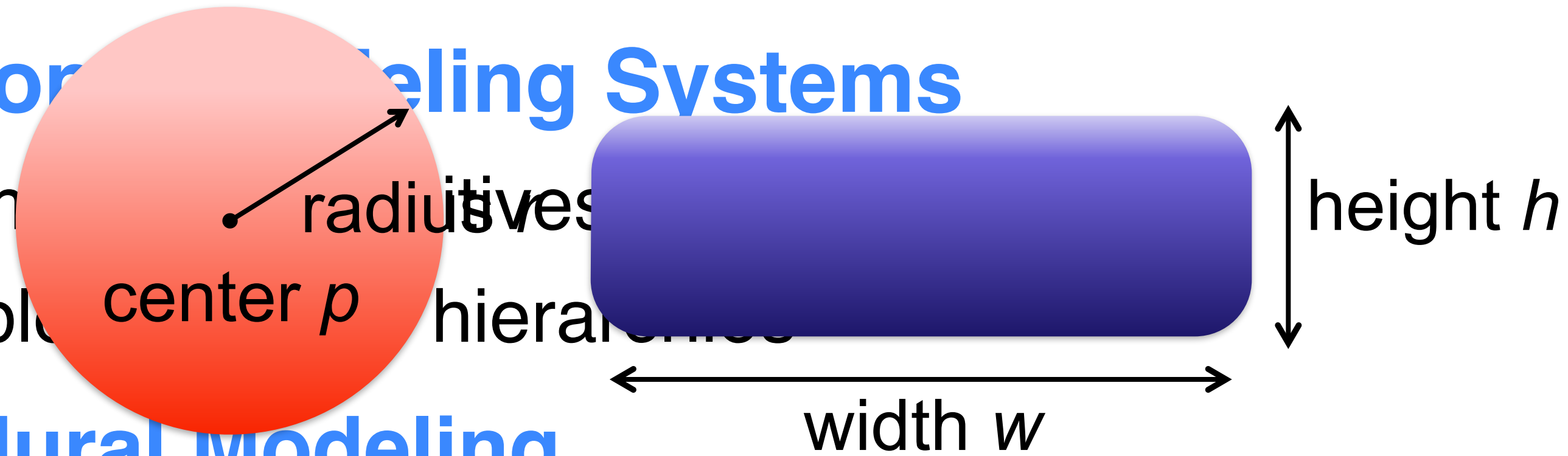
User Defined Parameters

- **Traditional Modeling Systems**

- Parametric primitives
- Variable center p hierarchies

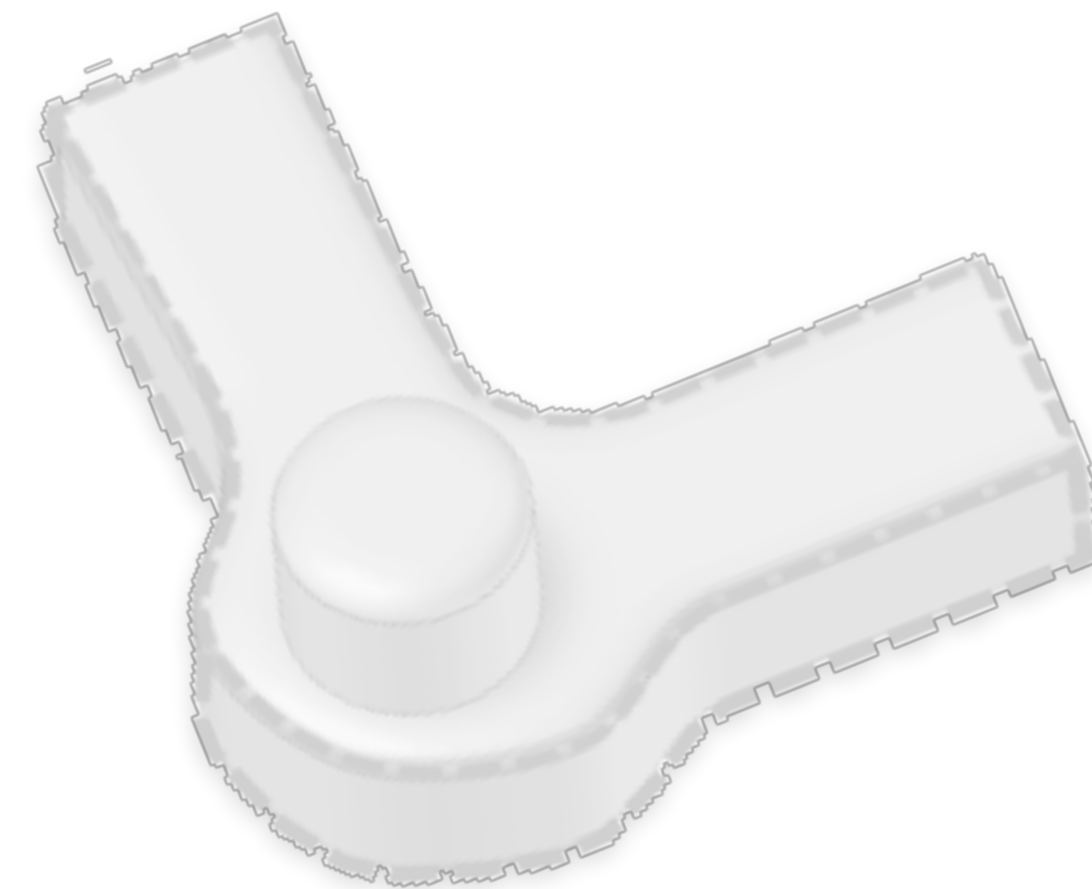
- **Procedural Modeling**

- Hierarchical model generation
- Scripts with local variables / arguments
e.g. [Gervautz et al. 1996]



- Modeling and Detecting Parameters of Parts
 - User defined parameters
 - Manual model setup
 - Fixed models
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Parameters



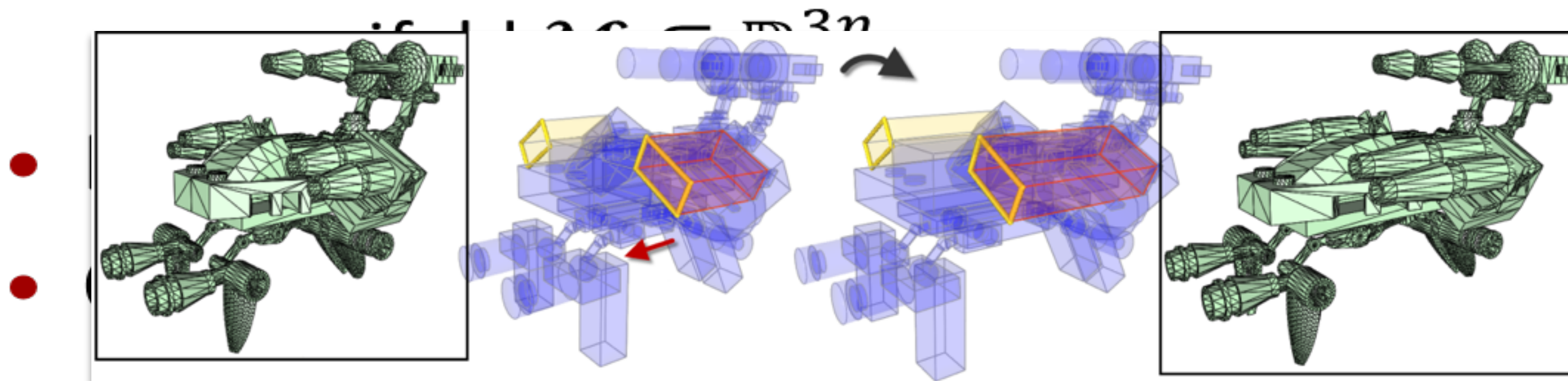
Fixed Parameter Models

- **Fixed Part Parameters**

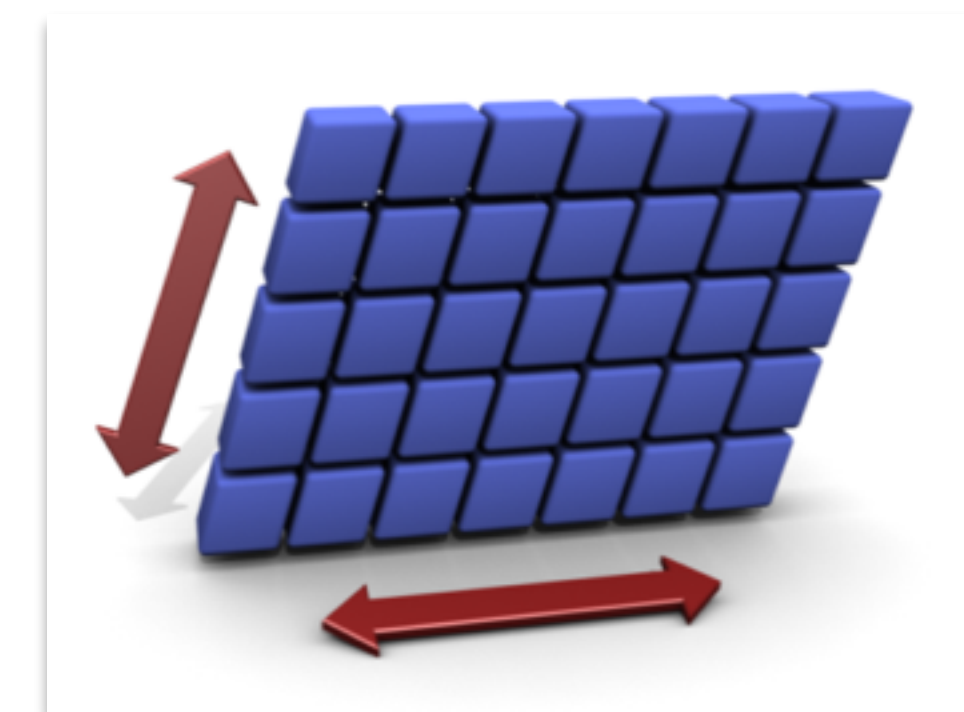
- Rigid/similarity-tr./affin
- General shape spaces
 - Vertices move in \mathbb{R}^{3n}
- Constraint manifolds
 - Vertices move on smooth



[Yang et al. SIGA 2011]



[Zheng et al. EG 2011]

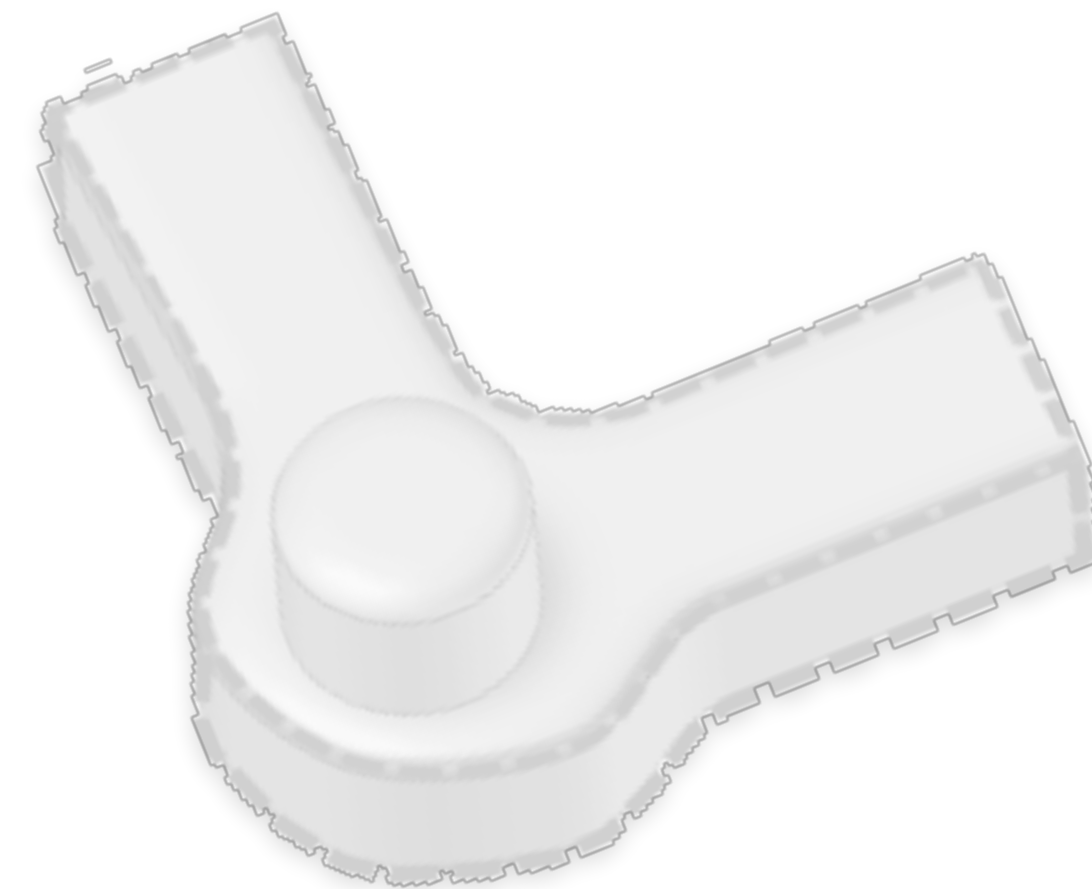


[Bokeloh et al. SG 2012]

- Modeling and Detecting Parameters of Parts
 - User defined parameters
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 - Predefined variables
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Parameters

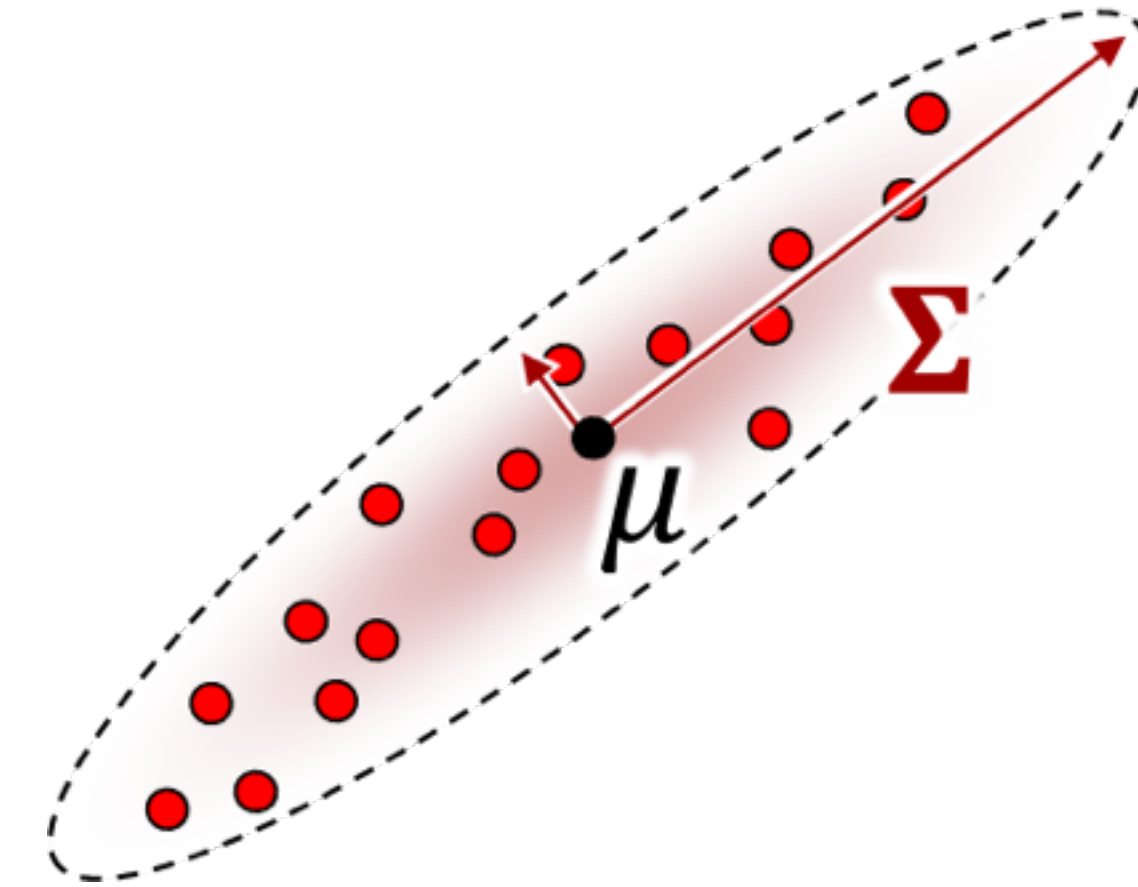


- **Learning Parameters from Data**

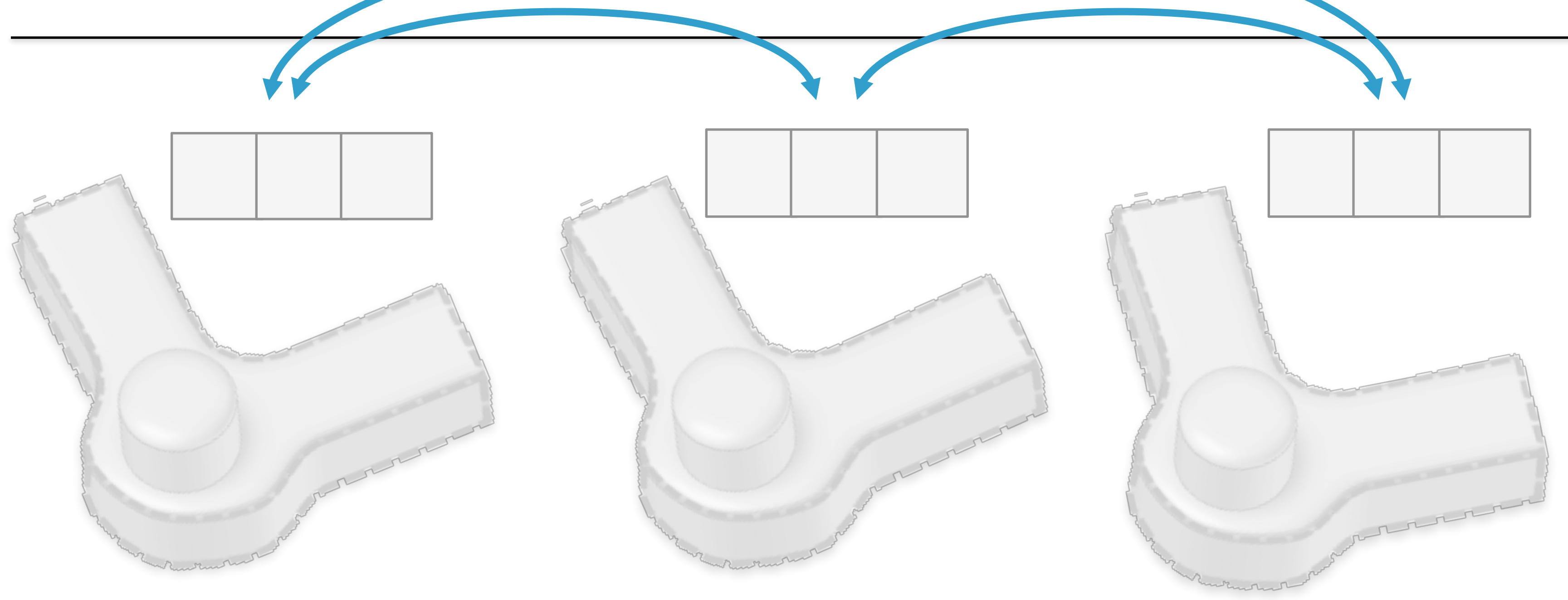
- No prescribed variables / mappings
- Discover latent variables

- **Common Approaches**

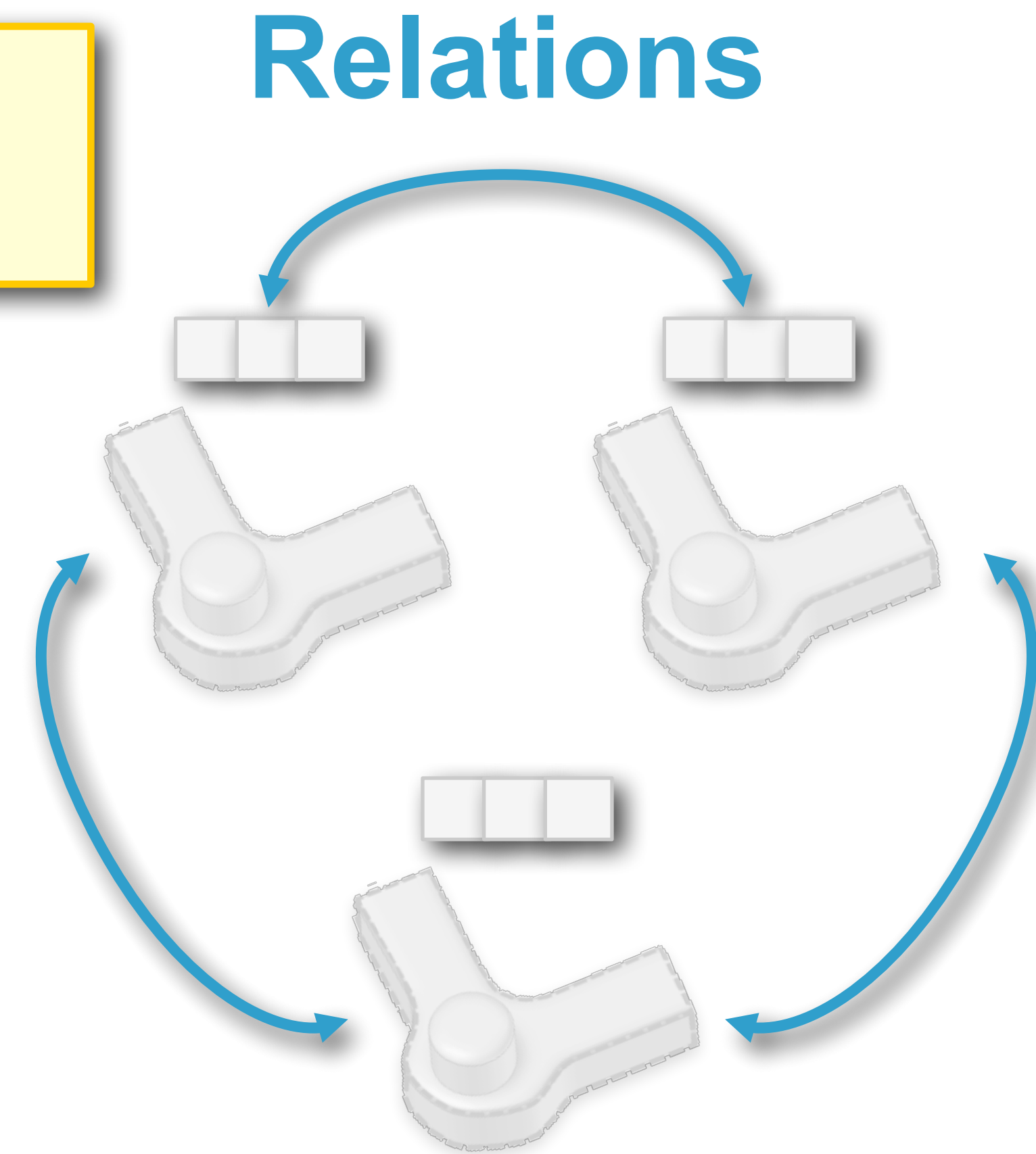
- Principal component analysis
 - “Morphable Models” [Blanz et al. 1999, Allan et al. 2003,...]
 - Kernel-PCA / spectral embedding for nonlinear models
- Independent component analysis
- In general: latent variable models
(e.g., latent variable Gaussian processes)



Parts



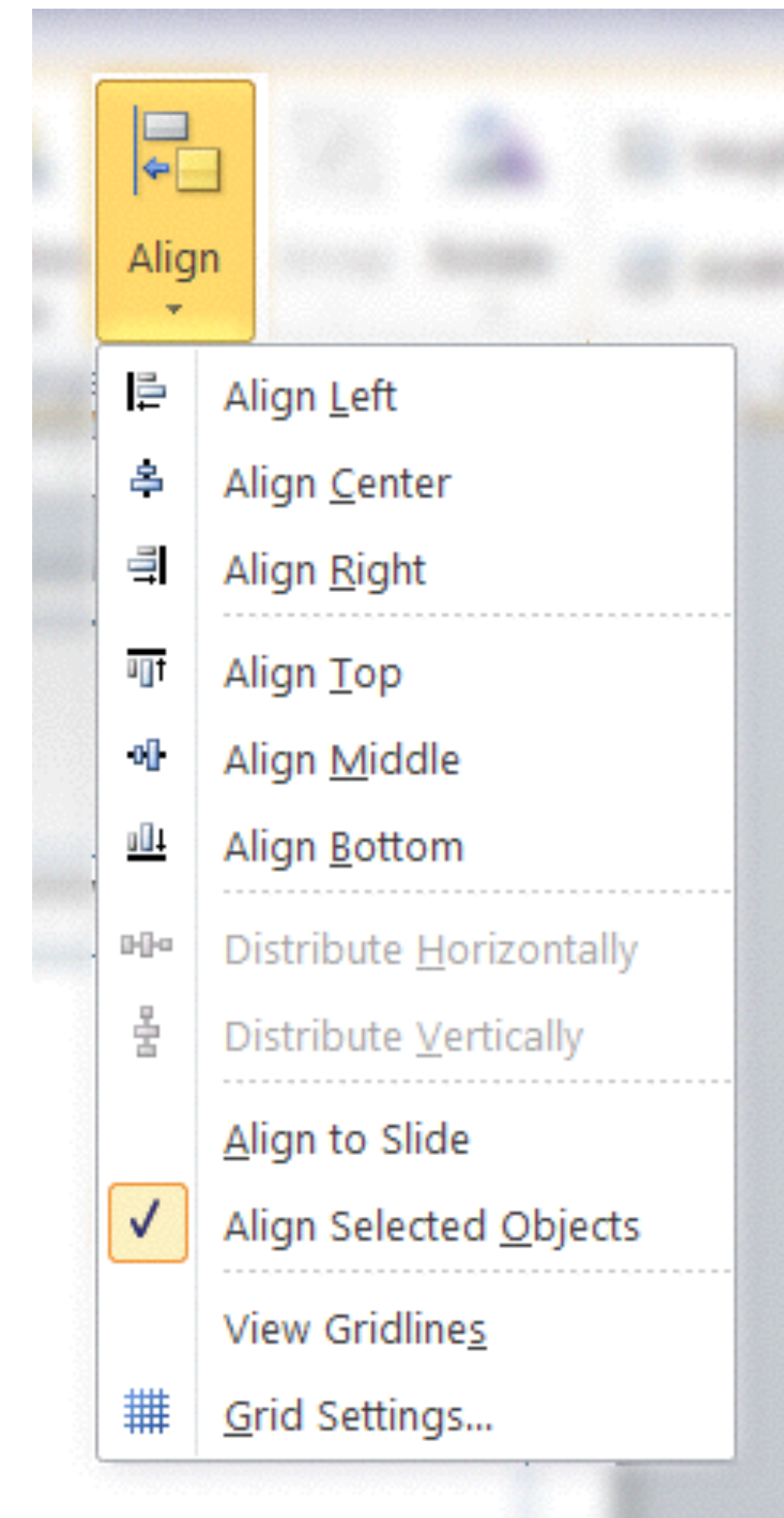
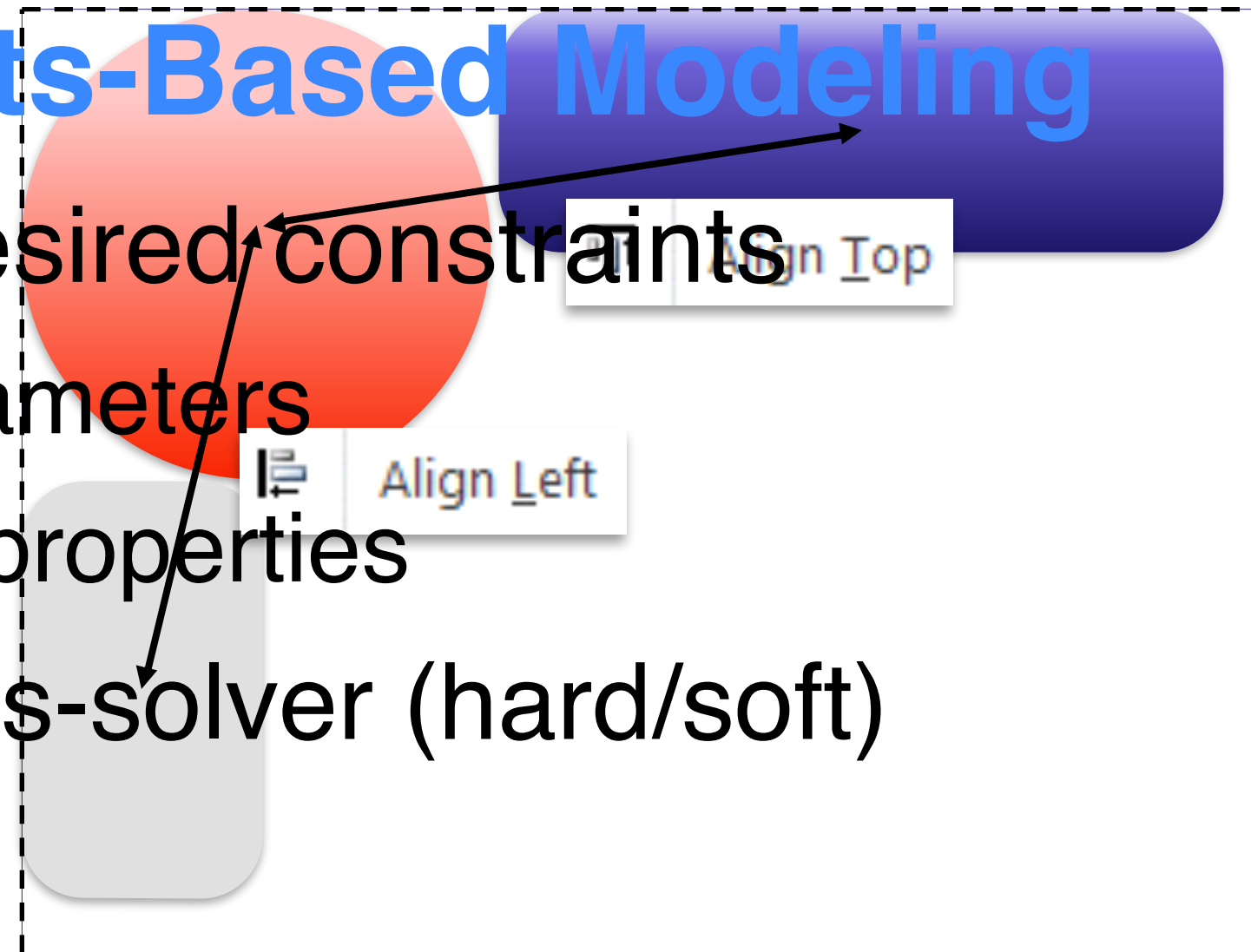
- Modeling and Detection of Relations
 - User defined relations
 - Traditional constrained modeling
 - Fixed models
 - Detect relations from predefined classes
 - Data-driven relations
 - Discover new types of invariants from data



Manual Relations

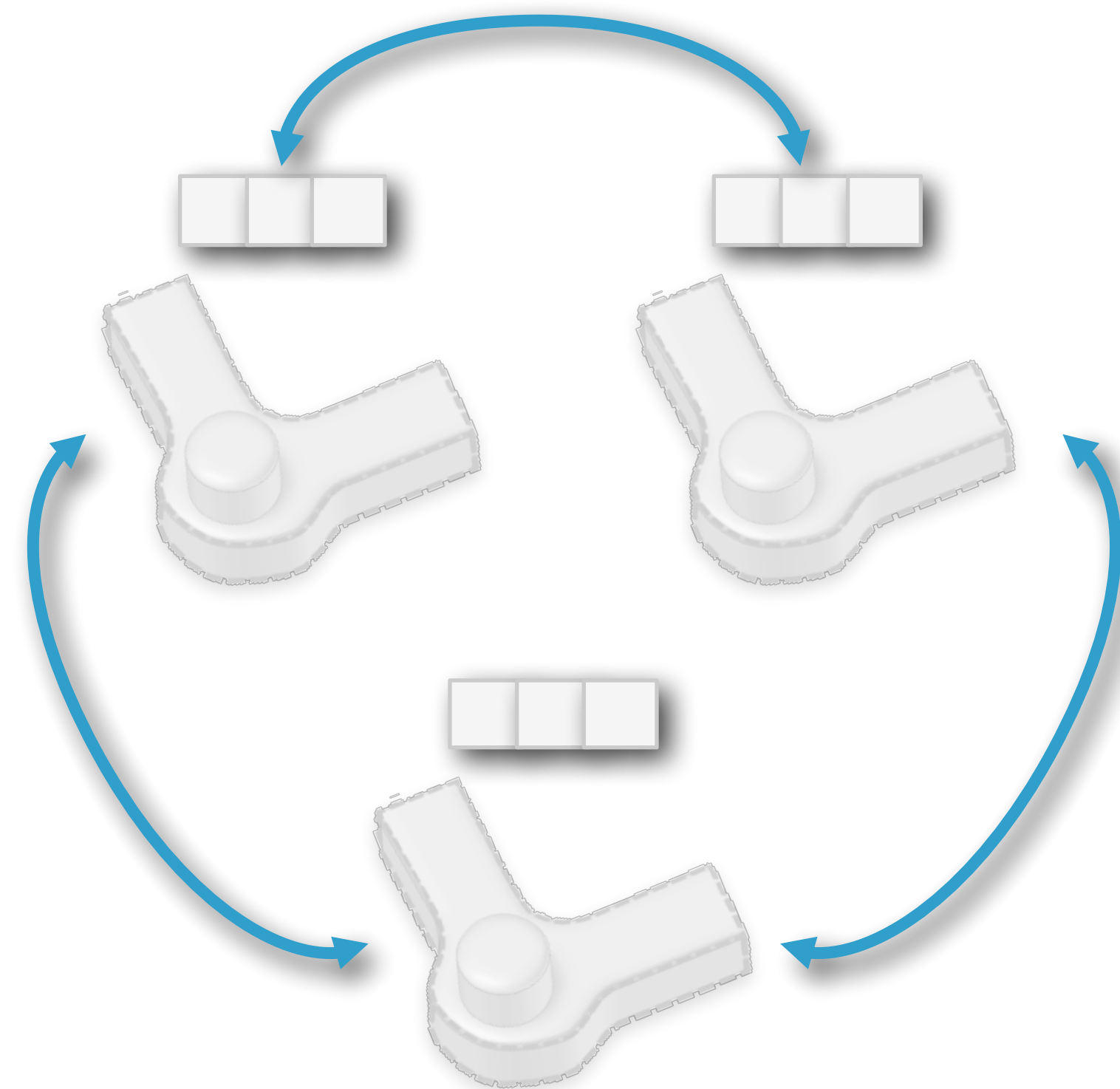
- **Constraints-Based Modeling**

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



[MS Powerpoint 2010]

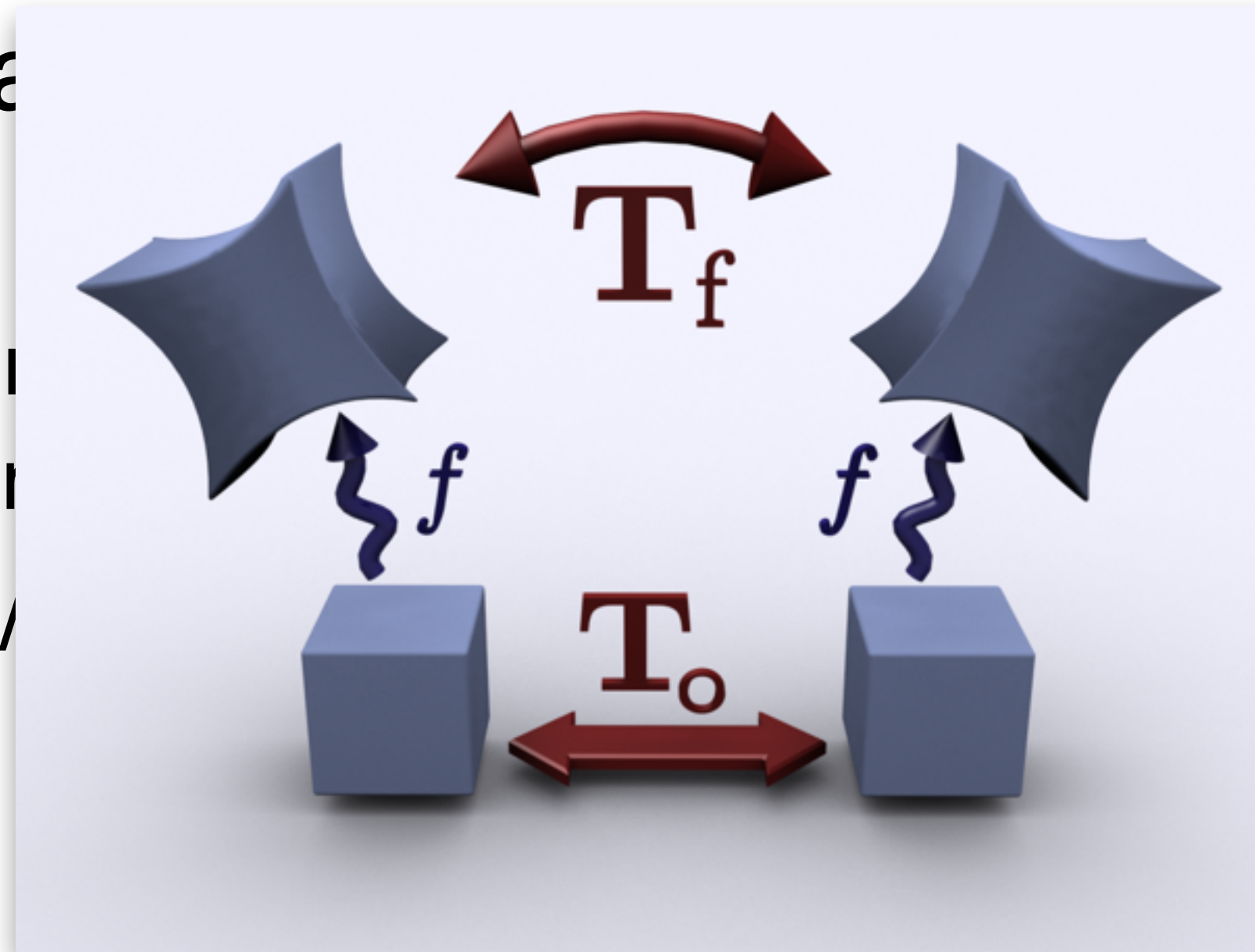
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Relations

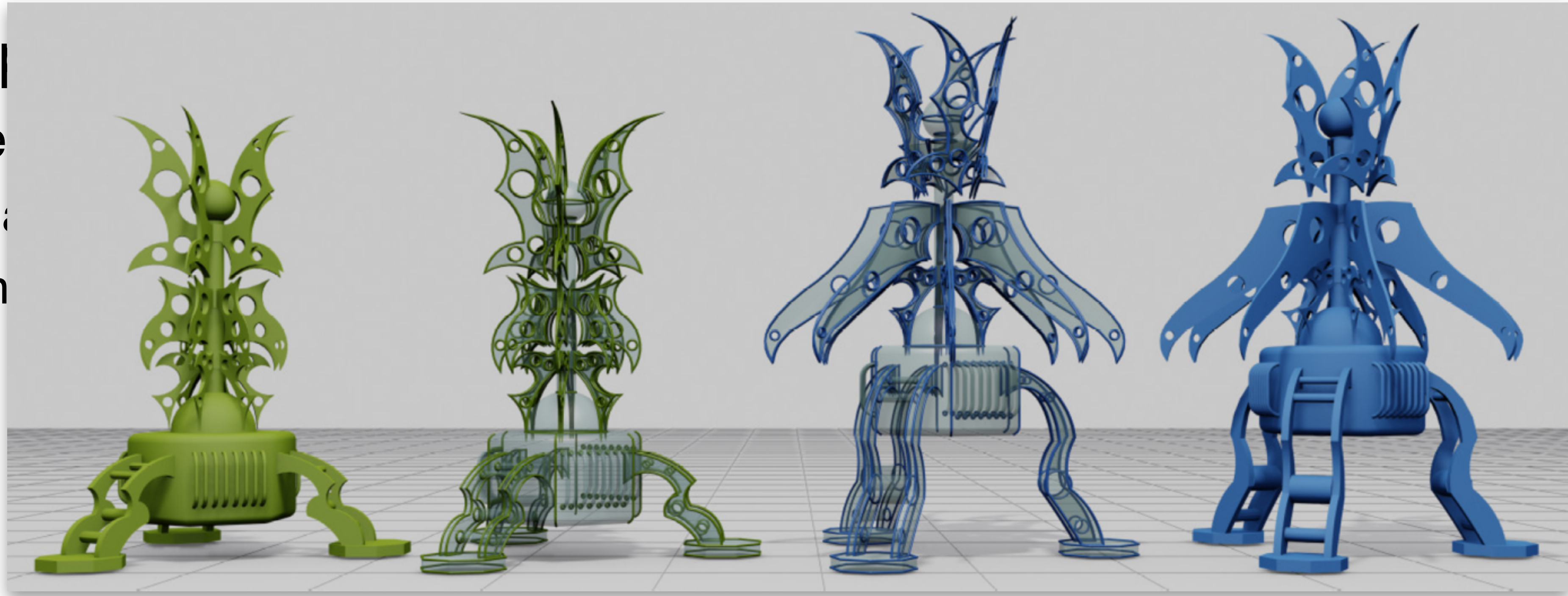
Predefined Classes of Relations

- Symmetry and Euclidean
– **Detect symmetries**
 - Also: partial Euclidean in (parallelity, distances, area)
- **Build constraints** (soft)



Predefined Classes of Relations

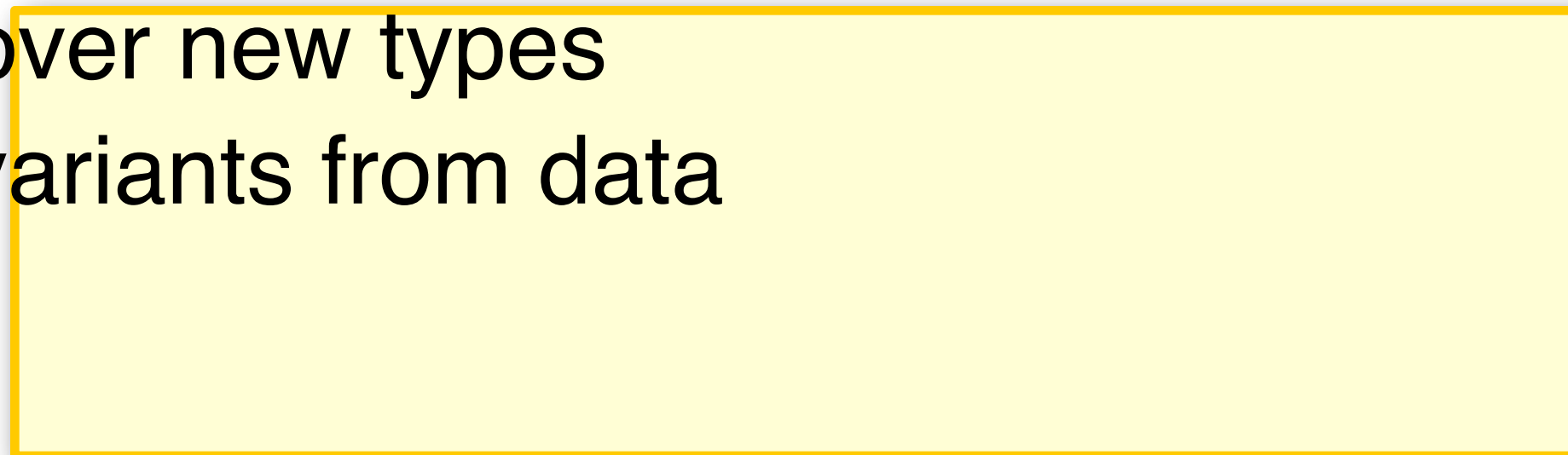
- Example
 - Detection
 - Feature
 - Line



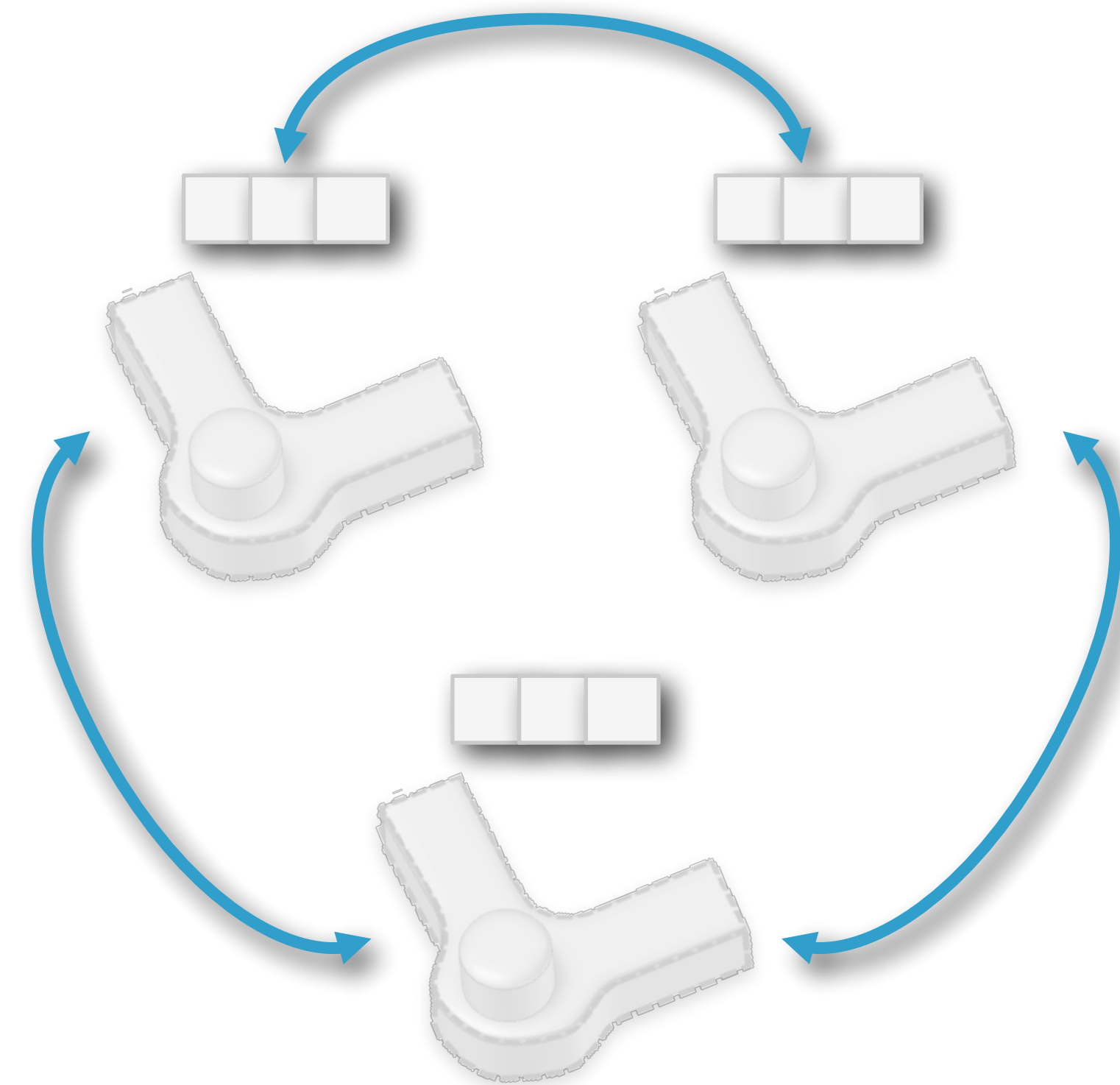
[Gal et al. SG 2009]

- 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



- **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]