Skinning: Real-time Shape Deformation

Automatic Skinning via Constrained Energy Optimization

Alec Jacobson

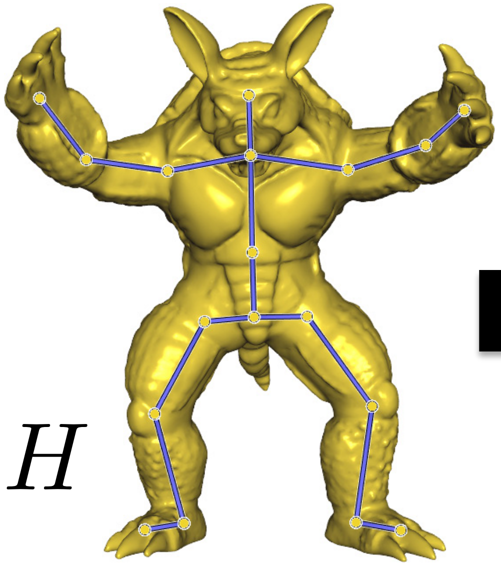
Columbia University

Traditional skinning pipeline is labor intensive

$$\mathbf{v}' = \sum_{j \in H} w_j(\mathbf{v}) \mathbf{T}_j \begin{pmatrix} \mathbf{v} \\ 1 \end{pmatrix}$$

Traditional skinning pipeline is labor intensive

H



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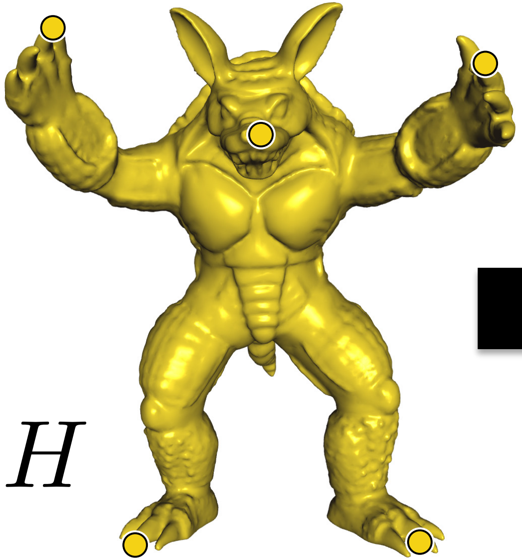

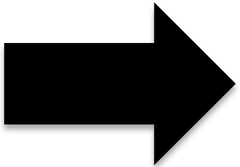

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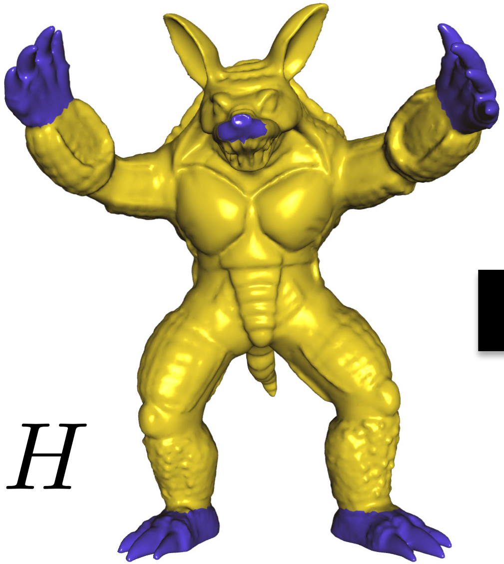

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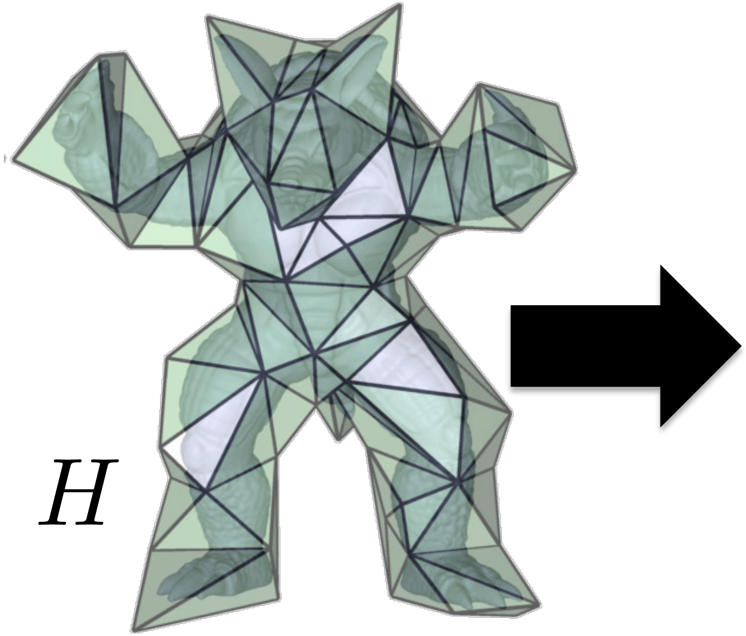

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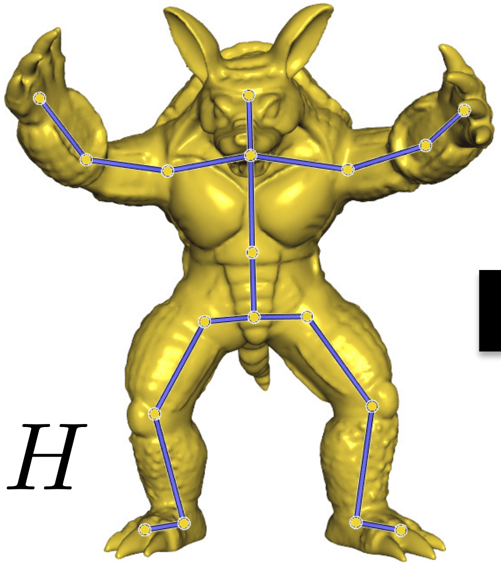

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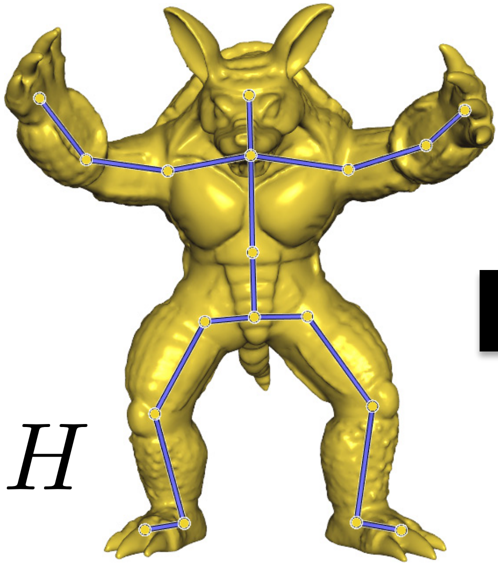

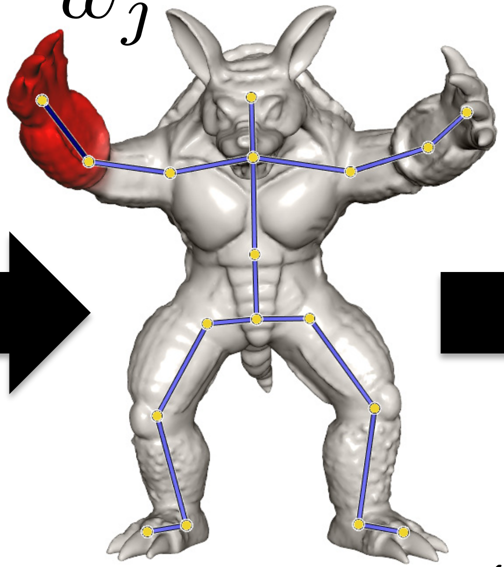

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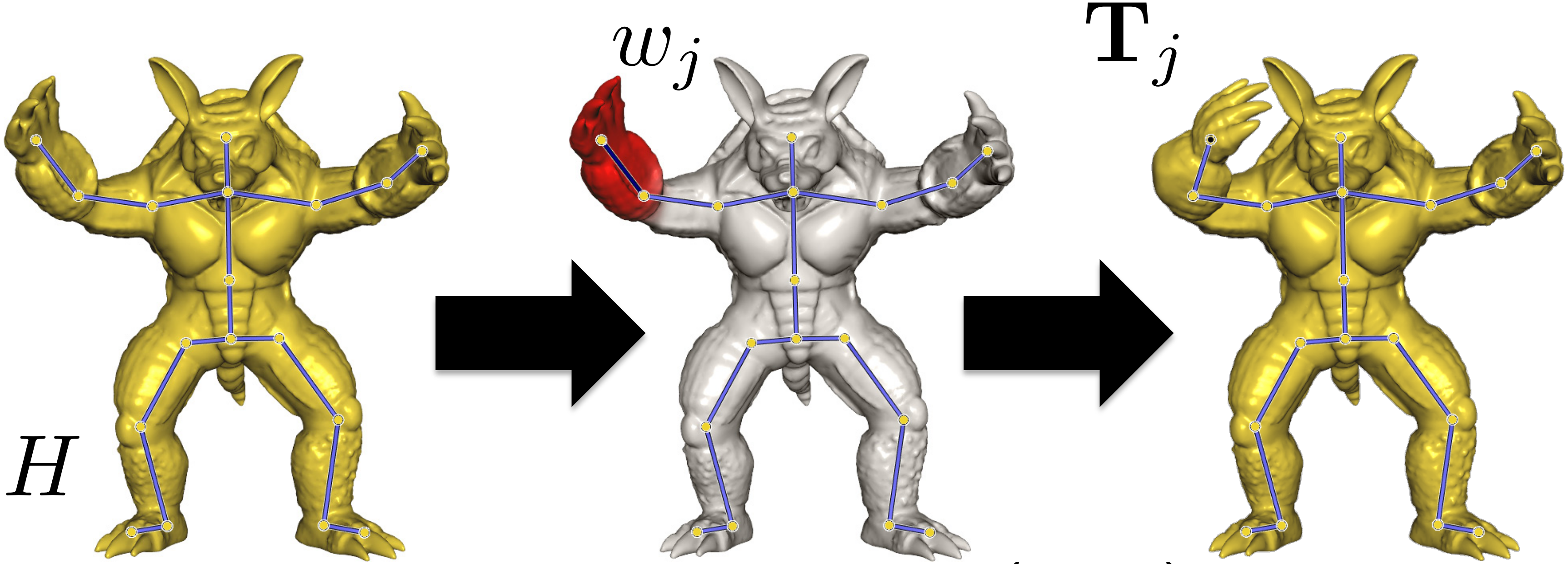

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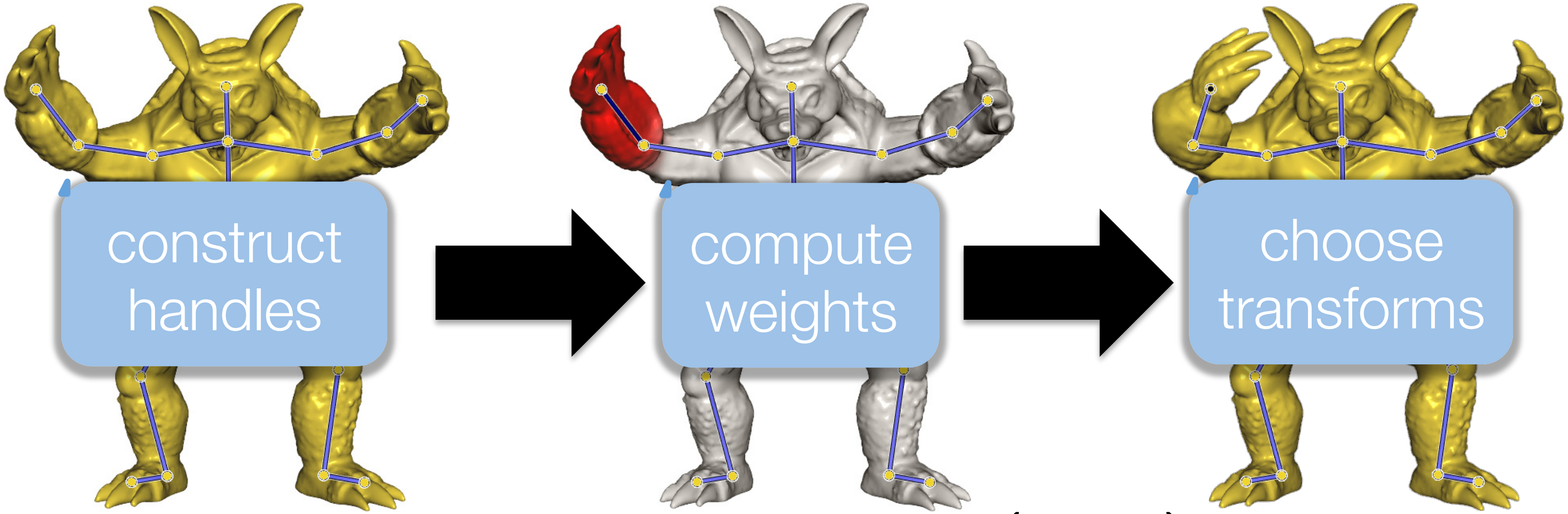
Recent research automates each step



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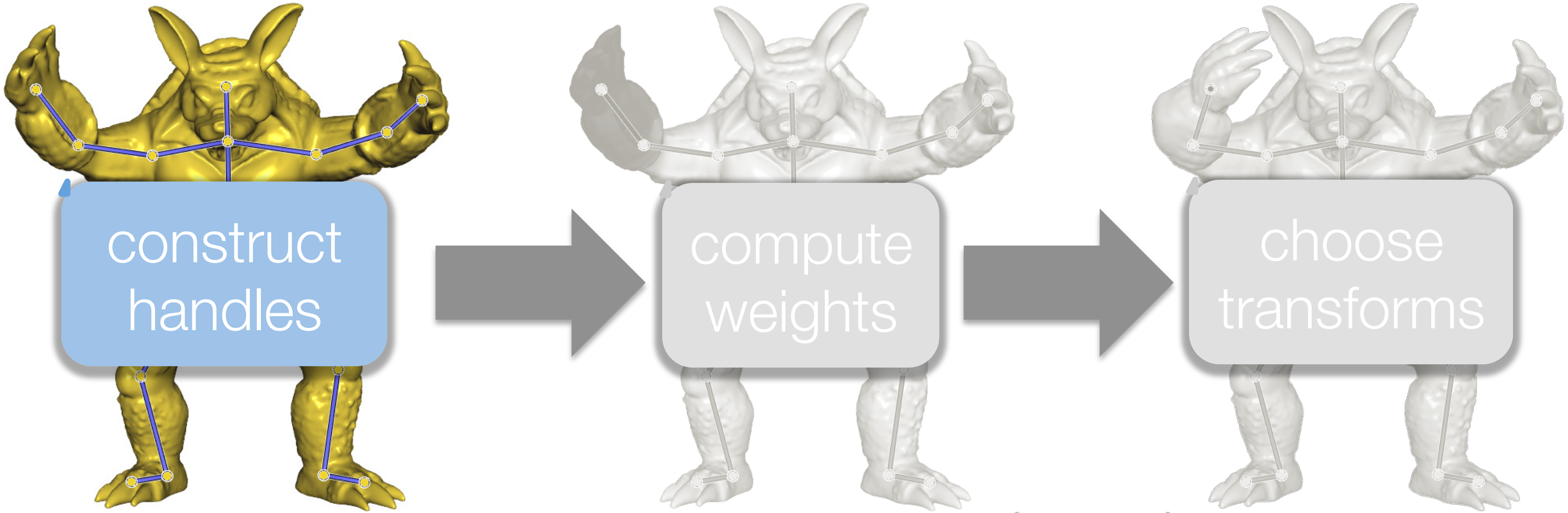

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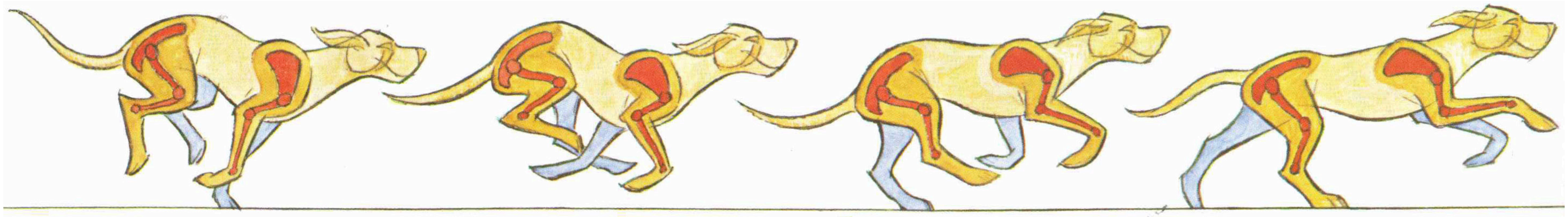
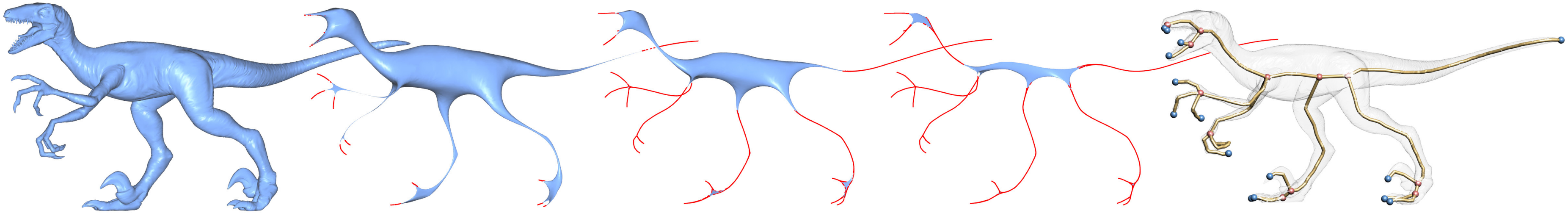
Skeleton implies shape…



[Blair 1994]

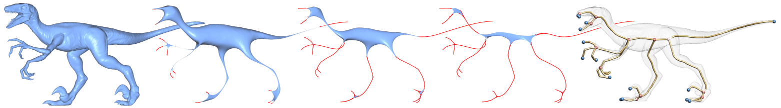
…and shape implies skeleton



[Au et al. 2008]

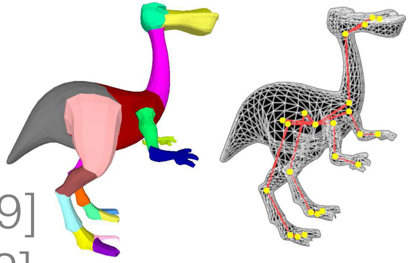
State-of-the-art skeleton extraction techniques split into two camps

Surface flow



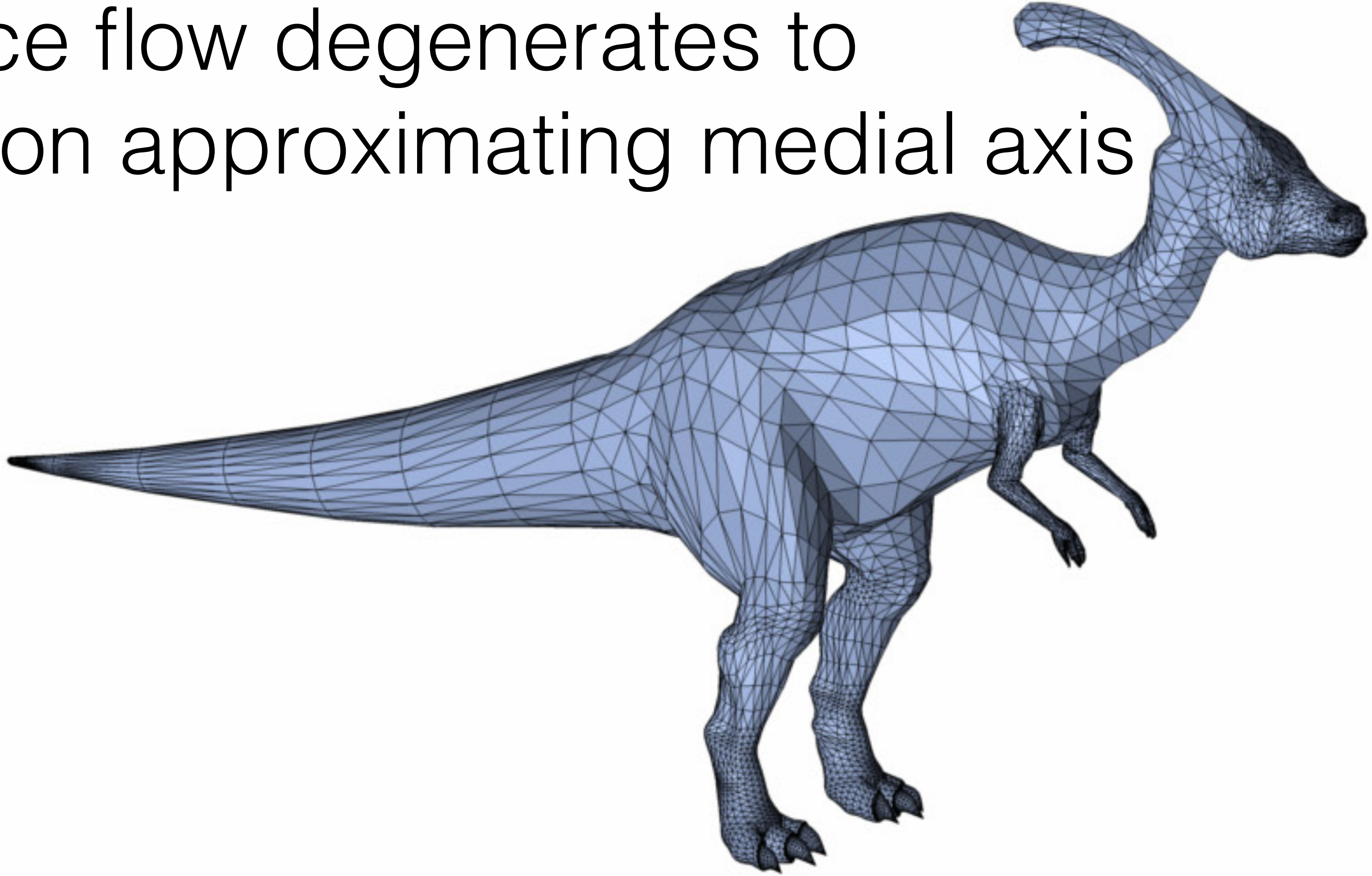
[Au et al. 2008]
[Wang & Lee 2008]
[Tagliasacchi et al. 2012]
[Cao et al. 2010; Huang et al. 2013]

Shape segmentation



[Katz & Tal 2003]
[Huang et al. 2009]
[Bharaj et al. 2012]

Surface flow degenerates to skeleton approximating medial axis



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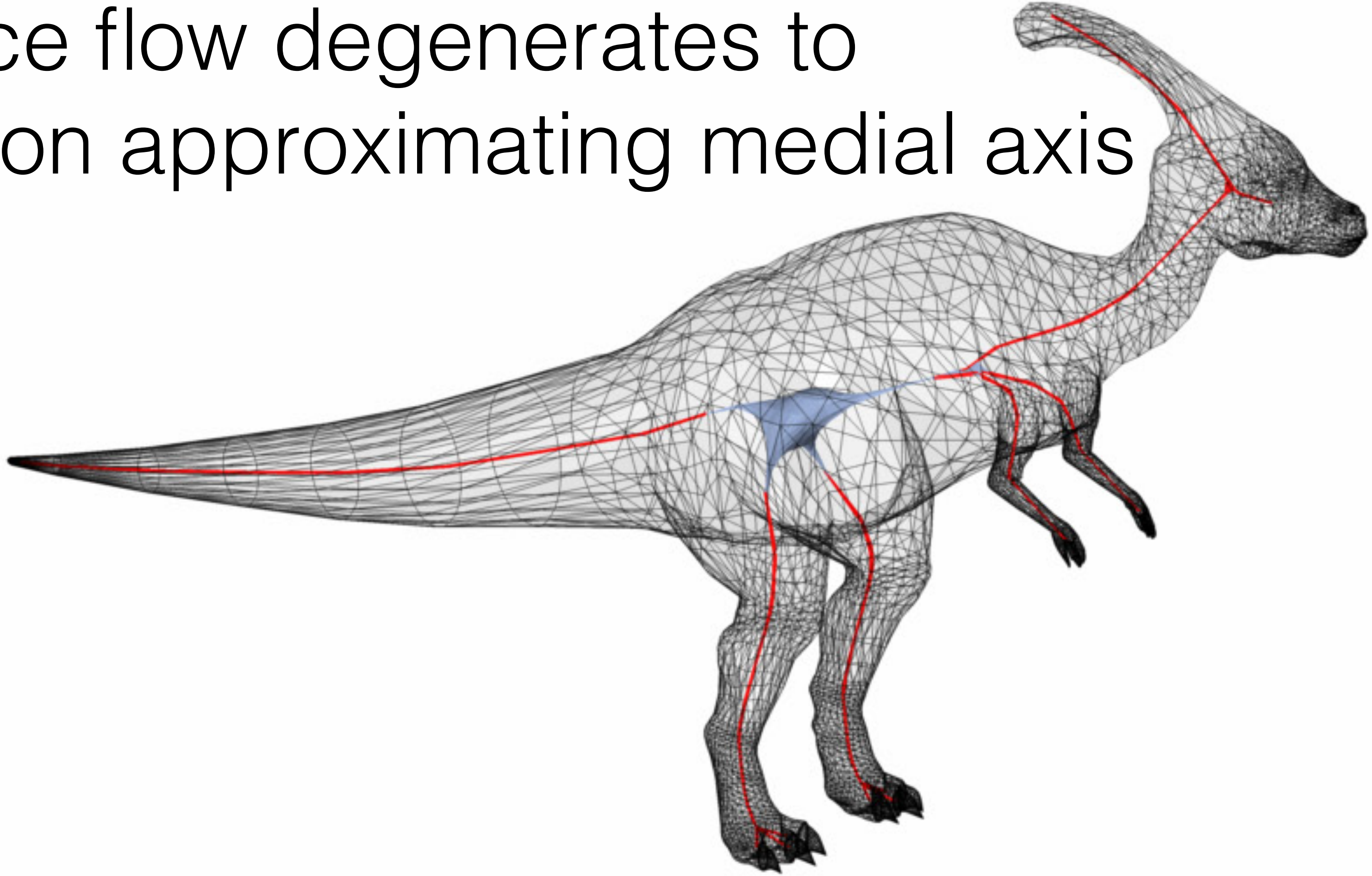
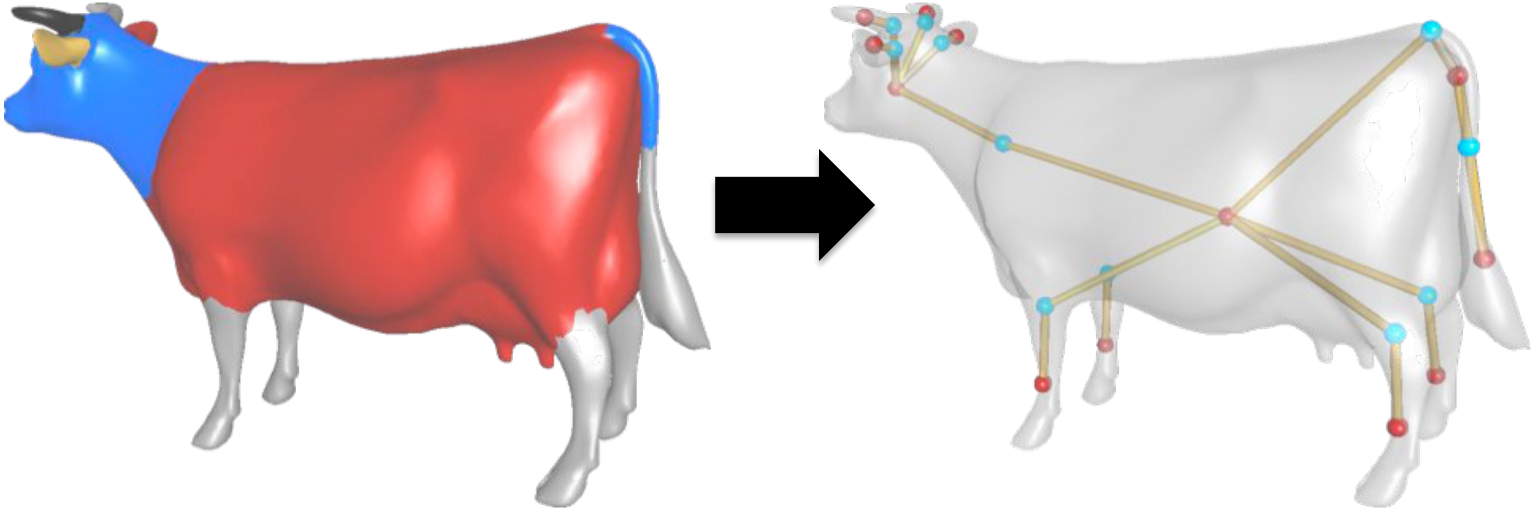


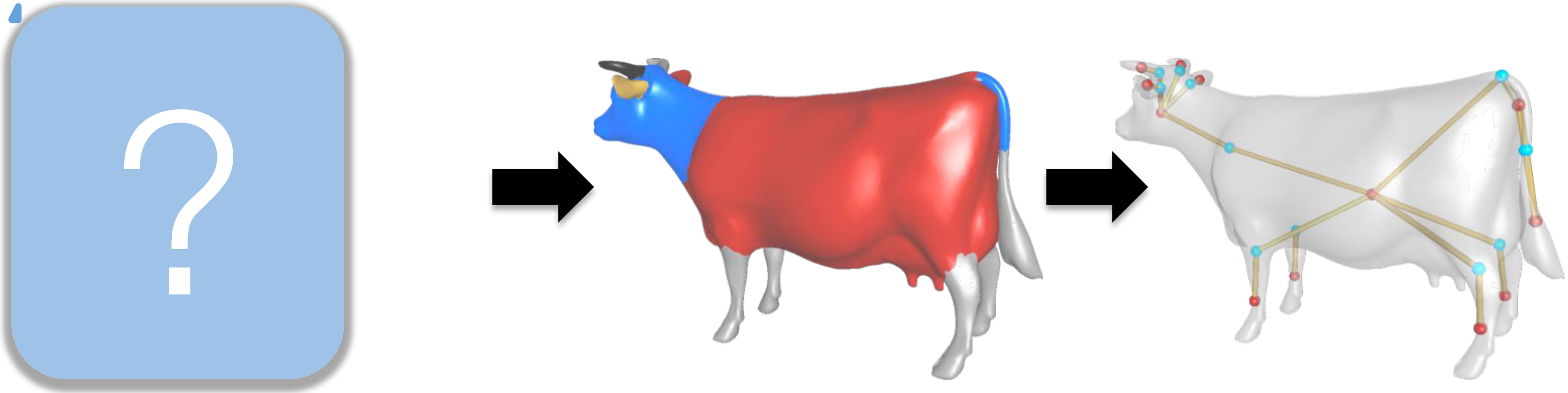
Adjacency graph of rigid segmentation encodes topology of skeleton



[Huang et al. 2009]

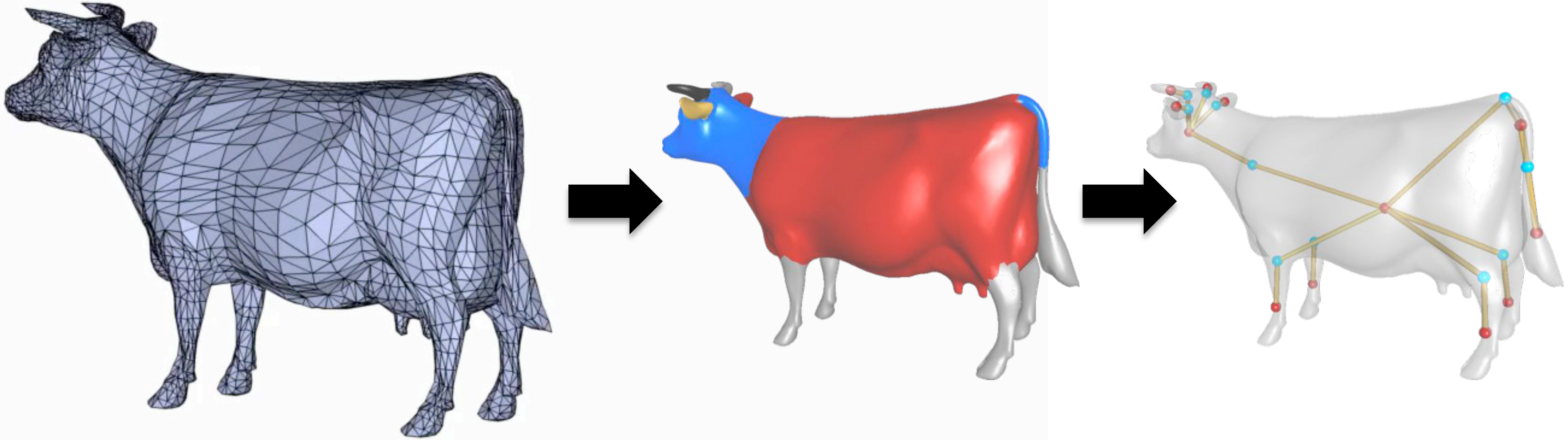
Assume we know which parts will deform rigidly

But which parts will deform rigidly?



[Huang et al. 2009]

Eigenmodes of as-rigid-as-possible energy form a reasonable *prior*



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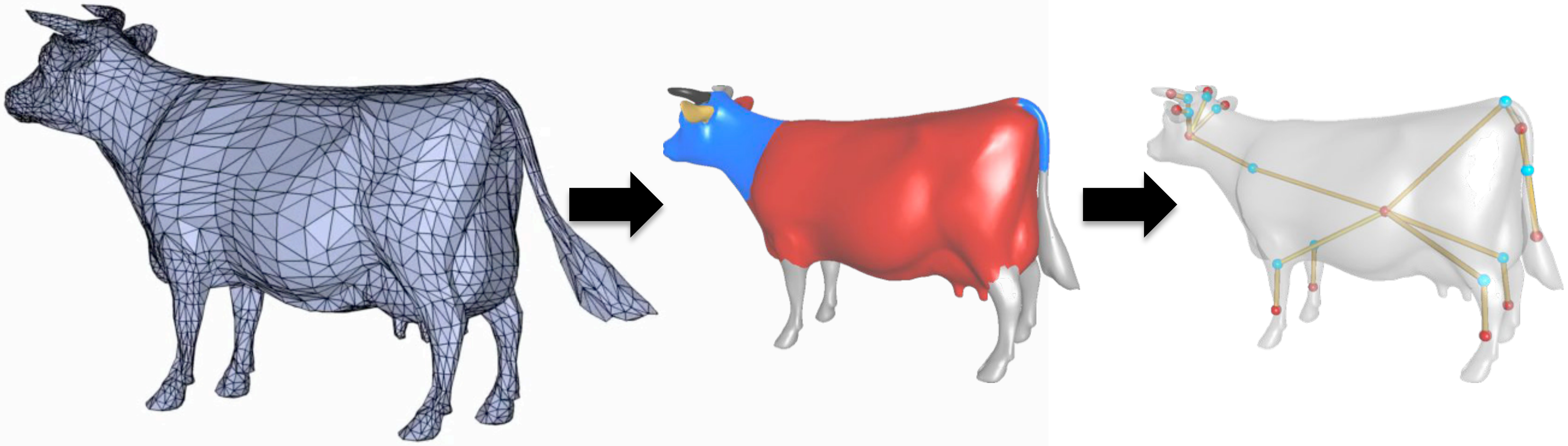

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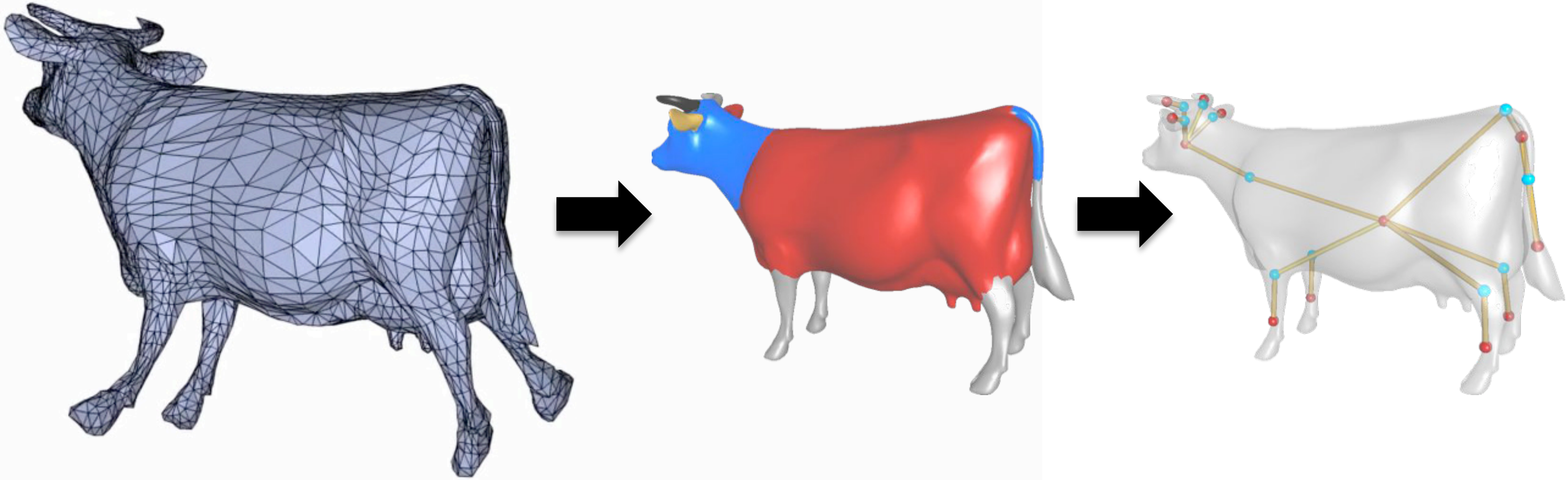

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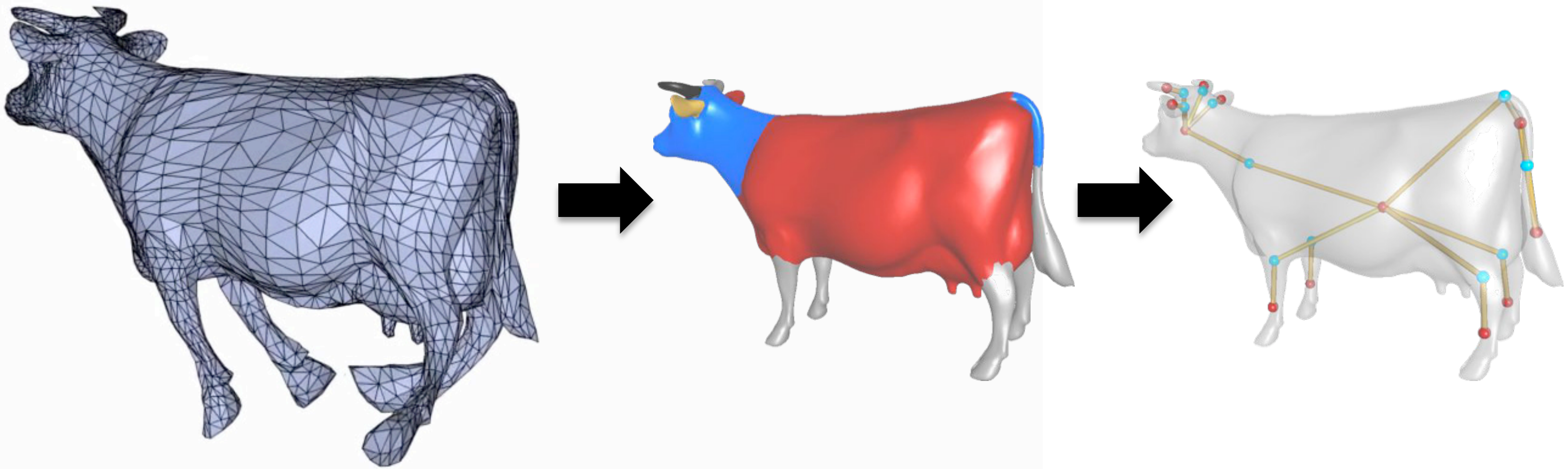
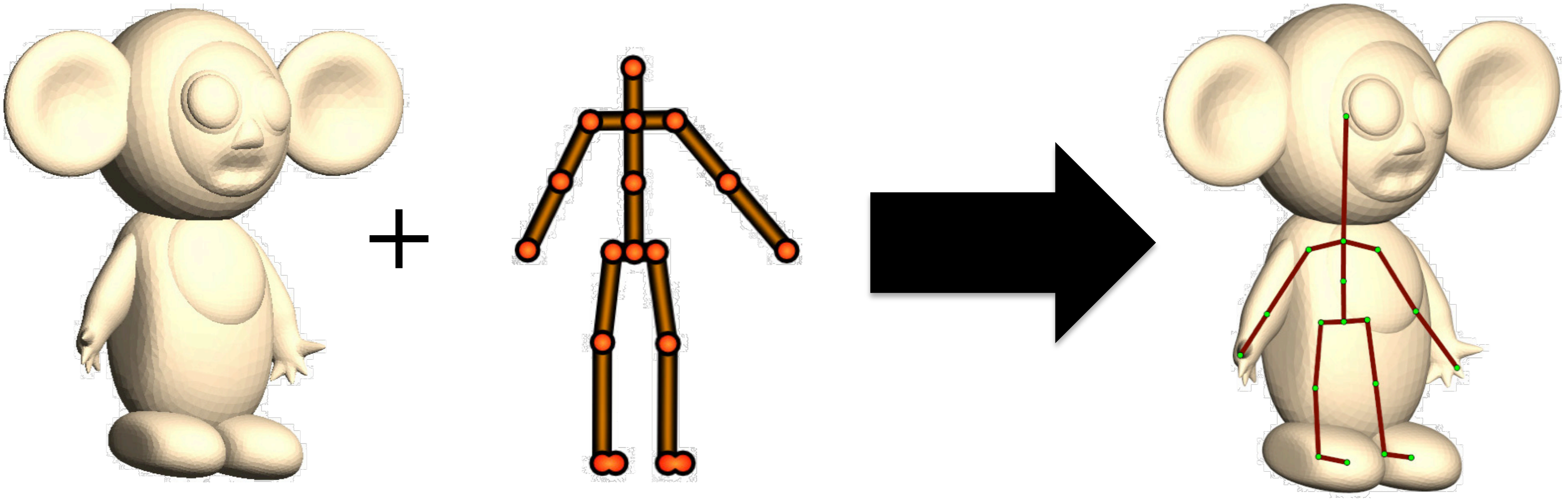


[Huang et al. 2009]

Skeleton extraction problems remain open

- Joint placement (center of rotation)?
- Guarantee *bones* are inside?
- Respect (intrinsic) symmetries?

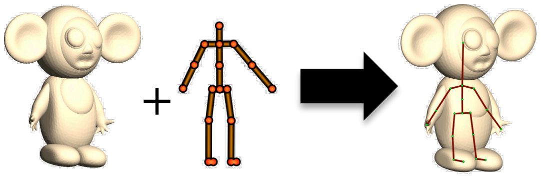
Skeleton *embedding* assumes skeletal topology is known



[Baran & Popovic 2007]

Categorization of desirable qualities implies energy minimization

1. avoid short bone chains,
2. maintain angles between bones,
3. keep lengths of symmetric bones proportional,
4. avoid overlapping bones,
5. place special “feet” bones below others,
6. avoid zero-length bones,
7. maintain bone orientations,
8. place extremities close to surface,
9. avoid disparities in Euclidean and bone-path distances
10. …



[Baran & Popovic 2007]

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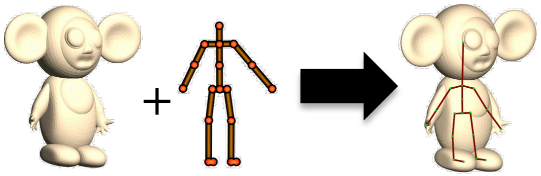

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6.
7.
8. place extremities close to surface,
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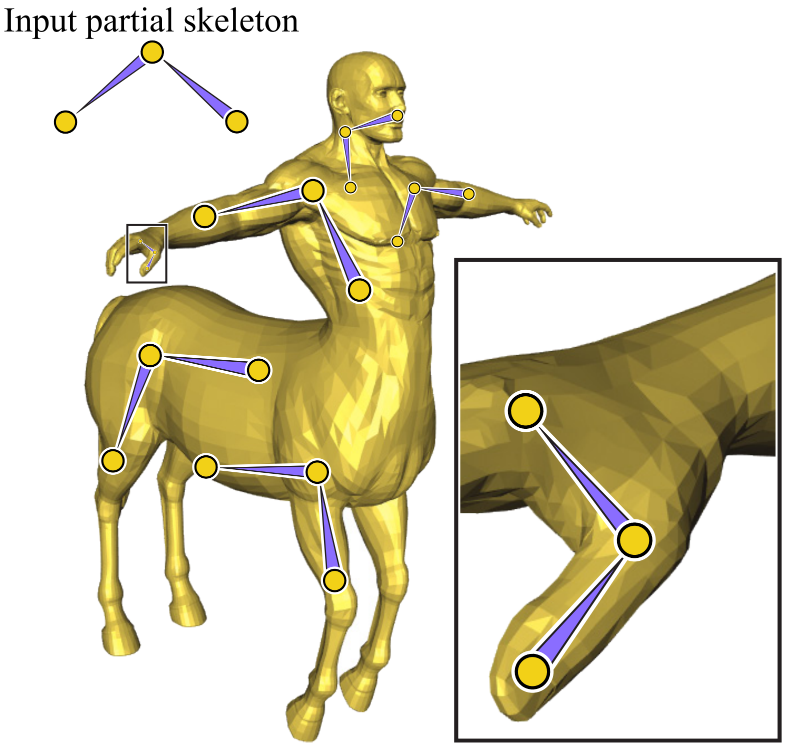
$$E(\mathbf{V}) = \sum_{i=1}^{9} \lambda_i E_i(\mathbf{V})$$

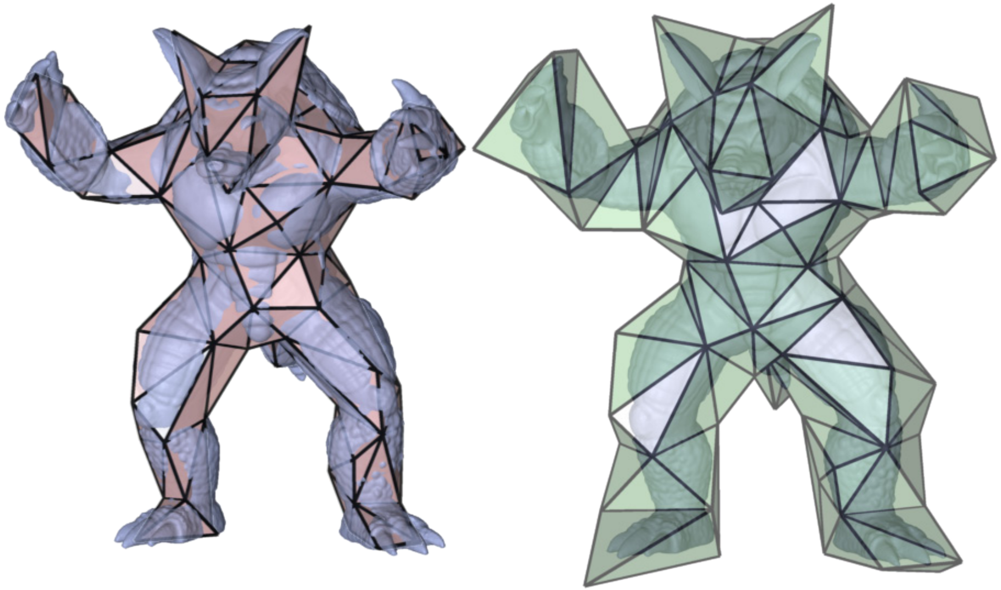
Skeleton embedding problems remain open

- Directly measure implied deformation?
- Partial skeletons?



Similar problems arise for automatic cages

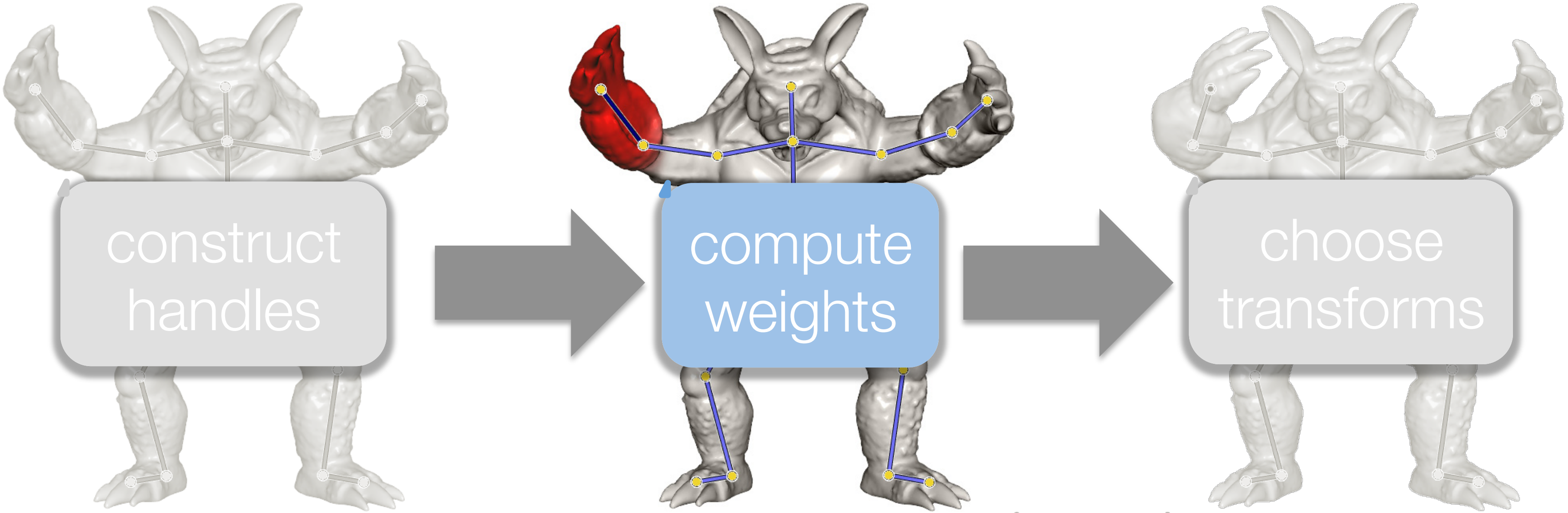
- Fully exterior?
- Tight fitting?
- Symmetric?
- “Well-placed”?



Interpenetrating mesh simplification

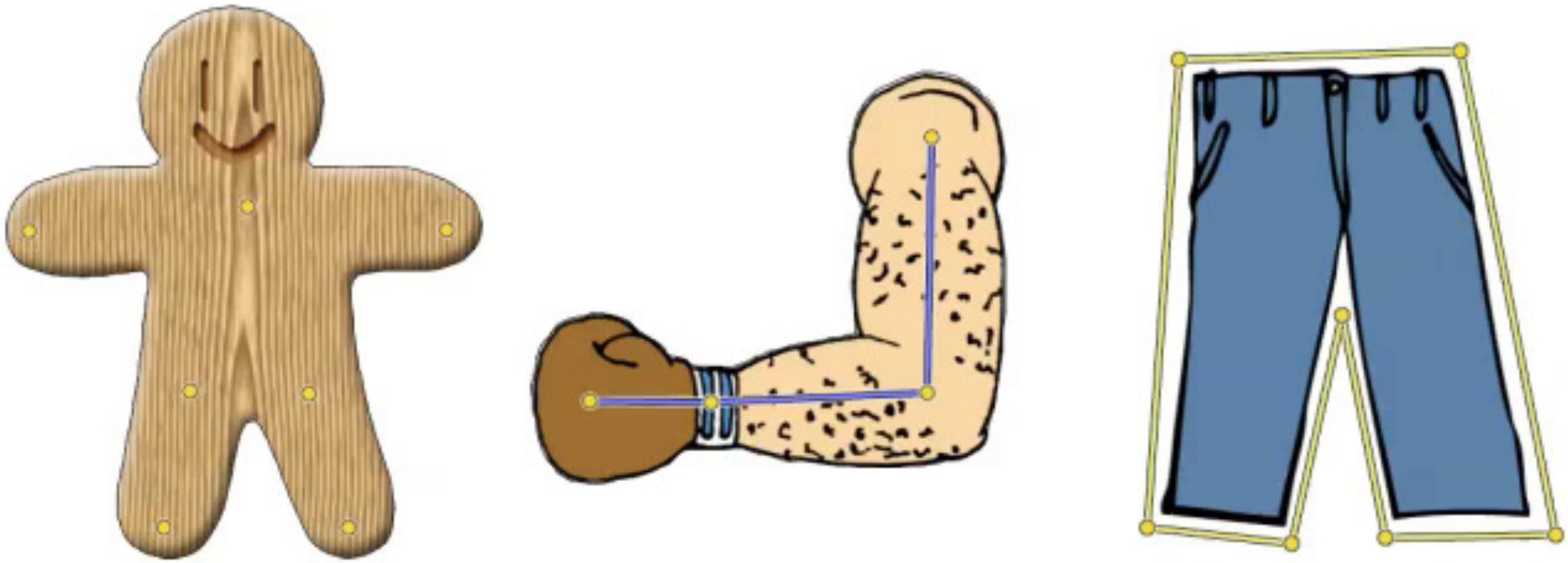
Fully enclosing cage

Recent research automates each step



$$\mathbf{v}' = \sum_{j \in H} w_j(\mathbf{v}) \mathbf{T}_j \begin{pmatrix} \mathbf{v} \\ 1 \end{pmatrix}$$

Weights should obtain a few basic qualities



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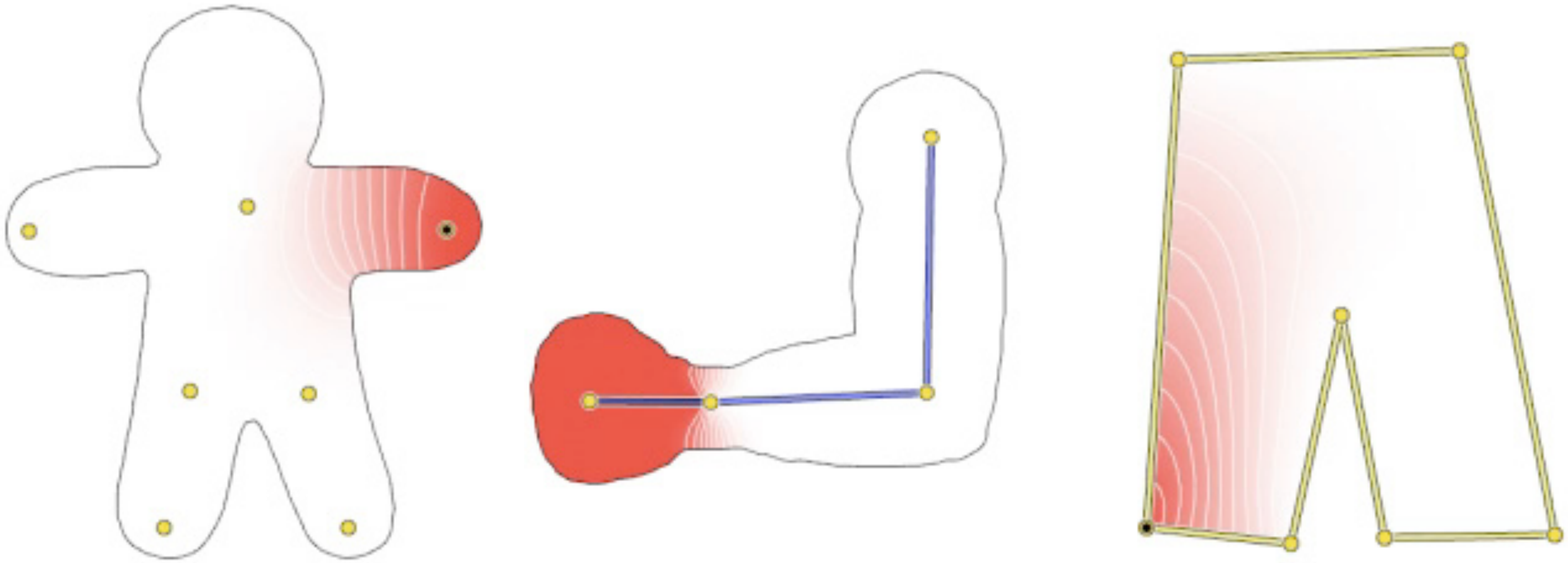
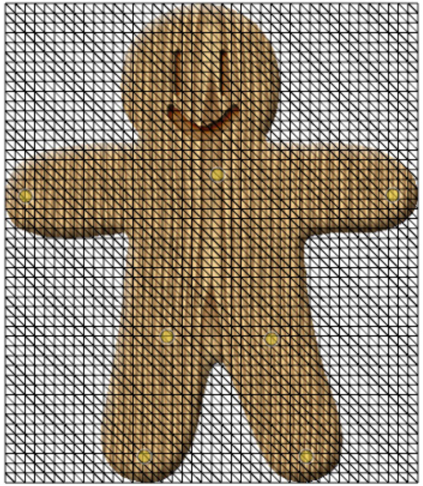


Inverse Euclidean distance weights are too crude, show obvious artifacts

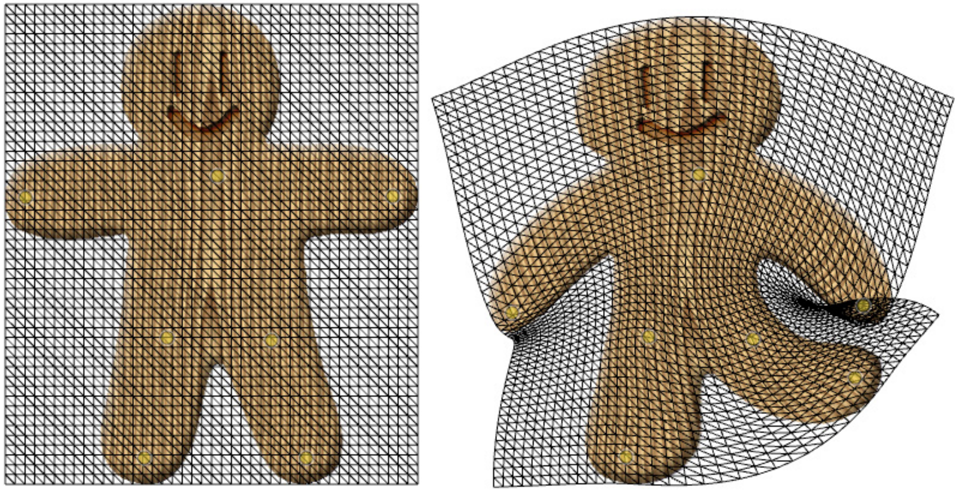


$$w_j(\mathbf{v}) = \frac{1}{\|\mathbf{c}_i - \mathbf{v}\|^2}$$

[Shepard 1968],
[Schaefer et al. 2006], etc.

weights optimized *inside* shape

Inverse Euclidean distance weights are too crude, show obvious artifacts



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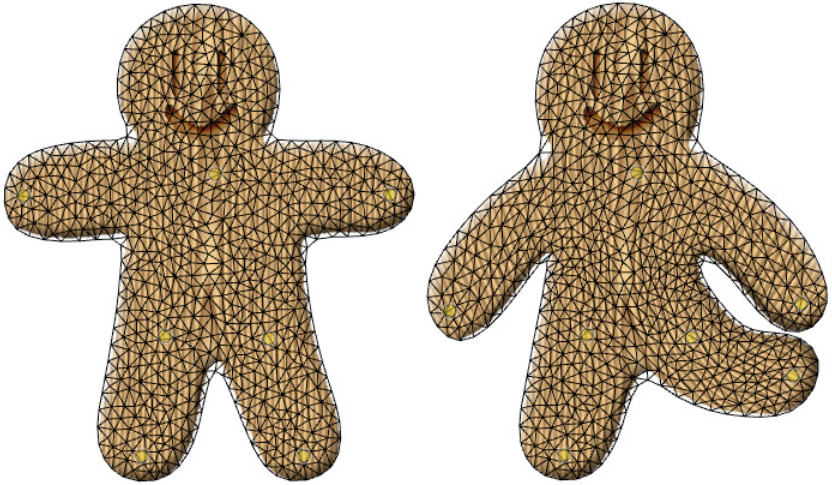
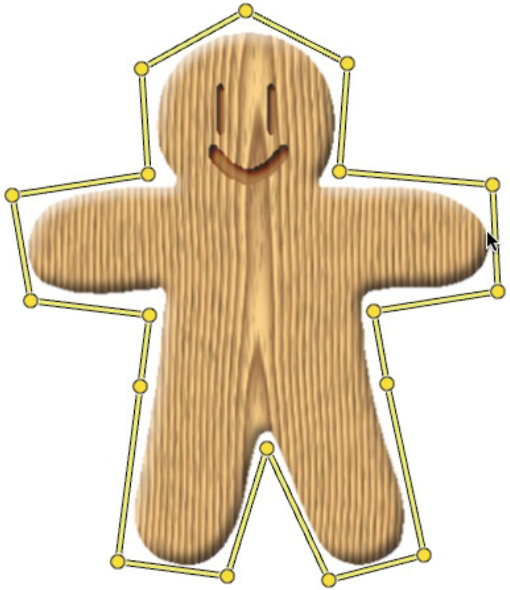


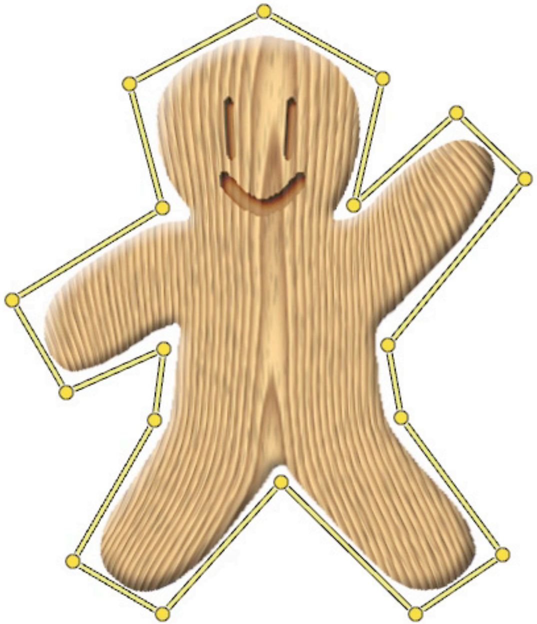
weights optimized *inside* shape

Generalize barycentric coordinates capture *shape-awareness* via low-resolution "cage"



$$\mathbf{v}' = \sum_{j=1}^{m} w_j(\mathbf{v})\mathbf{c}'_j$$

“Coordinate” or reproduction property defines any point in cage as weighted sum of vertices



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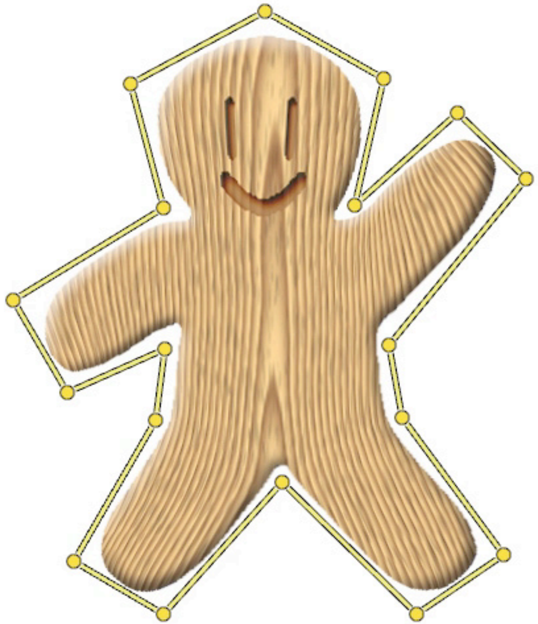
“coordinates”

$$\mathbf{v} = \sum_{j=1}^{m} w_j(\mathbf{v})\mathbf{c}_j$$

Coordinate-based deformation is a special case of linear blend skinning



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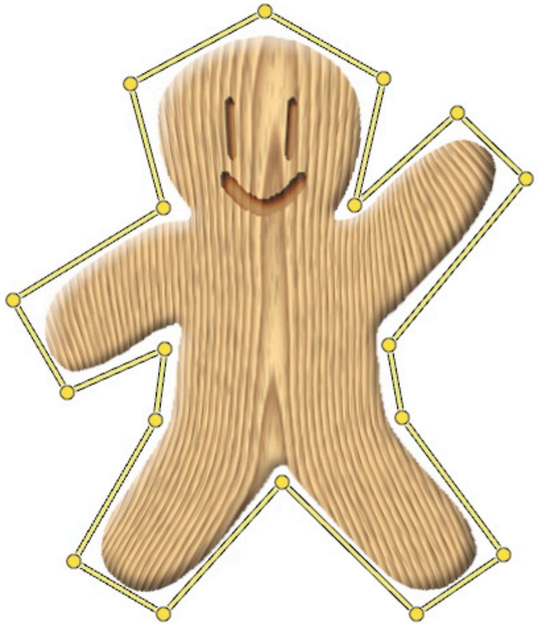
“coordinates”

$$\mathbf{v} = \sum_{j=1}^{m} w_j(\mathbf{v})\mathbf{c}_j$$

restricted to translation

$$\mathbf{v}' = \sum_{j=1}^{m} w_j(\mathbf{v})\mathbf{T}_j \begin{pmatrix} \mathbf{v} \\ 1 \end{pmatrix}$$

Coordinate-based deformation is a special case of linear blend skinning



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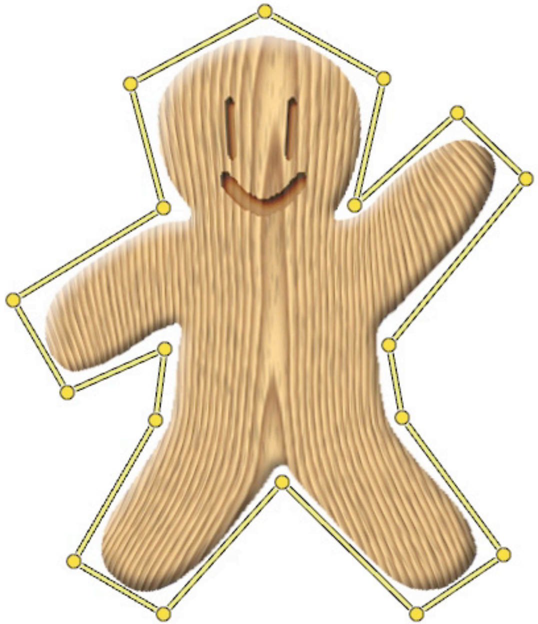

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$$\mathbf{v} = \sum_{j=1}^{m} w_j(\mathbf{v})\mathbf{c}_j$$

$$\mathbf{v}' = \sum_{j=1}^{m} w_j(\mathbf{v})\left(\mathbf{c}'_j - \mathbf{c}_j + \mathbf{v}\right)$$

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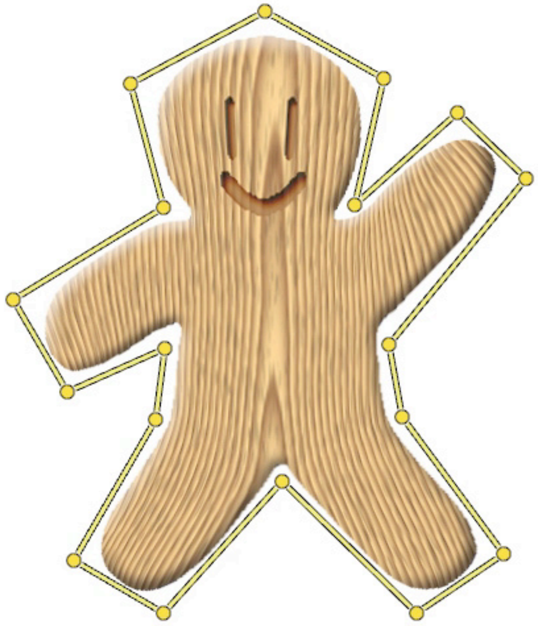

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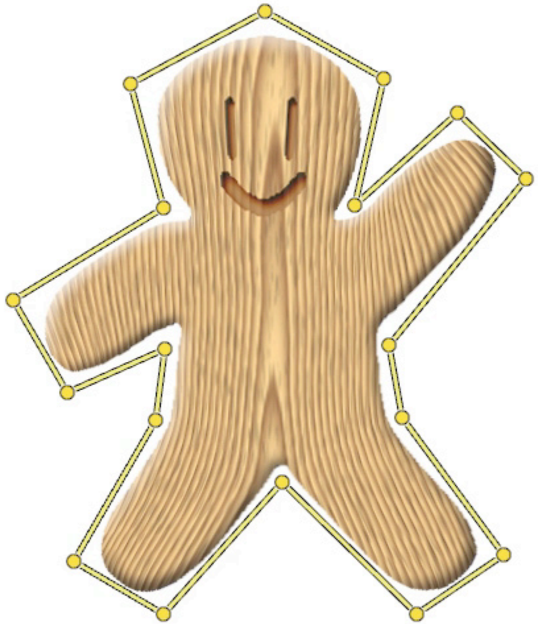

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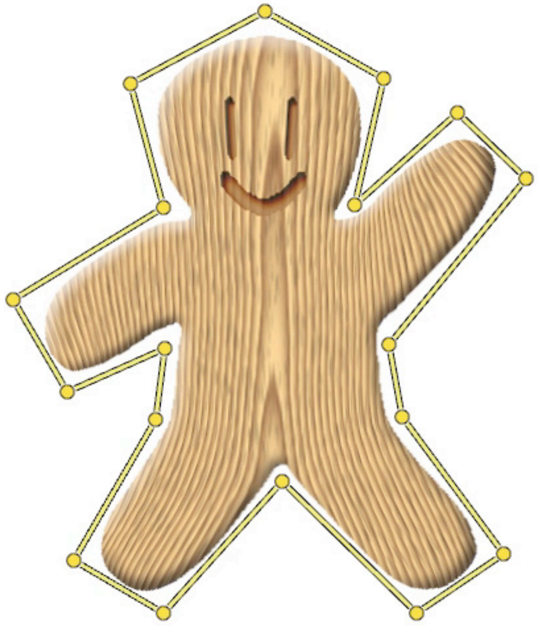

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"Higher order GBC" [Langer et al. 2008] are identical to linear blend skinning

Not all coordinates are created equal

Method	N-GON	CONCAVE	SHAPE	≥ 0	C^1	LAG.	CLOSED	MONO.	OUT	LOCAL	POLY	COORD.
Barycentric	X	X	●	●	●	●	●	●	●	X	X	●
Wachspress	●	X	●	X	●	●	●	X	?	X	X	●
Natural Neighbor	●	●	X	●	X	●	●	●	●	●	●	●
Mean Value	●	●	●	X	●	●	●	X	●	X	X	●
Green and others	●	●	●	X	●	X	●	X	X	X	X	●
Positive Mean Value	●	●	●	●	X	●	X	X	X	X	X	●
Harmonic	●	●	●	●	●	●	X	●	X	X	●	●
Maximum Entropy	●	●	●	●	●	●	X	?	X	X	●	●
Const. Biharmonic	●	●	●	●	●	●	X	●	X	●	●	X

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Barycentric	X	X	●	●	●	●	●	●	●	X	X	●
Wachspress	●	X	●	X	●	●	●	X	?	X	X	●
Natural Neighbor	●	●	X	●	X	●	●	●	●	●	●	●
Mean Value	●	●	●	X	●	●	●	X	●	X	X	●
Green and others	●	●	●	X	●	X	●	X	X	X	X	●
Positive Mean Value	●	●	●	●	X	●	X	X	X	X	X	●
Harmonic	●	●	●	●	●	●	X	●	X	X	●	●
Maximum Entropy	●	●	●	●	●	●	X	?	X	X	●	●
Const. Biharmonic	●	●	●	●	●	●	X	●	X	●	●	X

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Wachspress	●	X	●	X	●	●	●	X	?	X	X	●
Natural Neighbor	●	●	X	●	X	●	●	●	●	●	●	●
Mean Value	●	●	●	X	●	●	●	X	●	X	X	●
Green and others	●	●	●	X	●	X	●	X	X	X	X	●
Positive Mean Value	●	●	●	●	X	●	X	X	X	X	X	●
Harmonic	●	●	●	●	●	●	X	●	X	X	●	●
Maximum Entropy	●	●	●	●	●	●	X	?	X	X	●	●
Const. Biharmonic	●	●	●	●	●	●	X	●	X	●	●	X

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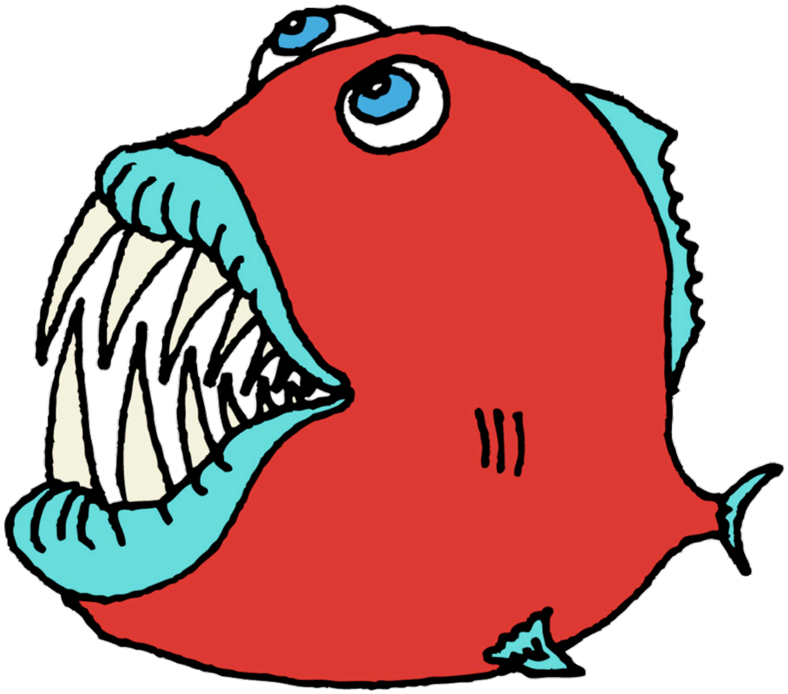
Barycentric	X	X	●	●	●	●	●	●	●	X	X	●
Wachspress	●	X	●	X	●	●	●	X	?	X	X	●
Natural Neighbor	●	●	X	●	X	●	●	●	●	●	●	●
Mean Value	●	●	●	X	●	●	●	X	●	X	X	●
Green and others	●	●	●	X	●	X	●	X	X	X	X	●
Positive Mean Value	●	●	●	●	X	●	X	X	X	X	X	●
Harmonic	●	●	●	●	●	●	X	●	X	X	●	●
Maximum Entropy	●	●	●	●	●	●	X	?	X	X	●	●
Const. Biharmonic	●	●	●	●	●	●	X	●	X	●	●	X

No free lunch?
Are some properties mutually exclusive?

Working only with cages is too restrictive…



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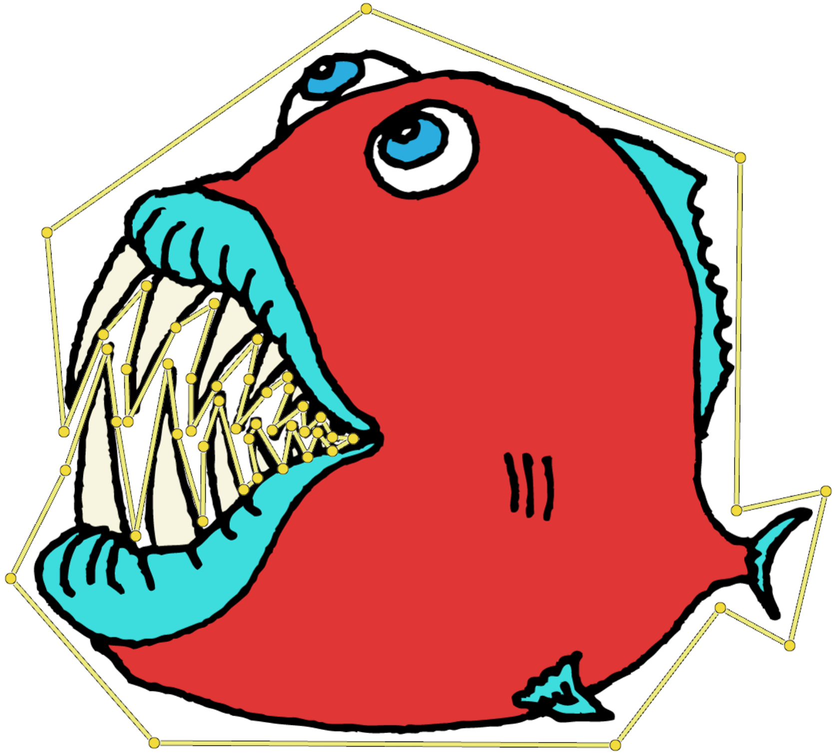

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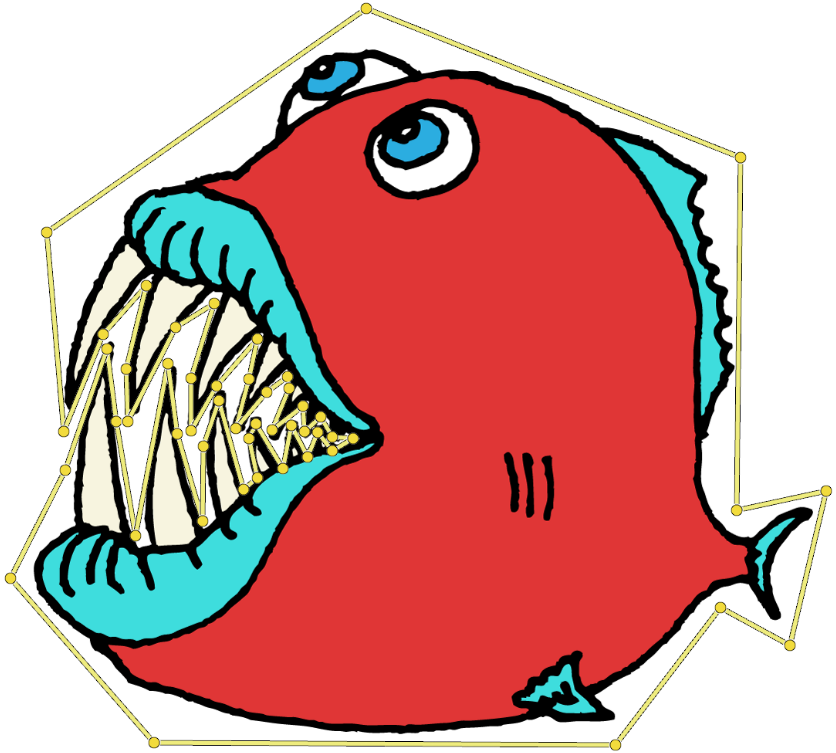

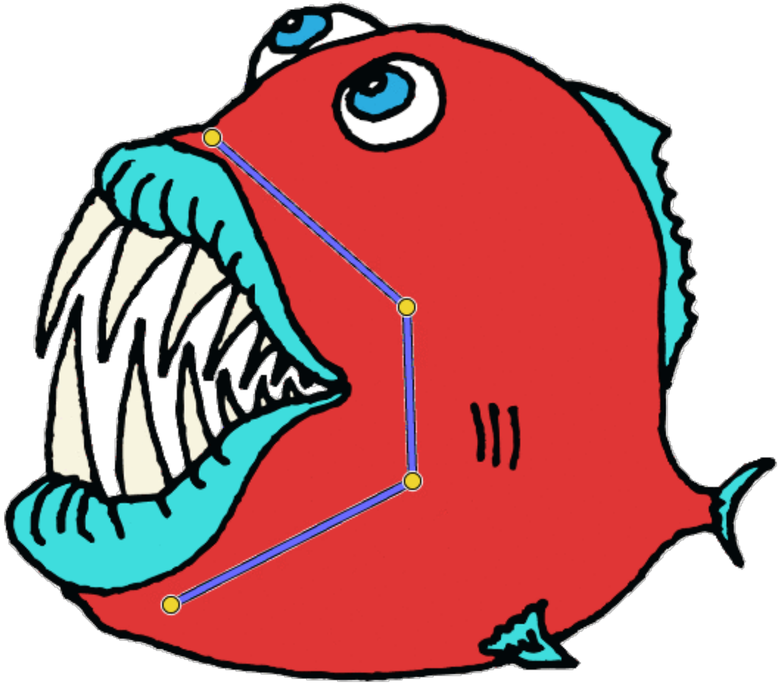

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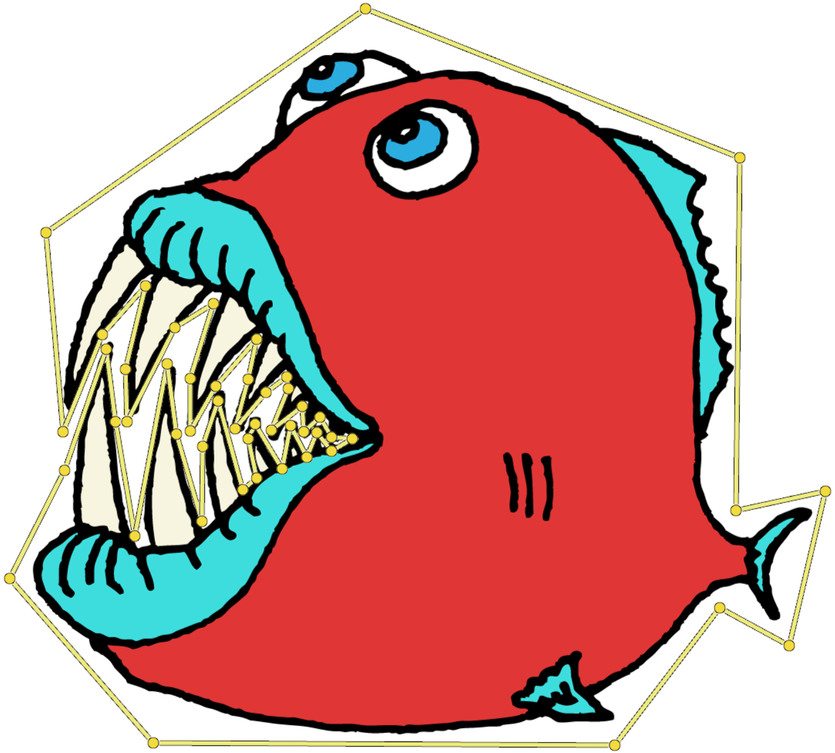
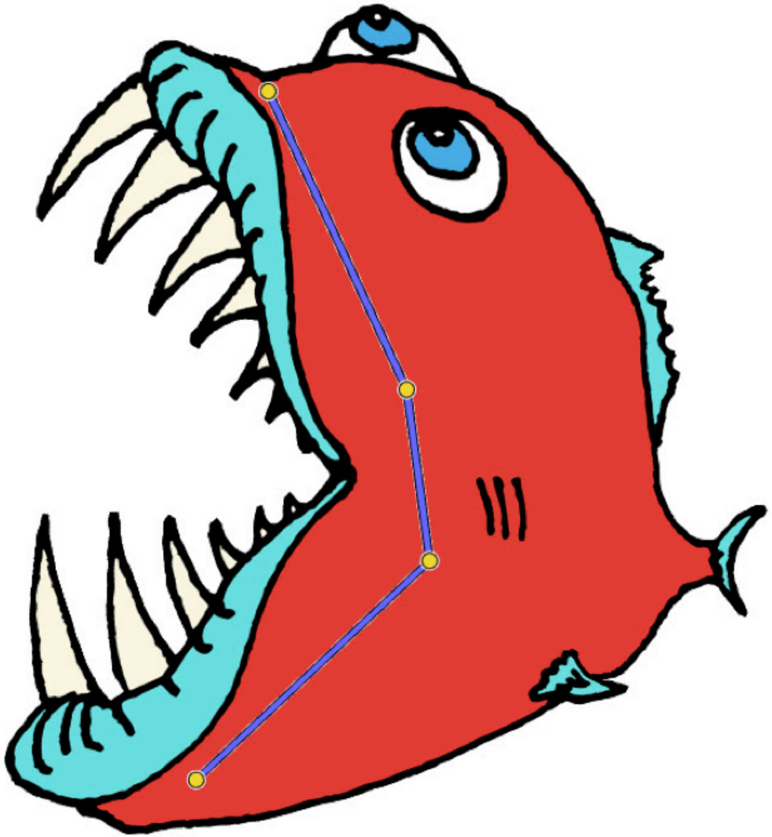
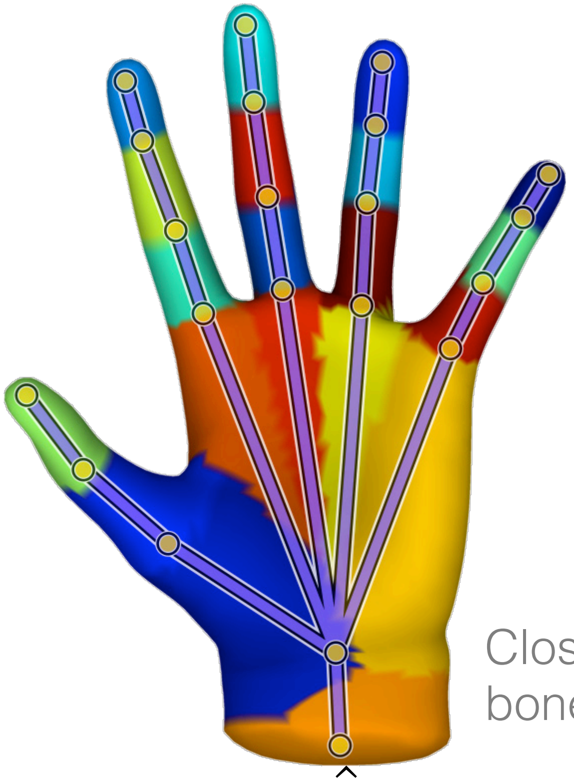




Discontinuous projection onto surface can be smoothed out

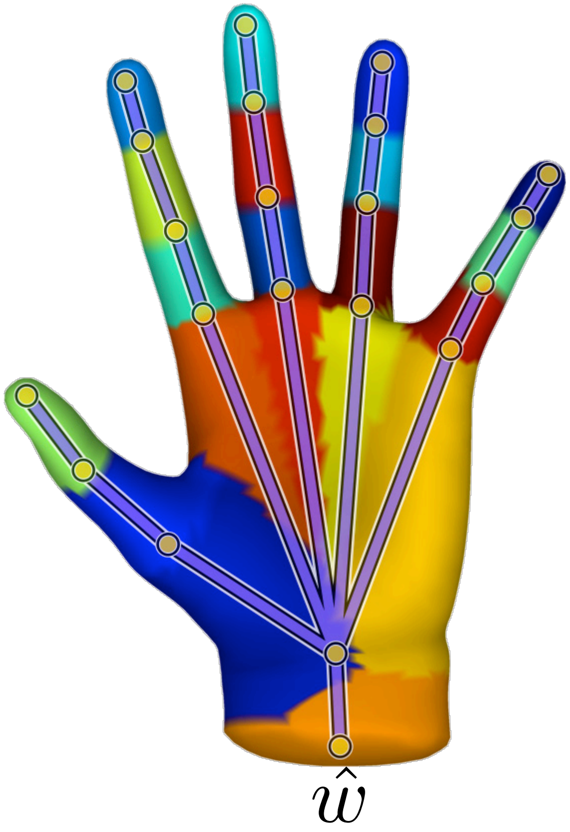


Closest *visible* bone

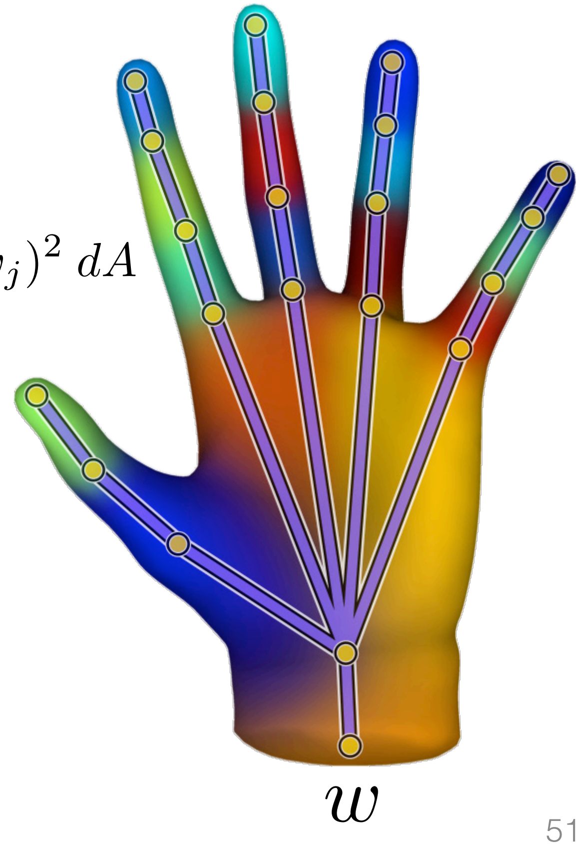
$\hat{w}$

[Baran & Popović 2007]

Discontinuous projection onto surface can be smoothed out



$$\underset{w_j}{\operatorname{argmin}} \int_\Omega \|\nabla w_j\|^2 + h_j(w_j - \hat{w}_j)^2 \, dA$$



[Baran & Popović 2007]

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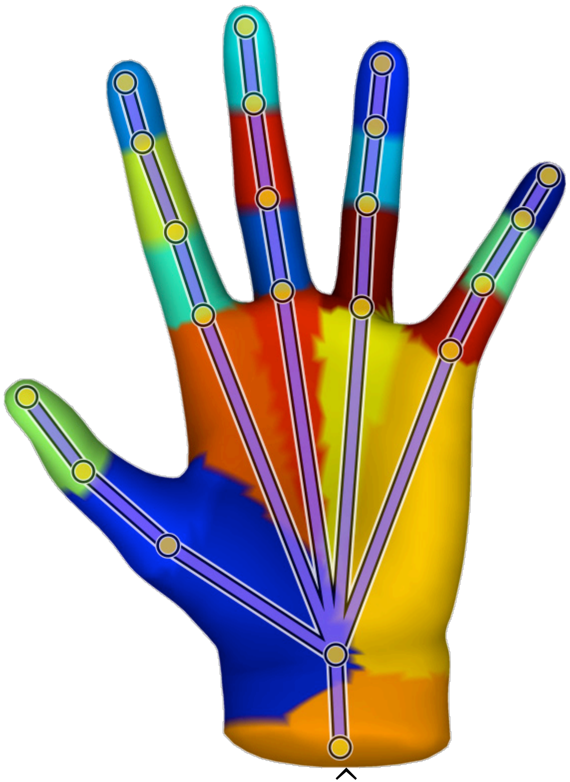
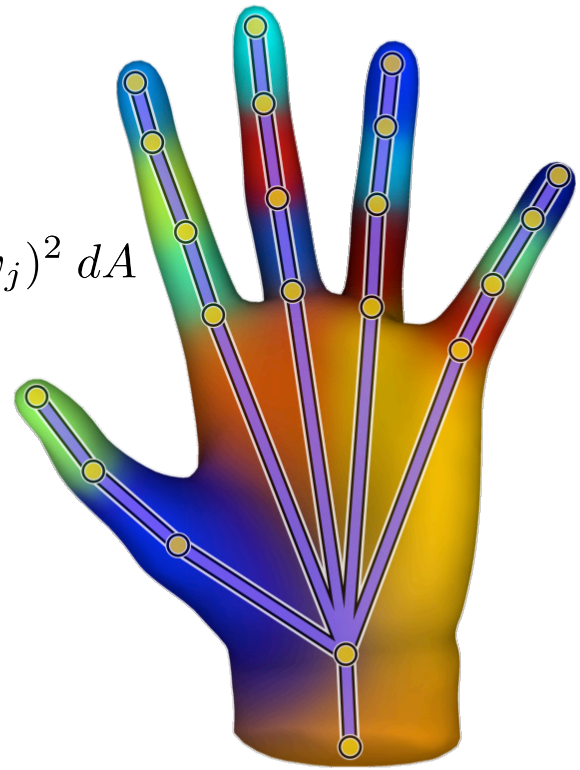


$\hat{w}$

smoothness

$$\underset{w_j}{\operatorname{argmin}} \int_\Omega \boxed{\|\nabla w_j\|^2} + h_j(w_j - \hat{w}_j)^2 \, dA$$



w

[Baran & Popović 2007]

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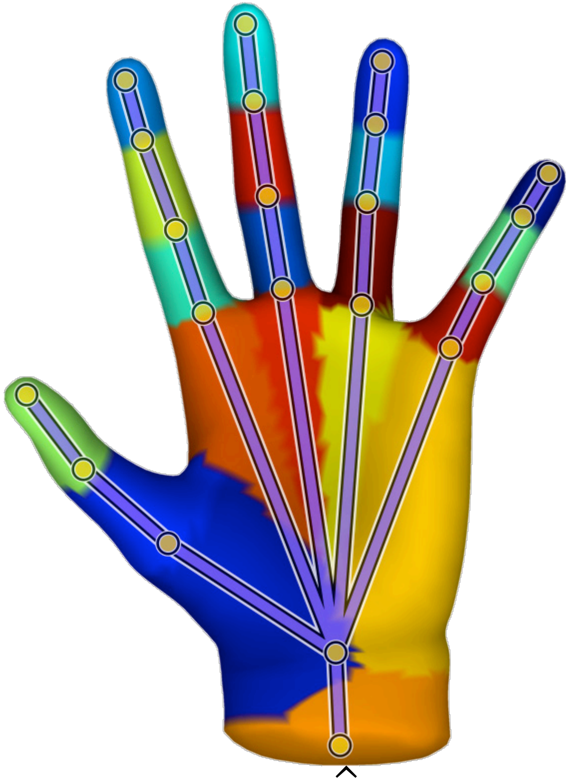
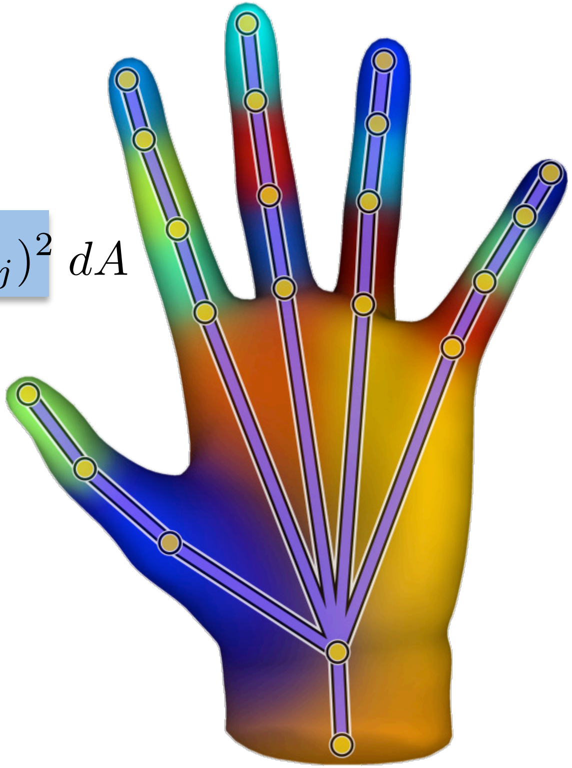


$\hat{w}$

“data”

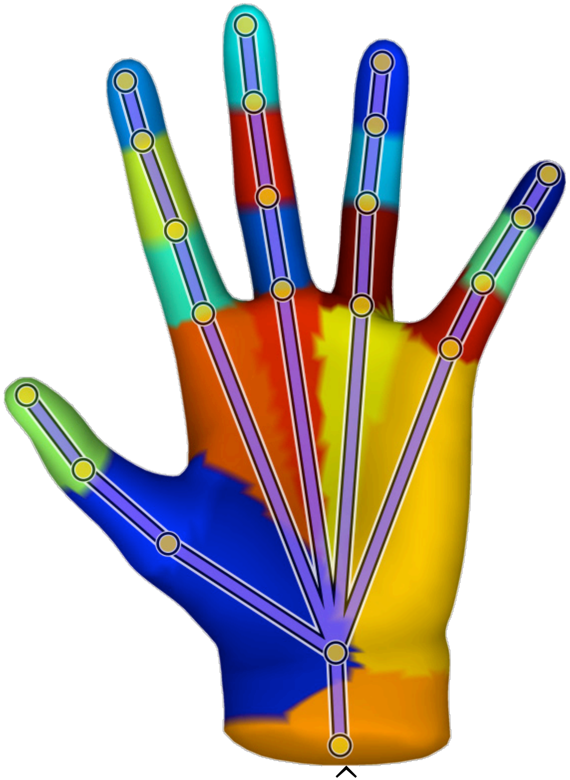
$$\underset{w_j}{\operatorname{argmin}} \int_\Omega \|\nabla w_j\|^2 + \boxed{h_j(w_j - \hat{w}_j)^2}\, dA$$



w

[Baran & Popović 2007]

Discontinuous projection onto surface can be smoothed out



$\hat{w}$

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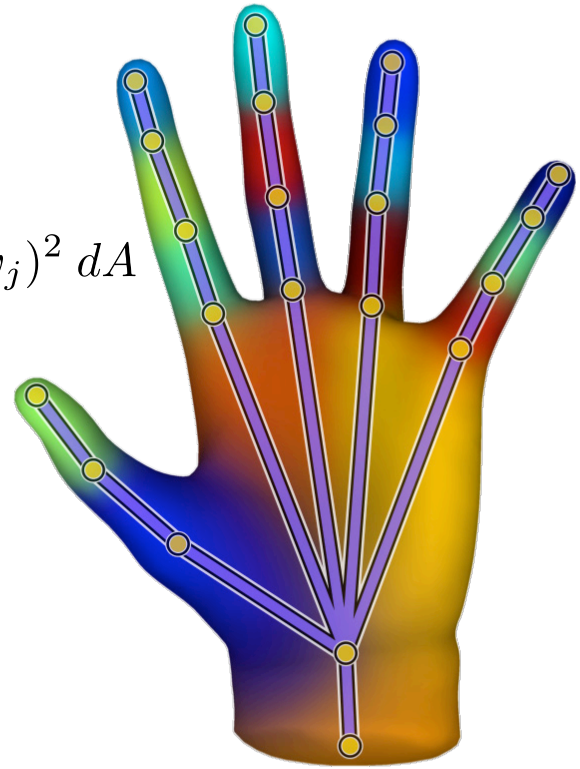
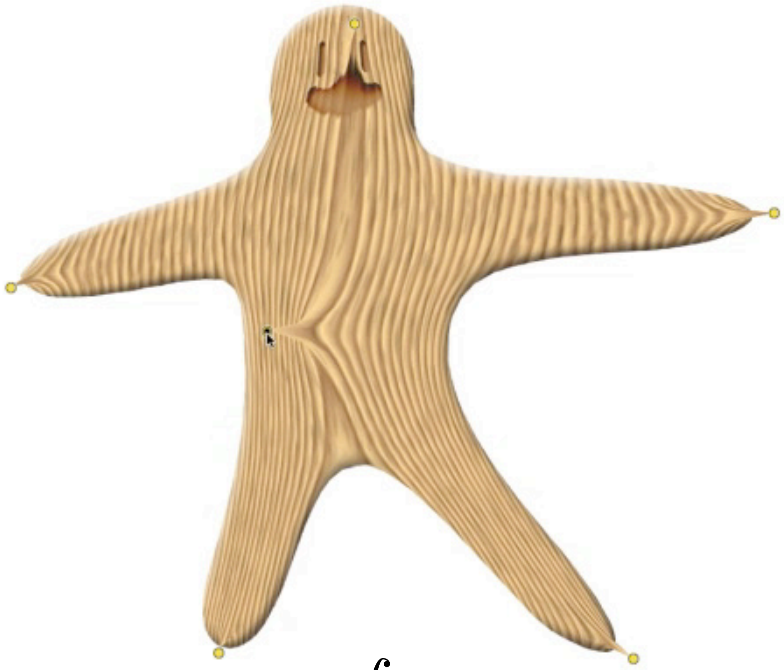


w

[Baran & Popović 2007]

Gradient energy weights not smooth at handles

$$\underset{w_j}{\operatorname{argmin}} \int_\Omega \boxed{(\Delta w_j)^2}\, dA$$



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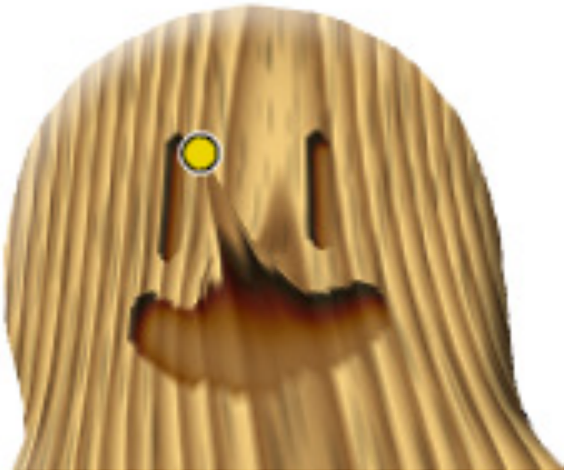
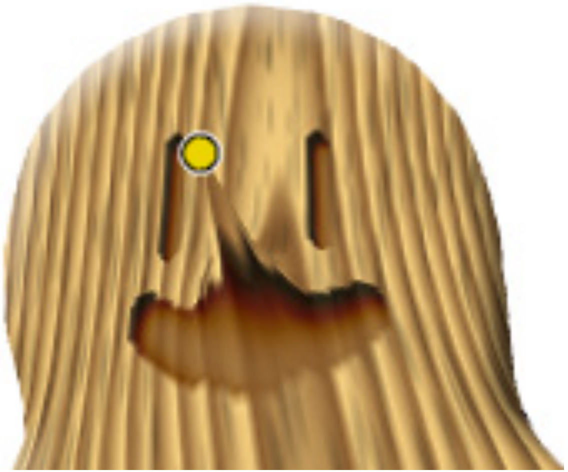


$$\underset{w_j}{\operatorname{argmin}} \int_\Omega \|\nabla w_j\|^2 \, dA$$

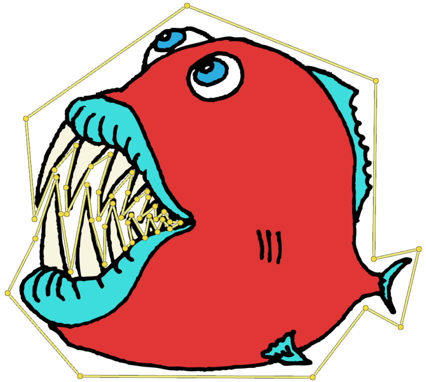
Gradient energy weights not smooth at handles

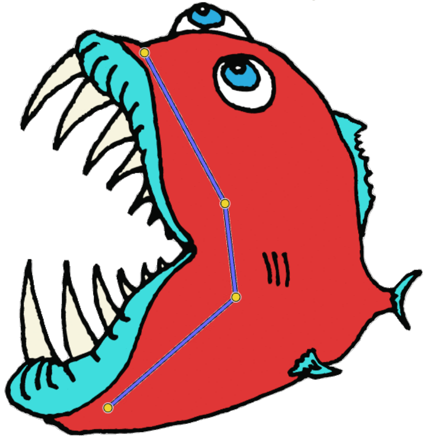
$$\Delta^2 w_j = 0$$

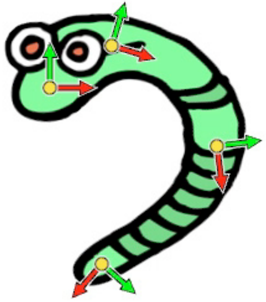


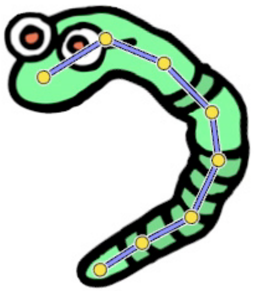
$$\Delta w_j = 0$$

Any single handle type is too restrictive…









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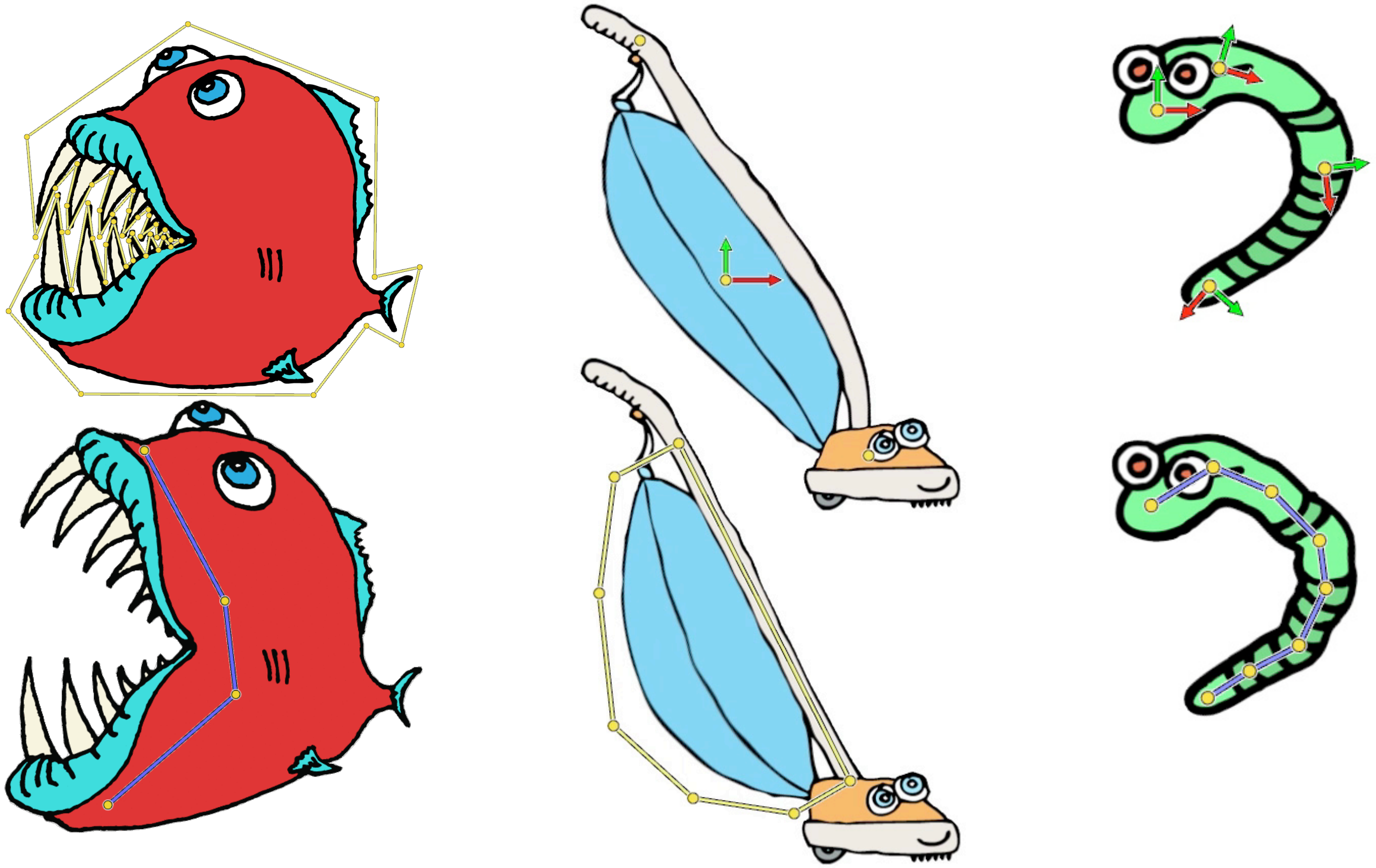
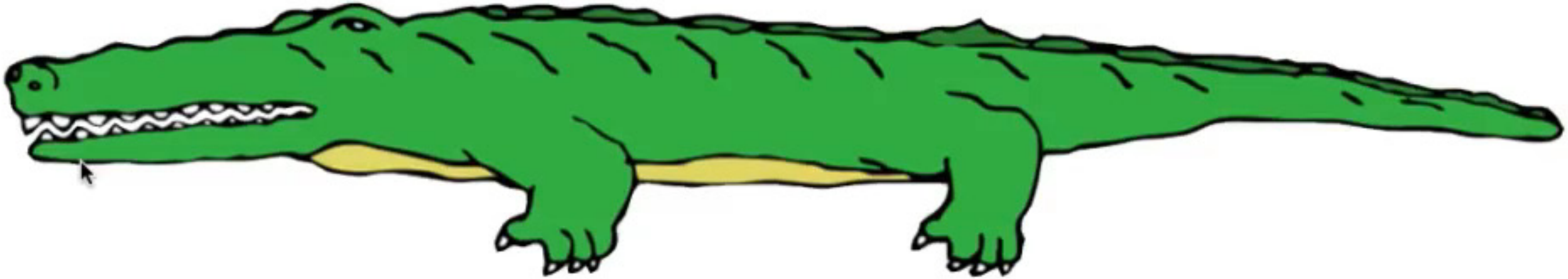


Each handle type has a specific task, more than just a *different modeling metaphor*



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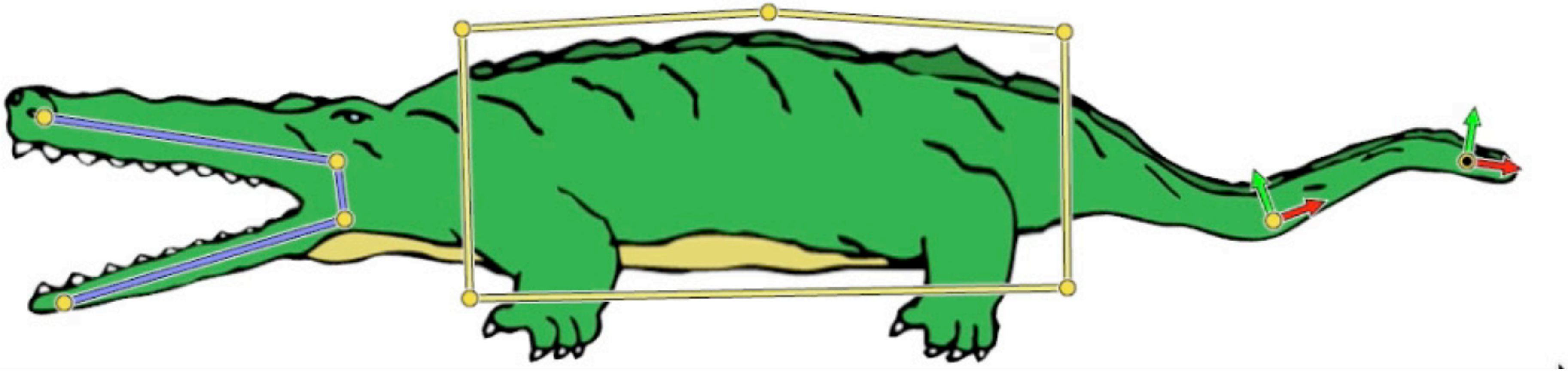
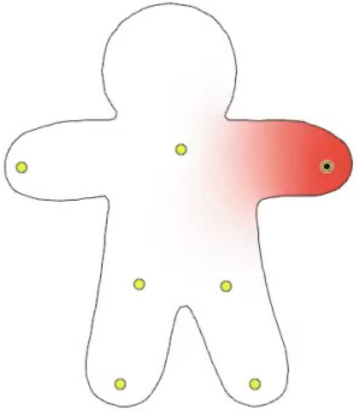


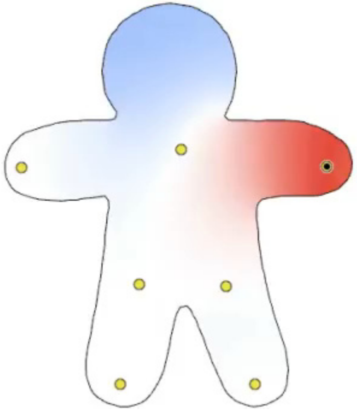
Non-negative, local weights are mandatory

$$0 \leq w_j \leq 1$$



$$\underset{w_j}{\operatorname{argmin}} \int_\Omega (\Delta w_j)^2 \, dA$$

[Botsch & Kobbelt 2004]



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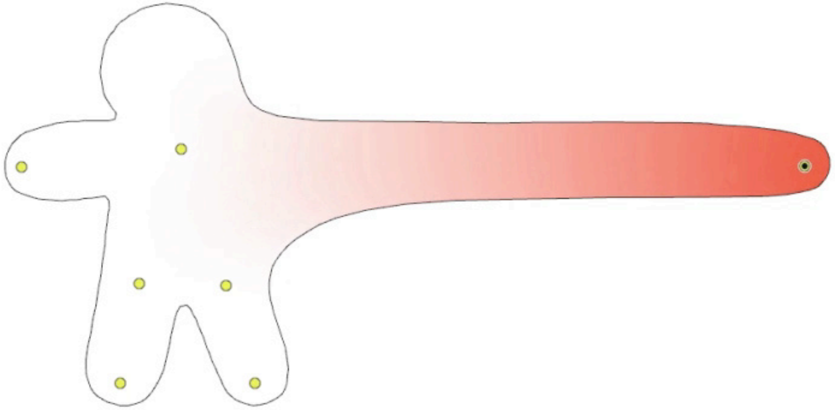

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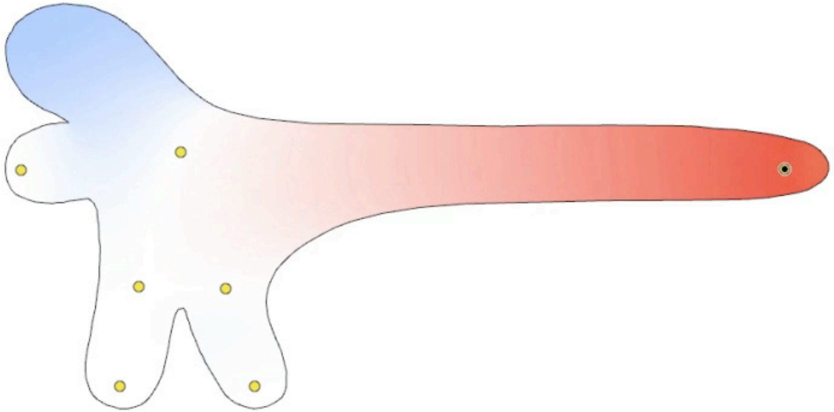
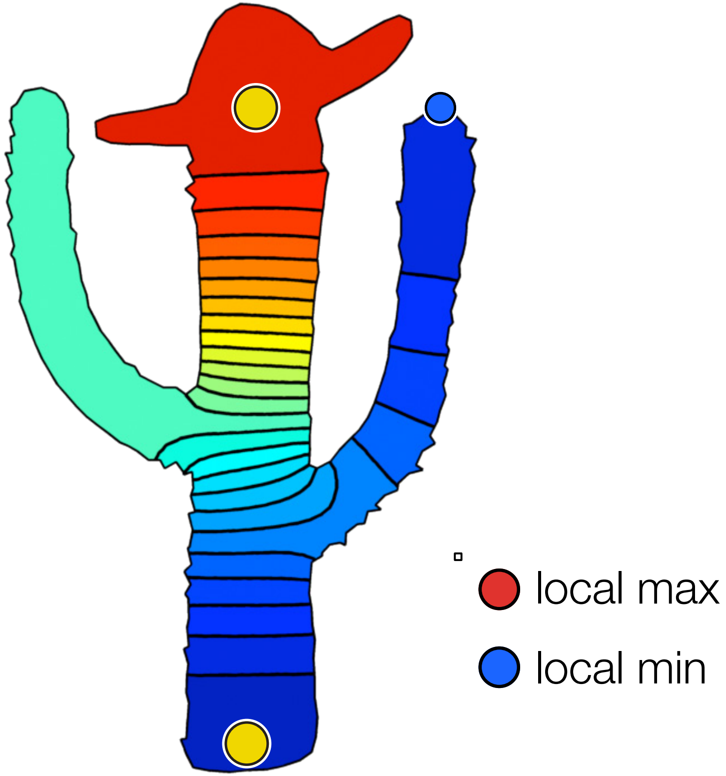


Spurious extrema cause distracting artifacts



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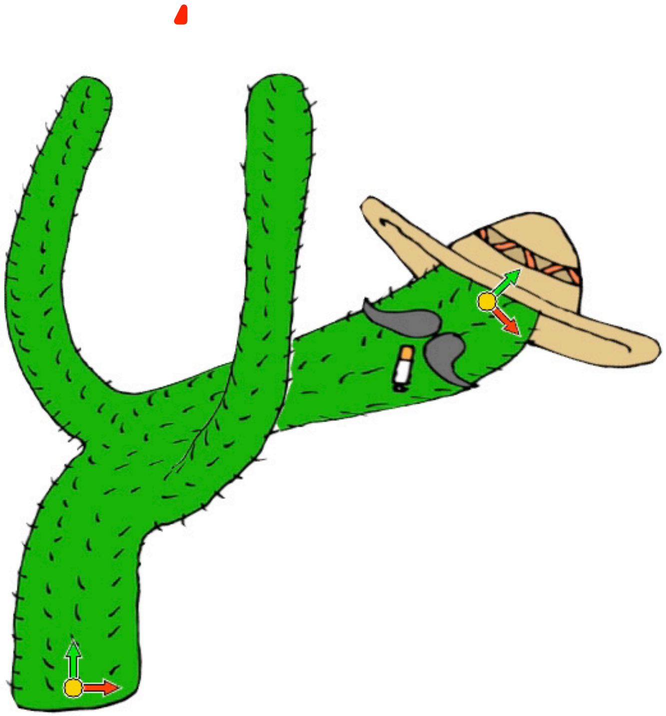
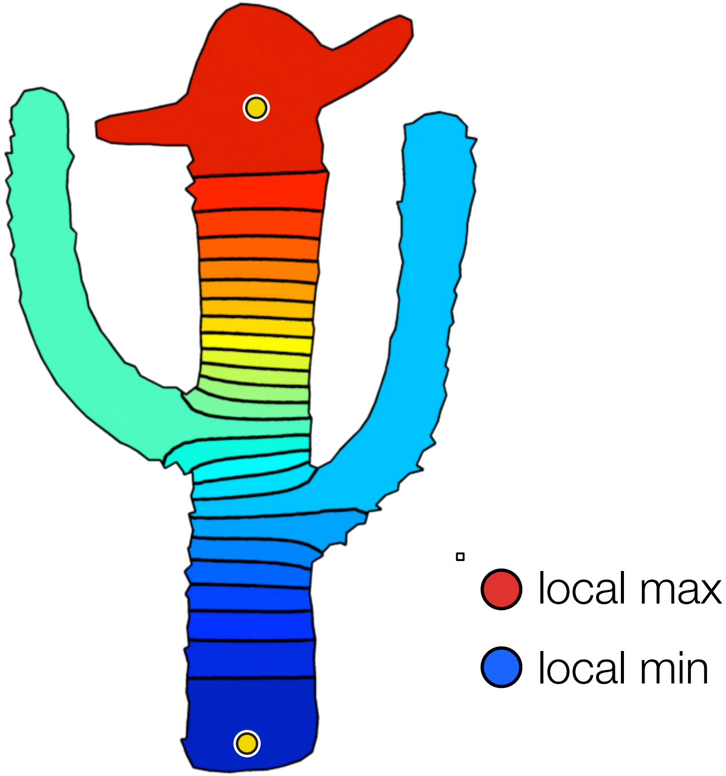
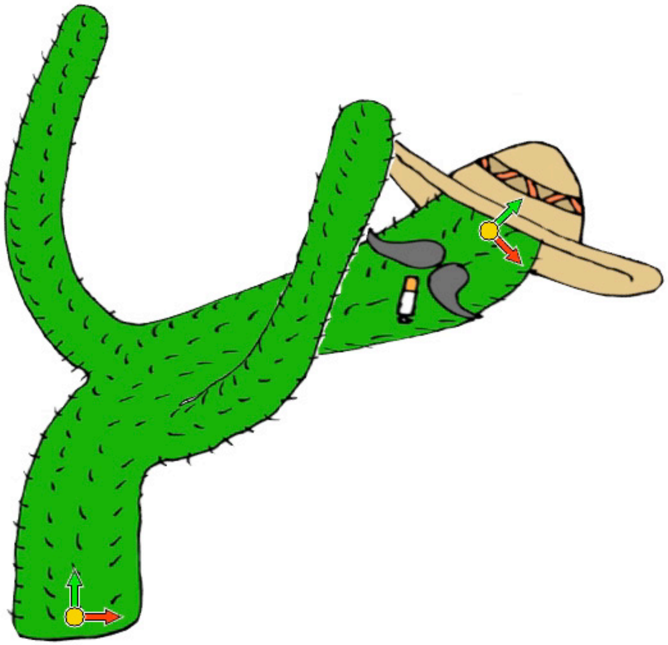


Must explicitly prohibit spurious extrema



w_j is “monotonic”



Previous methods fail in one way or another

	Euclidean	Δw_j	$\Delta^2 w_j$
smooth	✓	-	✓
non-negative	✓	✓	-
shape-aware	-	✓	✓
local	-/✓	-	-
monotonic	-	✓	-
arbitrary handles	-	✓	✓
	[Shepard 1968, Sibson 1980, Schaefer et al. 2006]	[Baran & Popovic 2007, Joshi et al. 2007]	[Botsch & Kobbelt 2004, Sorkine et al. 2004, Finch et al. 2011]

No free lunch?
Are some properties mutually exclusive?

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~~No free lunch?~~

~~Are some properties mutually exclusive?~~

Constrained optimization ensures satisfaction of all properties

$$\underset{w_j, j=1,\ldots,m}{\operatorname{argmin}} \sum_{j=1}^{m} \int_\Omega (\Delta w_j)^2 \, dV$$

+ shape-aware
+ smoothness

[Botsch & Kobbelt 2004, Sorkine et al. 2004, Joshi & Carr 2008, Jacobson et al. 2010, Finch et al. 2011, Andrews et al. 2011]

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$$\underset{w_j, j=1,\ldots,m}{\operatorname{argmin}} \sum_{j=1}^{m} \int_{\Omega} (\Delta w_j)^2 \, dV$$

$$w_j(\mathbf{v}) = \begin{cases} 1 & \mathbf{v} \in h_j, \\ 0 & \mathbf{v} \in h_k \\ \text{linear on cage facets} & \end{cases}$$

+ shape-aware
+ smoothness
+ arbitrary handles

[Botsch & Kobbelt 2004, Sorkine et al. 2004, Joshi & Carr 2008, Jacobson et al. 2010, Finch et al. 2011, Andrews et al. 2011]

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$$\sum_{j=1}^{m} w_j = 1$$

+ shape-aware
+ smoothness
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+ non-negativity

[Jacobson et al. 2011]

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Constrained optimization ensures satisfaction of all properties

$$\operatorname*{argmin}_{w_j, j=1,\ldots,m} \sum_{j=1}^{m} \int_\Omega (\Delta w_j)^2 \, dV$$

$$\|w\|_1 = 1$$

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+ smoothness
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+ locality

[Rustamov 2011]

Constrained optimization ensures satisfaction of all properties

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$$\|w\|_1 = 1 \rightarrow \sum_{j=1}^{m} |w_j| = 1$$

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[Rustamov 2011]

Constrained optimization ensures satisfaction of all properties

$$\underset{w_j, j=1,\ldots,m}{\operatorname{argmin}} \sum_{j=1}^{m} \int_{\Omega} (\Delta w_j)^2 \, dV$$

$$\nabla w_j \cdot \nabla u_j > 0$$

+ shape-aware
+ smoothness
+ arbitrary handles
+ non-negativity
+ locality
+ monotonicity

[Weinkauf et al. 2011, Jacobson et al. 2012, Günther et al. 2014]

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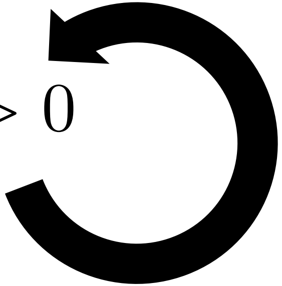

+ shape-aware
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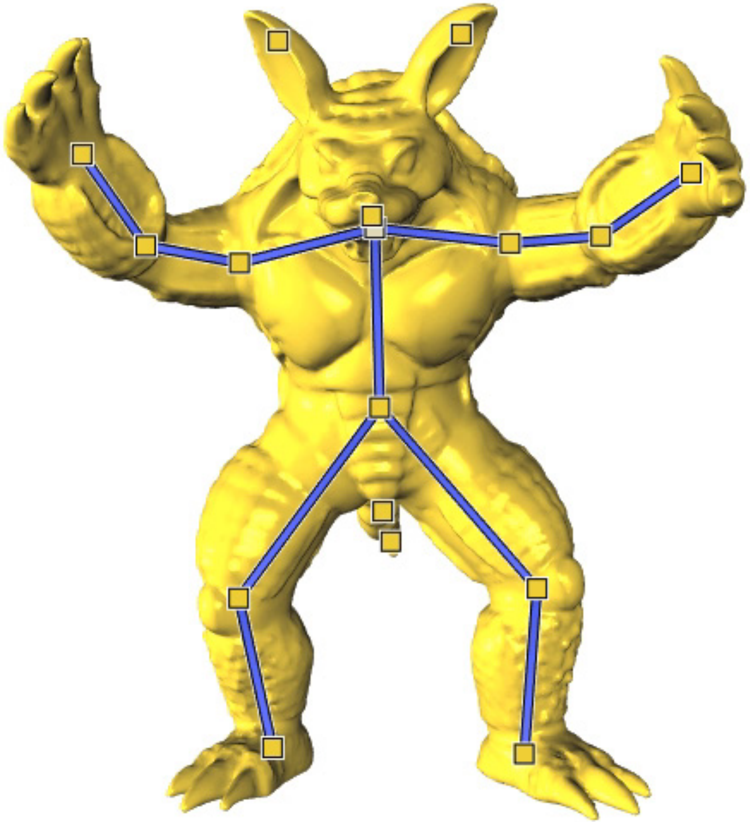
[Weinkauf et al. 2011, Jacobson et al. 2012, Günther et al. 2014]

Weights retain nice properties in 3D



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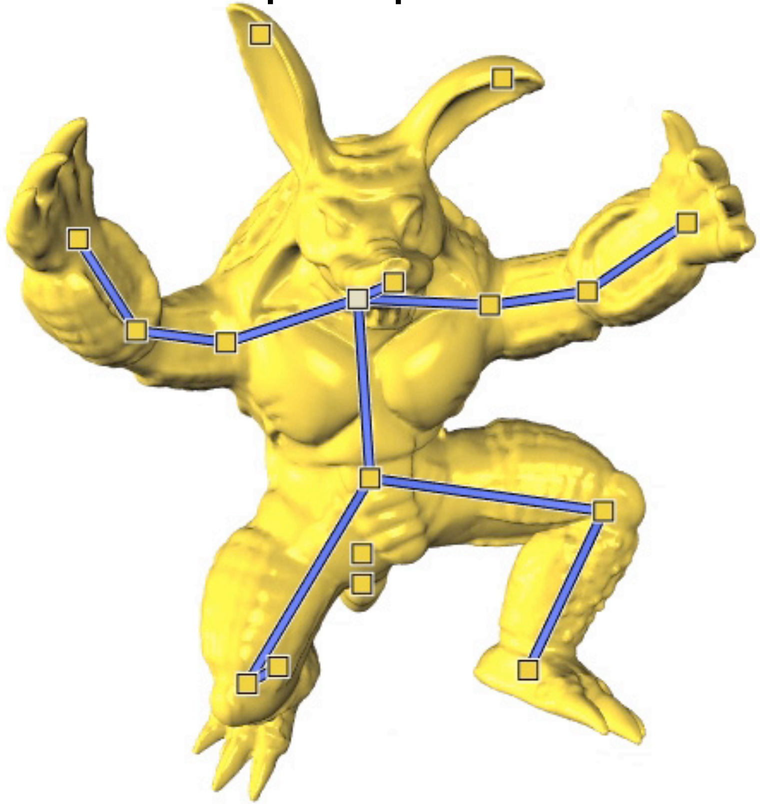
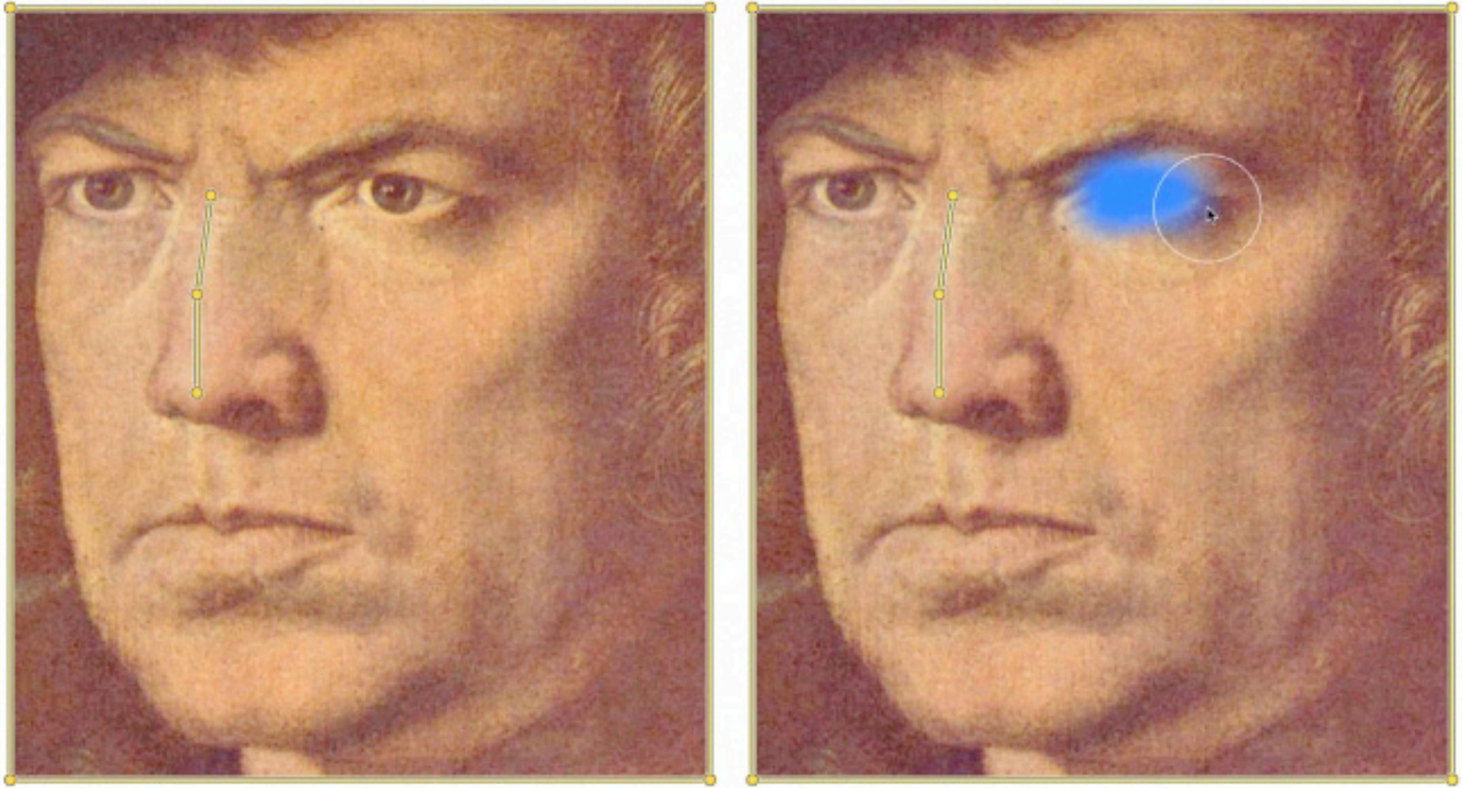


Variational formulation allows additional, problem-specific constraints



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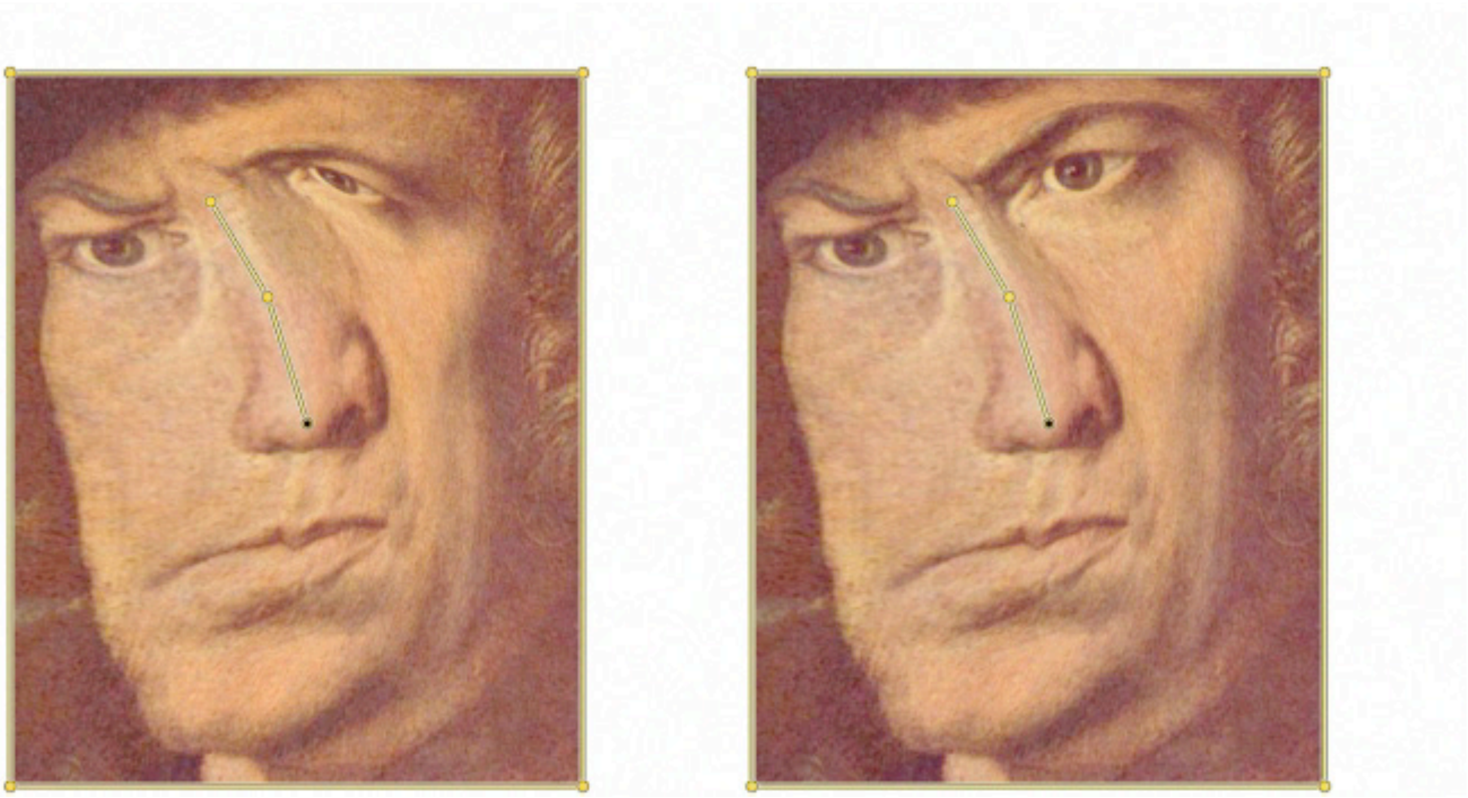
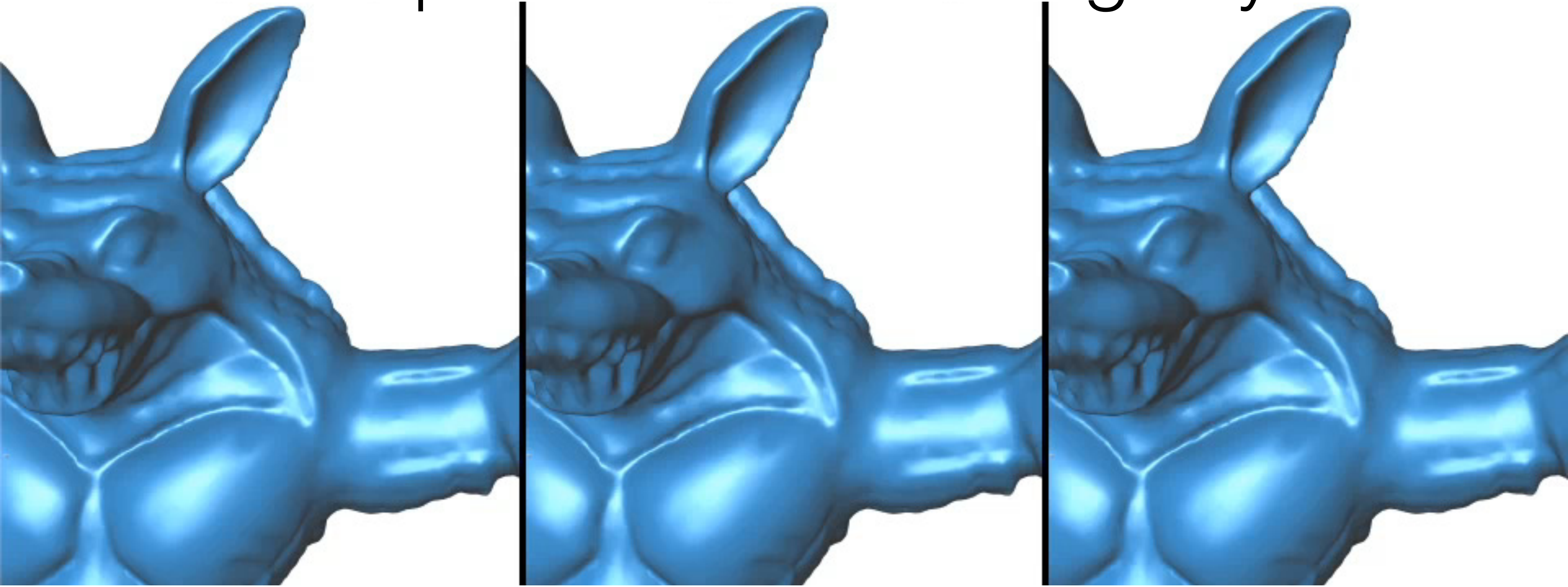


Energy encodes *prior* on deformation, could swap smoothness for rigidity



Left, middle: smoothness energy

Right: [Kavan & Sorkine 2012]

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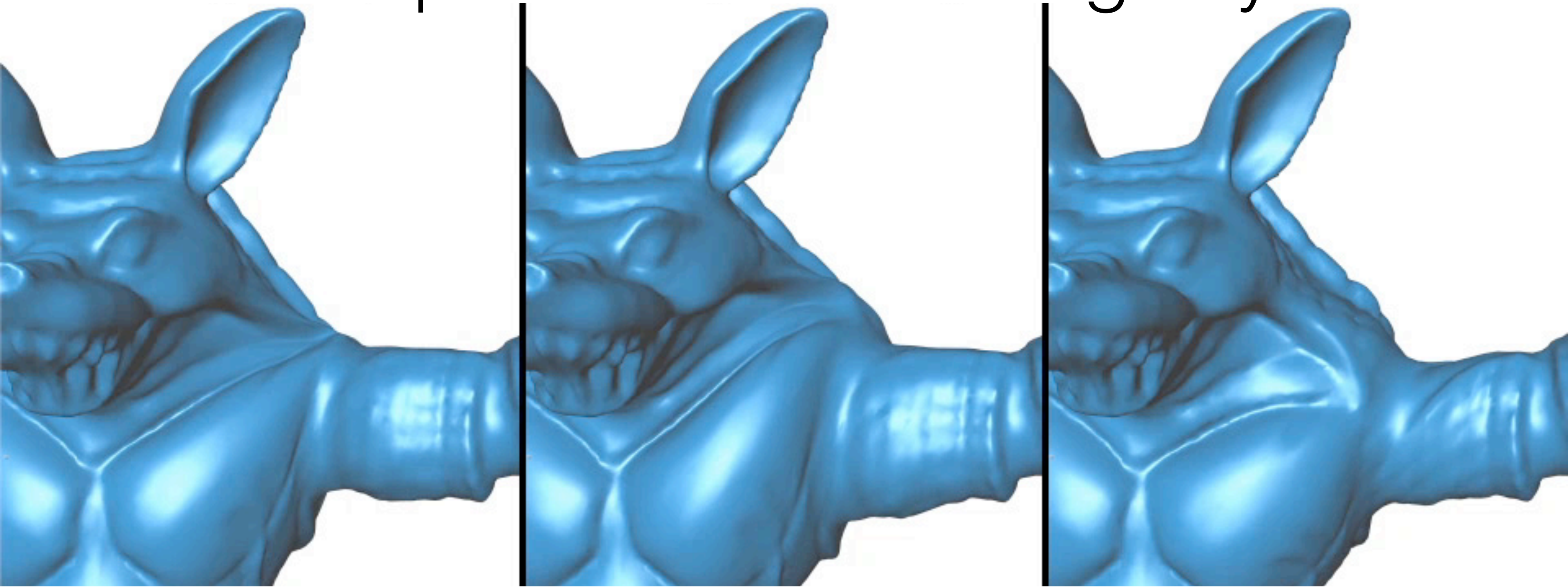
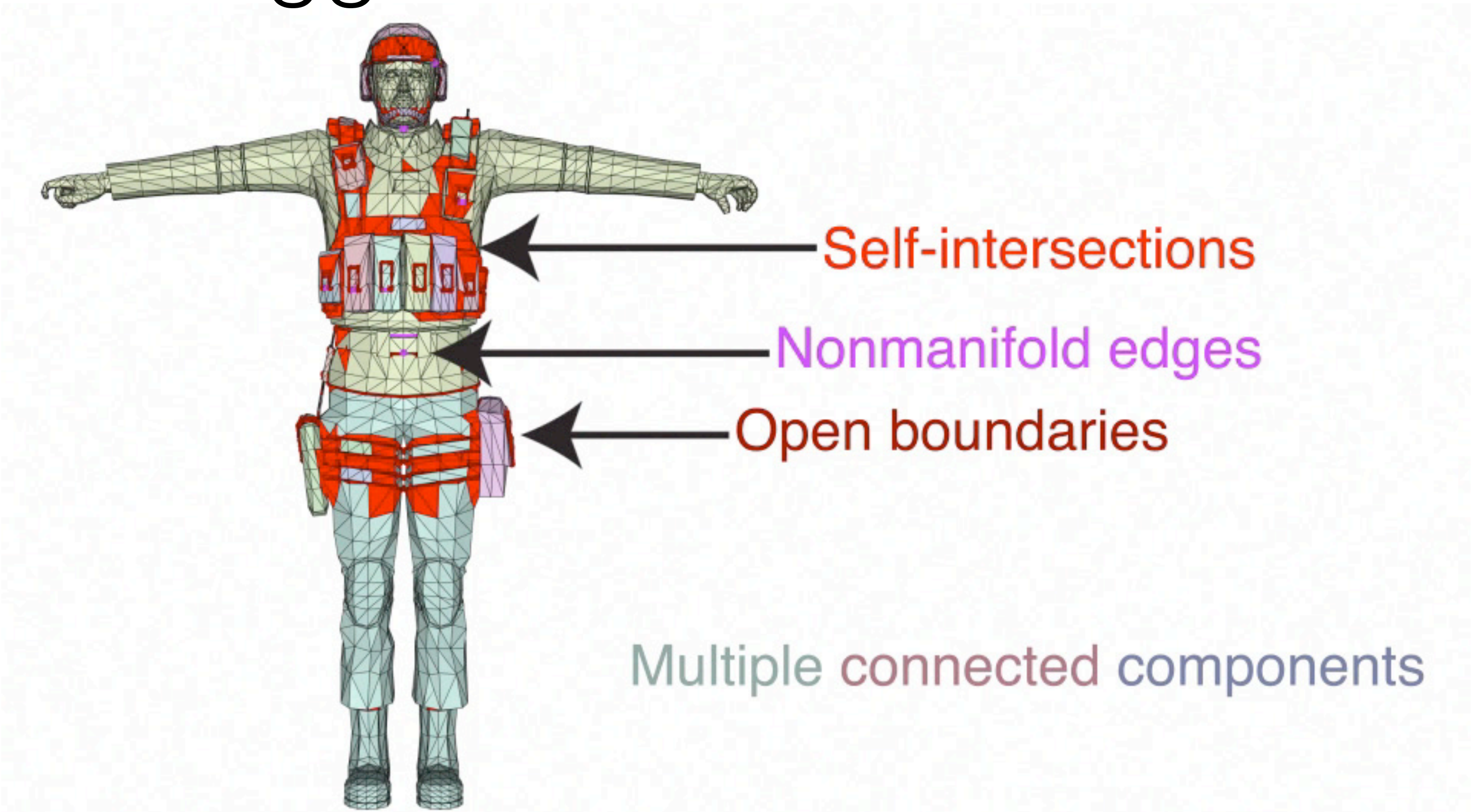


Left, middle: smoothness energy

Right: [Kavan & Sorkine 2012]

FEM struggles with meshes *in the wild*



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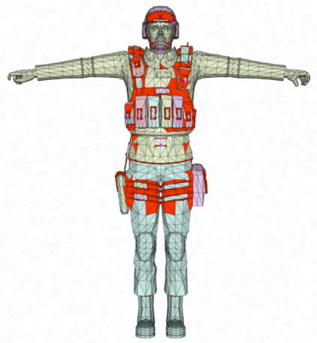
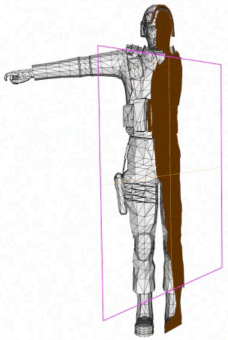


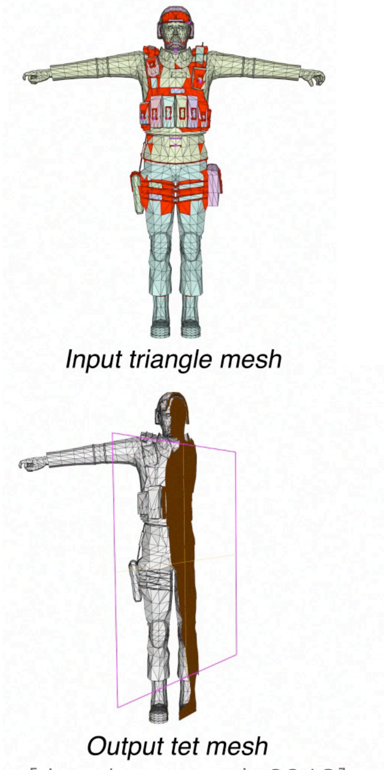
Input triangle mesh



Output tet mesh

[Jacobson et al. 2013]

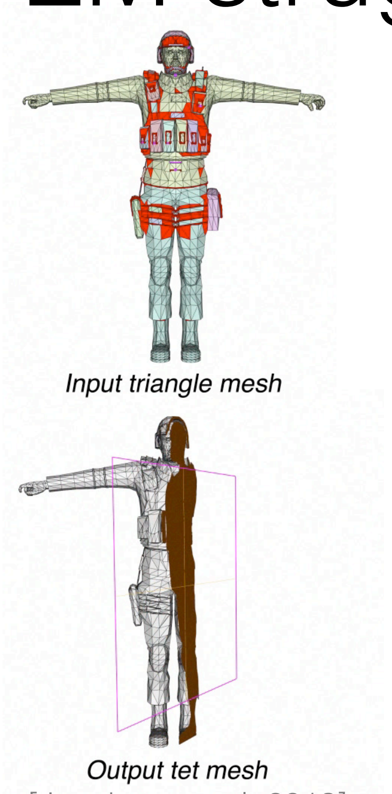
FEM struggles with meshes *in the wild*



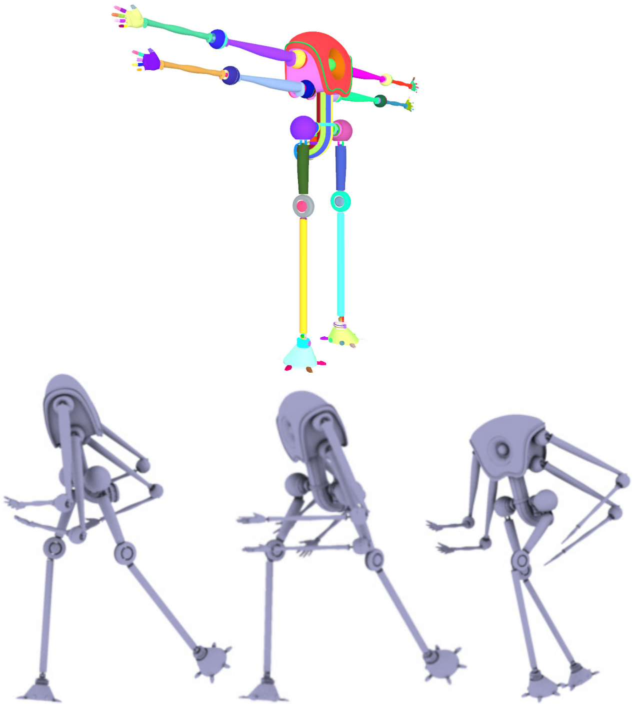
[Jacobson et al. 2013]

[Dionne & de Lasa 2013]

FEM struggles with meshes *in the wild*



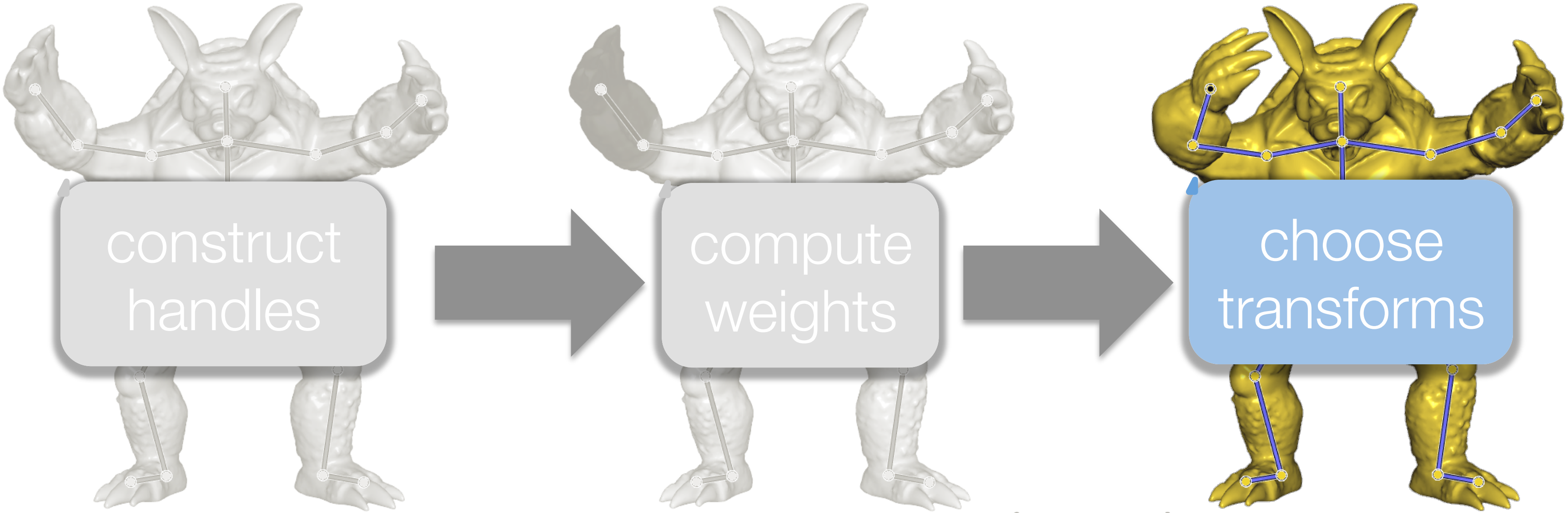
[Jacobson et al. 2013]



[Bharaj et al. 2012]

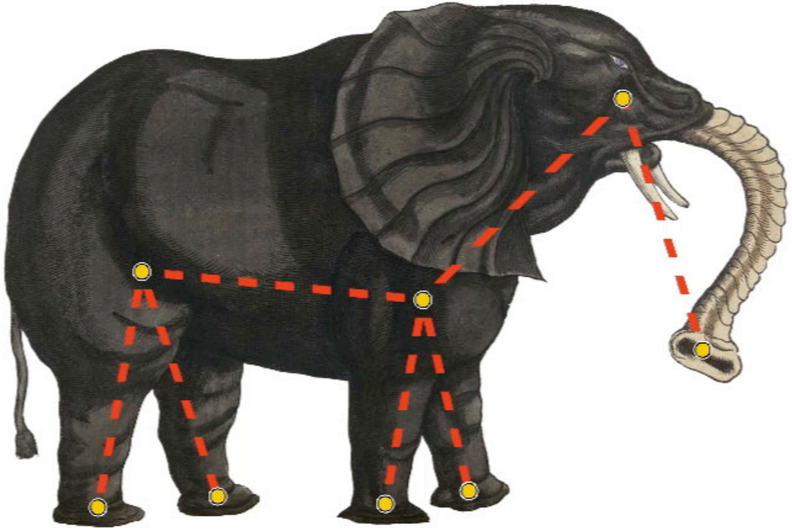
[Dionne & de Lasa 2013]

Recent research automates each step

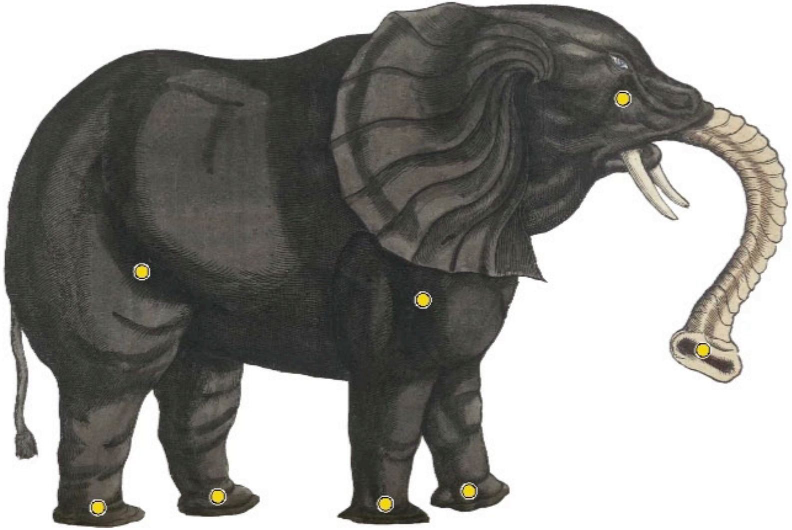


$$\mathbf{v}' = \sum_{j \in H} w_j(\mathbf{v}) \mathbf{T}_j \begin{pmatrix} \mathbf{v} \\ 1 \end{pmatrix}$$

Good weights are not enough

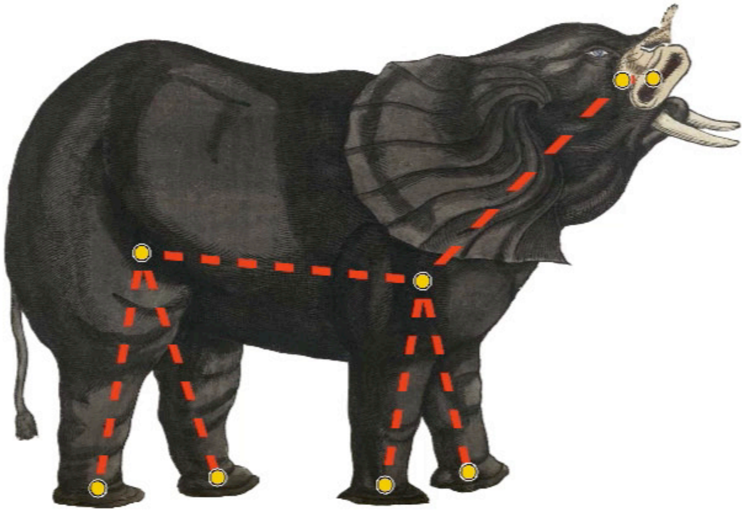


Rotation chosen ignorant of shape's deformation
[Jacobson et al. 2011], cf. traditional IK



Rotation *optimized* for best deformation
[Jacobson et al. 2011]

Good weights are not enough



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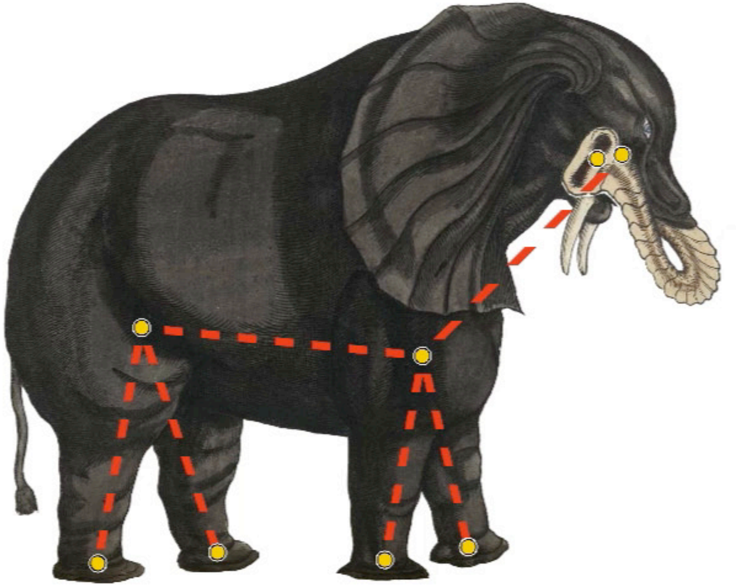
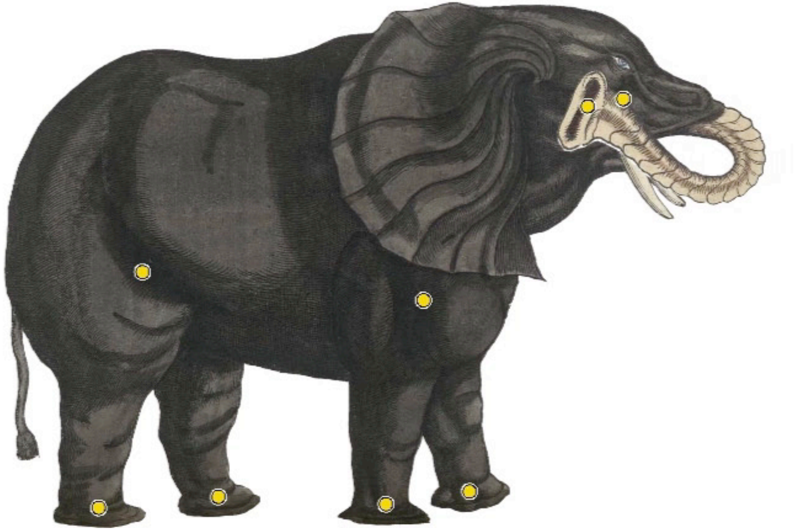
[Jacobson et al. 2011]

Good weights are not enough

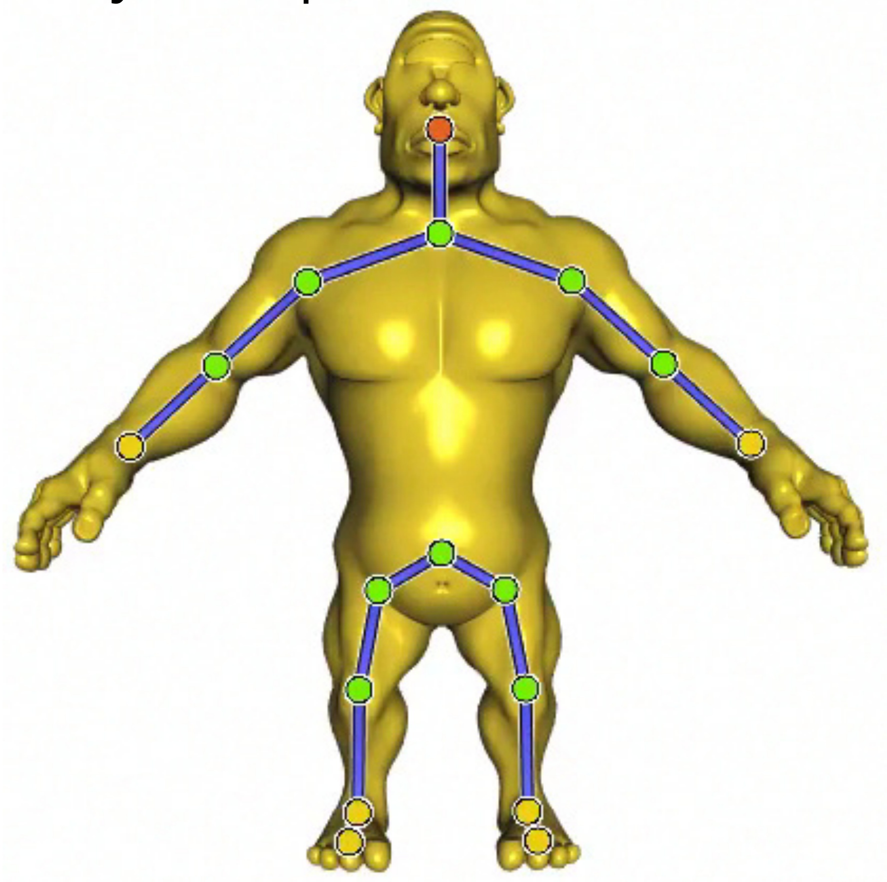


Rotation chosen ignorant of shape's deformation
[Jacobson et al. 2011], cf. traditional IK

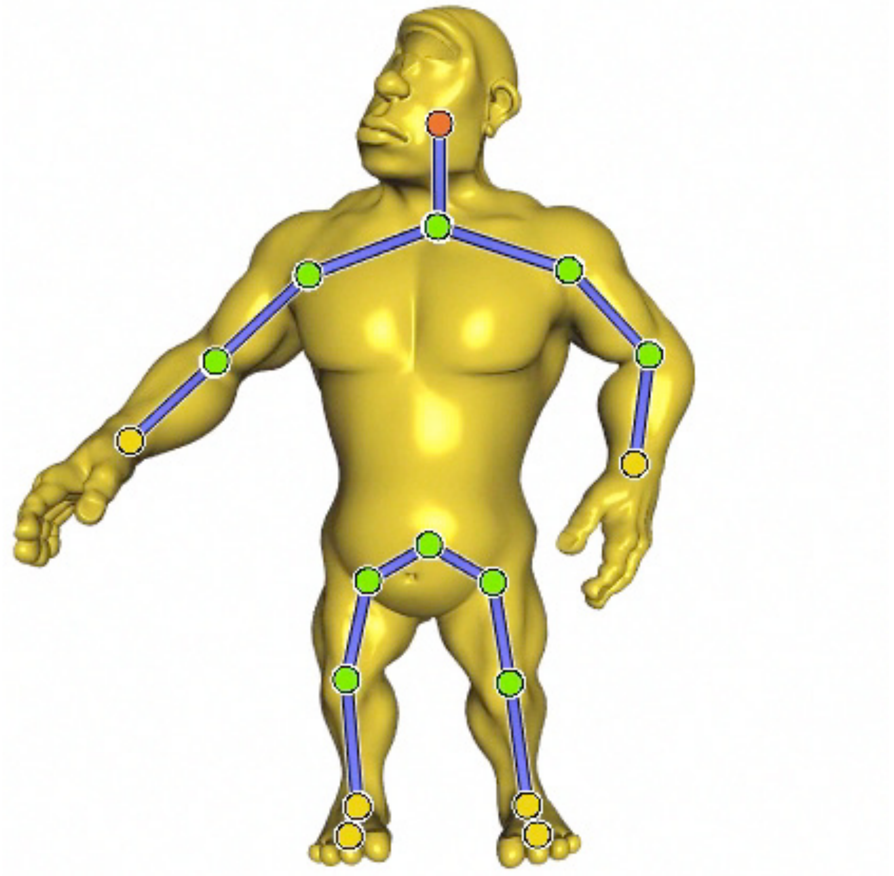


Rotation *optimized* for best deformation
[Jacobson et al. 2011]

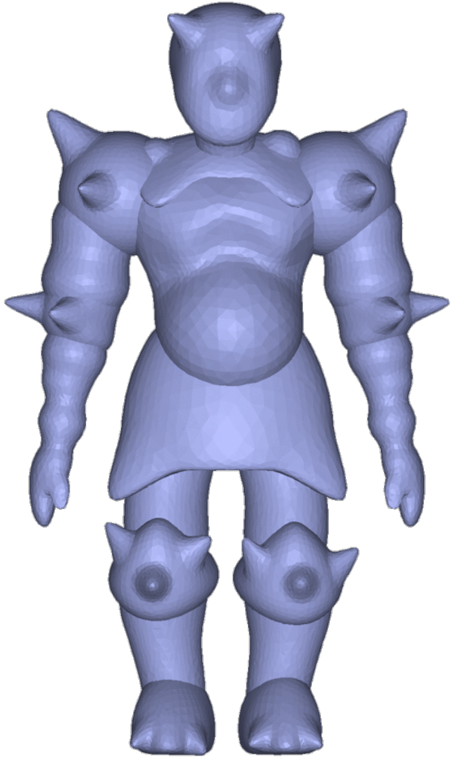
Shape-aware IK finds *best* transformations as measured by shape's deformation



Shape-aware IK finds *best* transformations as measured by shape's deformation



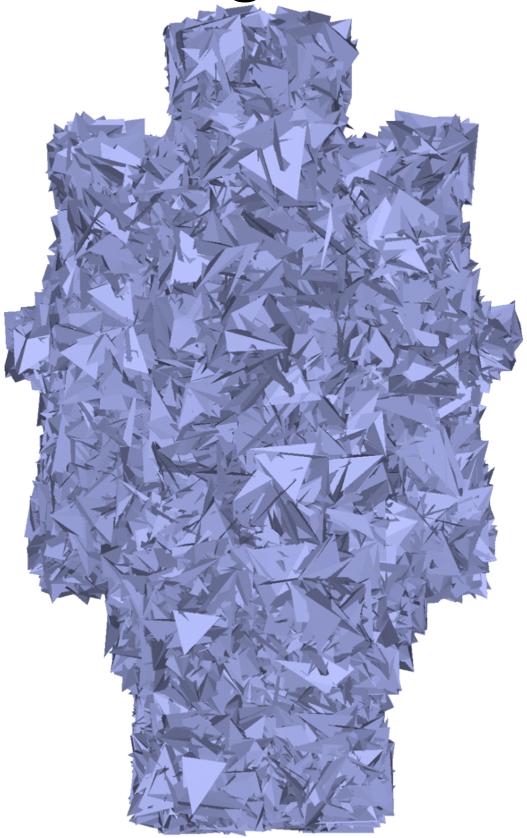
Skinning is a coherent **sub**space of deformation

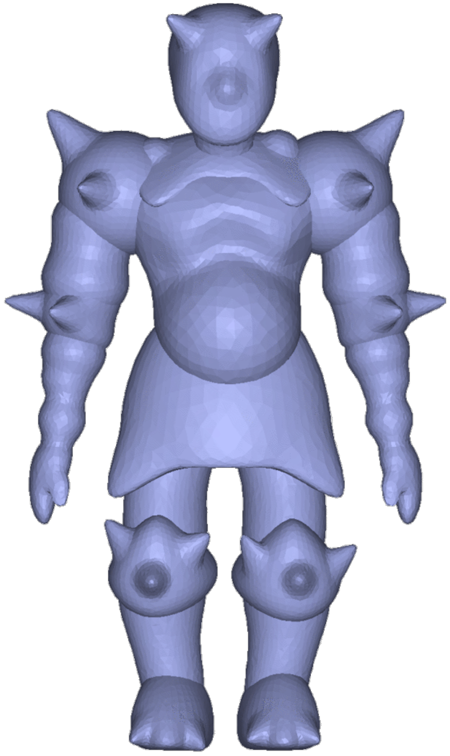


full space: #V x 3 DOFs

[traditional physics, modeling]

Skinning is a coherent **sub**space of deformation

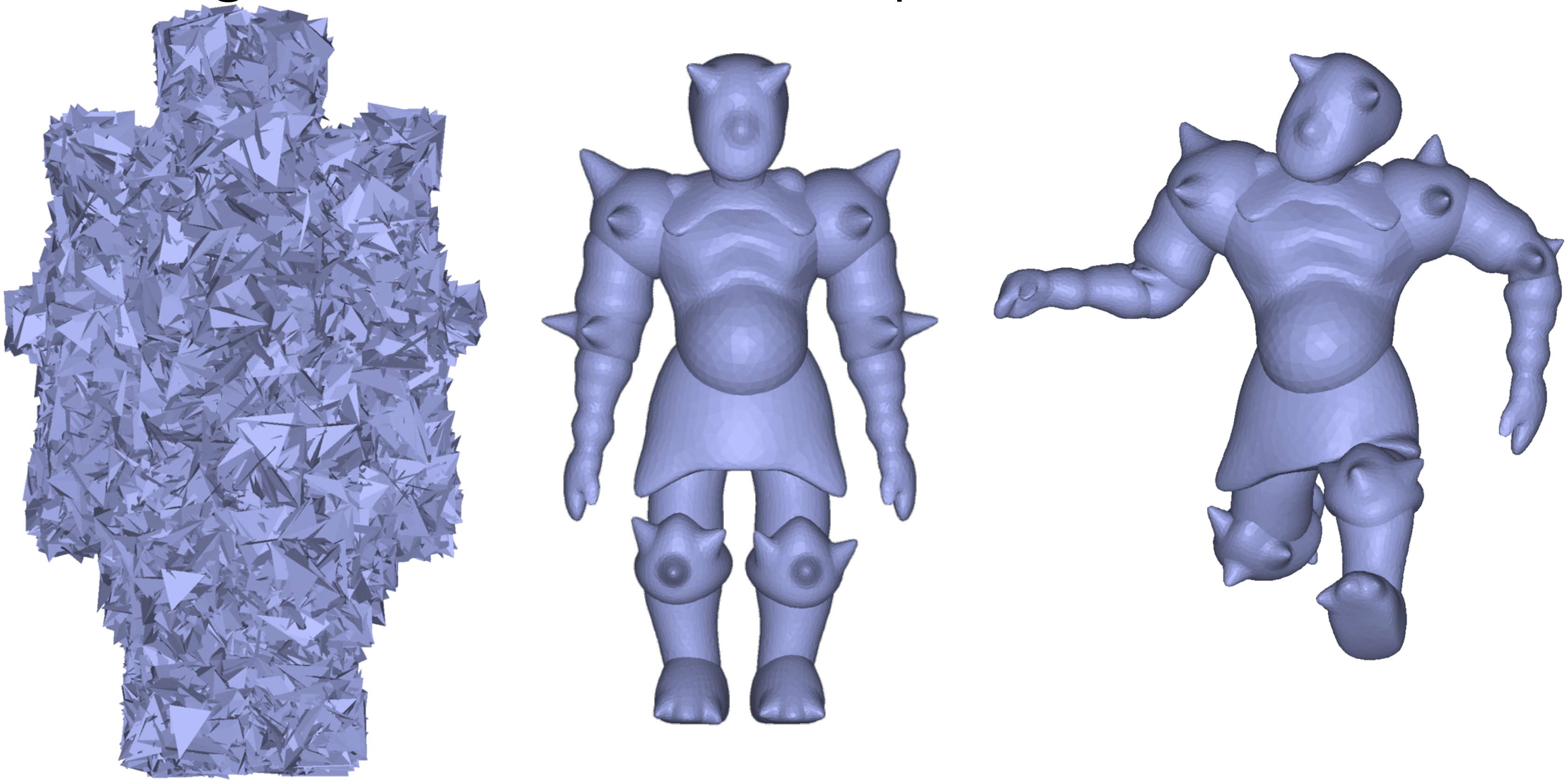




skinning space: #B x 12 DOFs

[Der et al. 2006, Huang et al. 2006, Au et al. 2007, Jacobson et al. 2012]

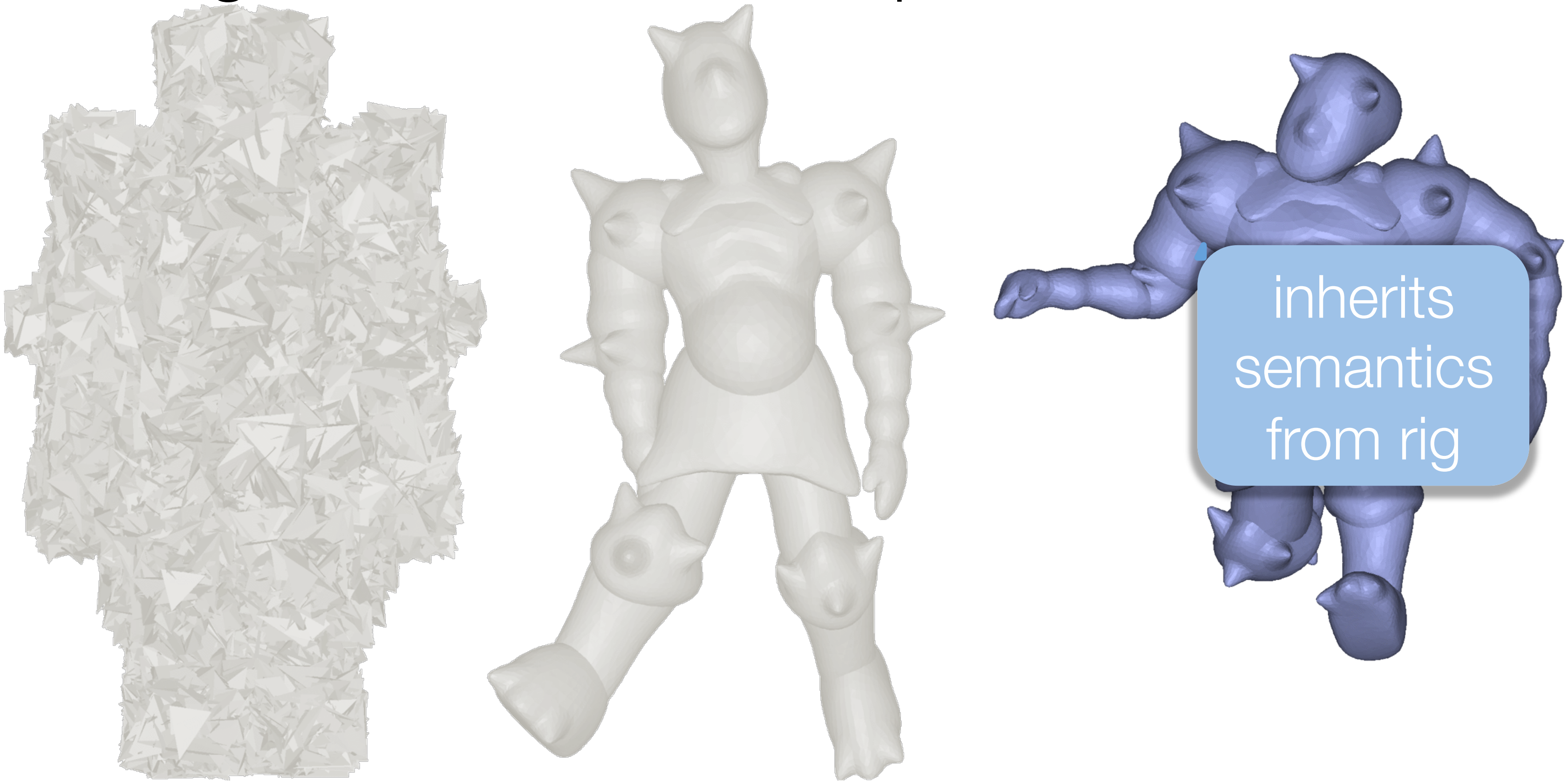
Skinning is a coherent **sub**space of deformation



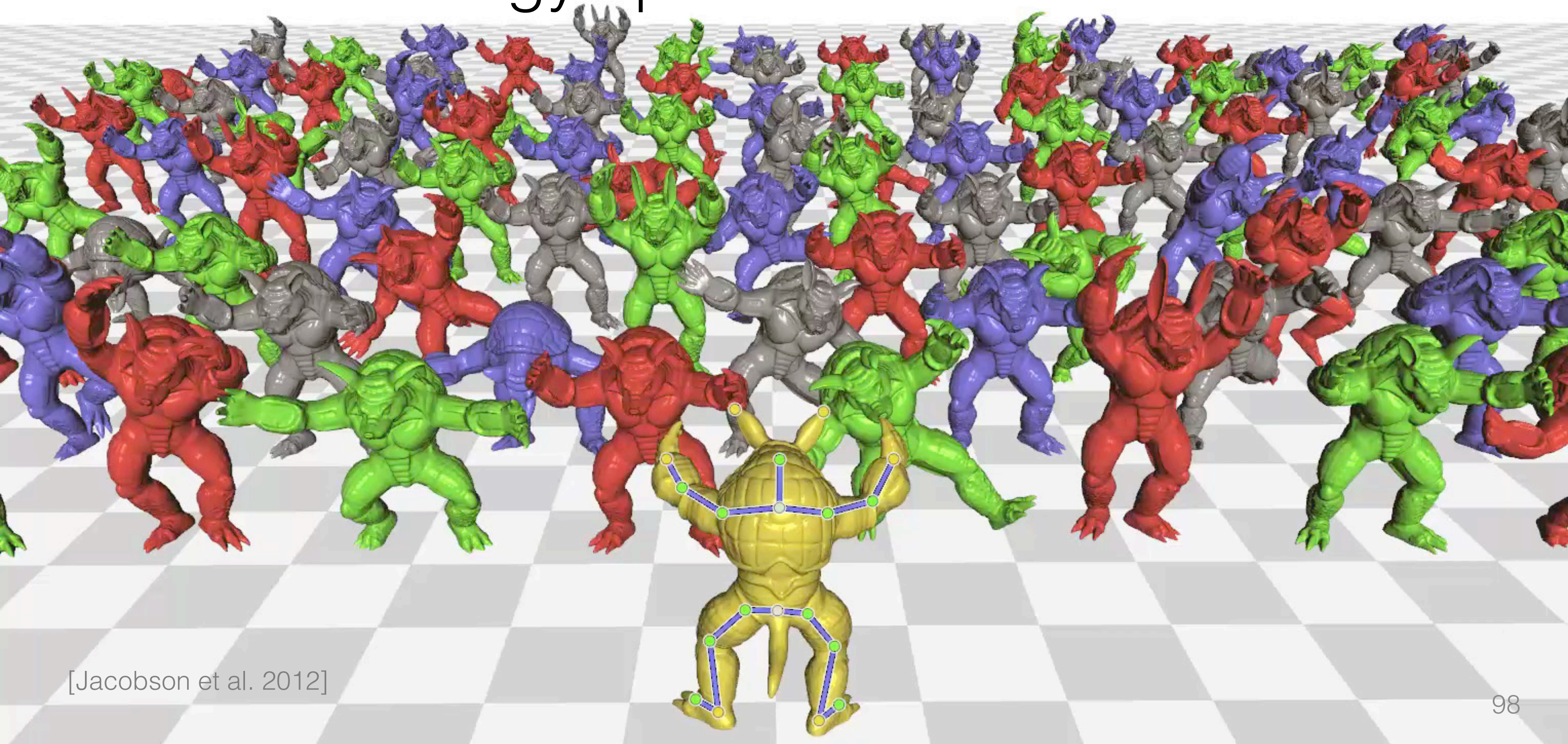
modal space: 50 linear modes

[Hildebrandt et al. 2011, Barbic et al. 2012]

Skinning is a coherent **sub**space of deformation

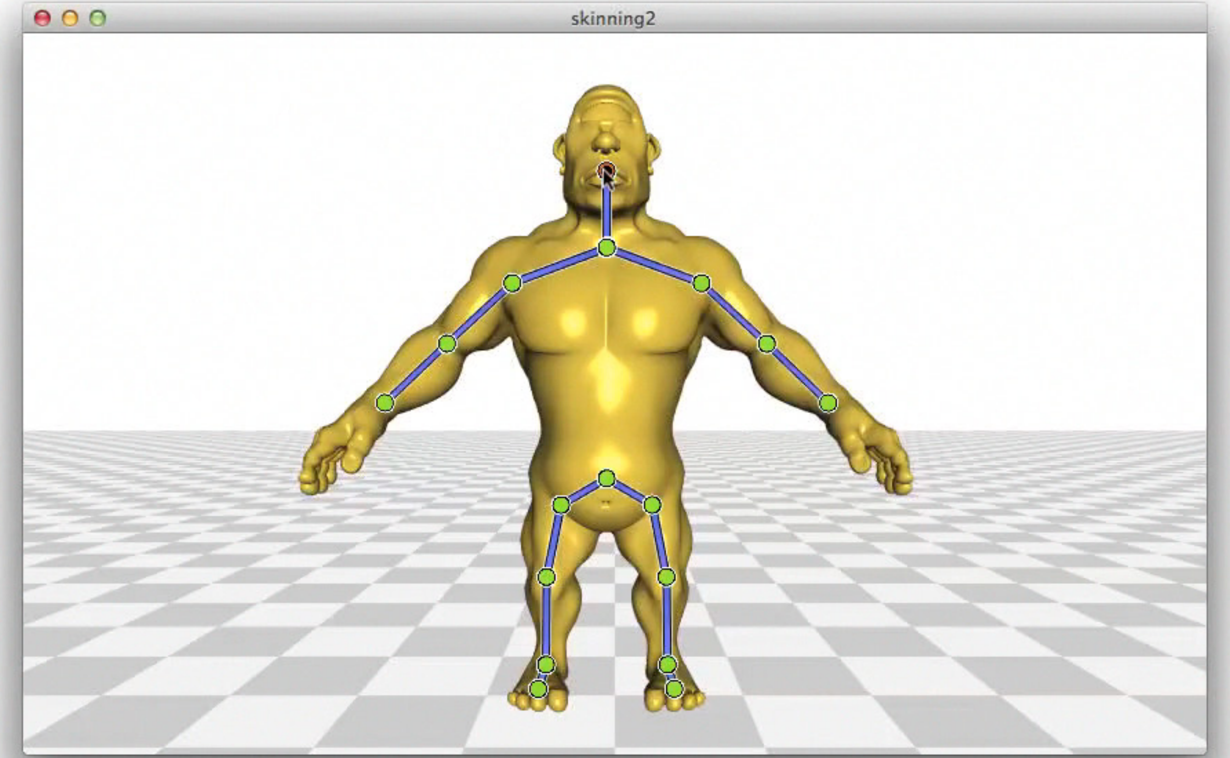


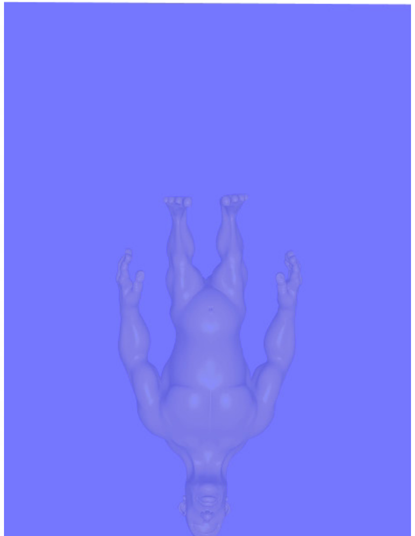
Regularity and parsimony allows *very fast* non-linear energy optimization at runtime



[Jacobson et al. 2012]

Same idea applies for real-time physically based dynamics



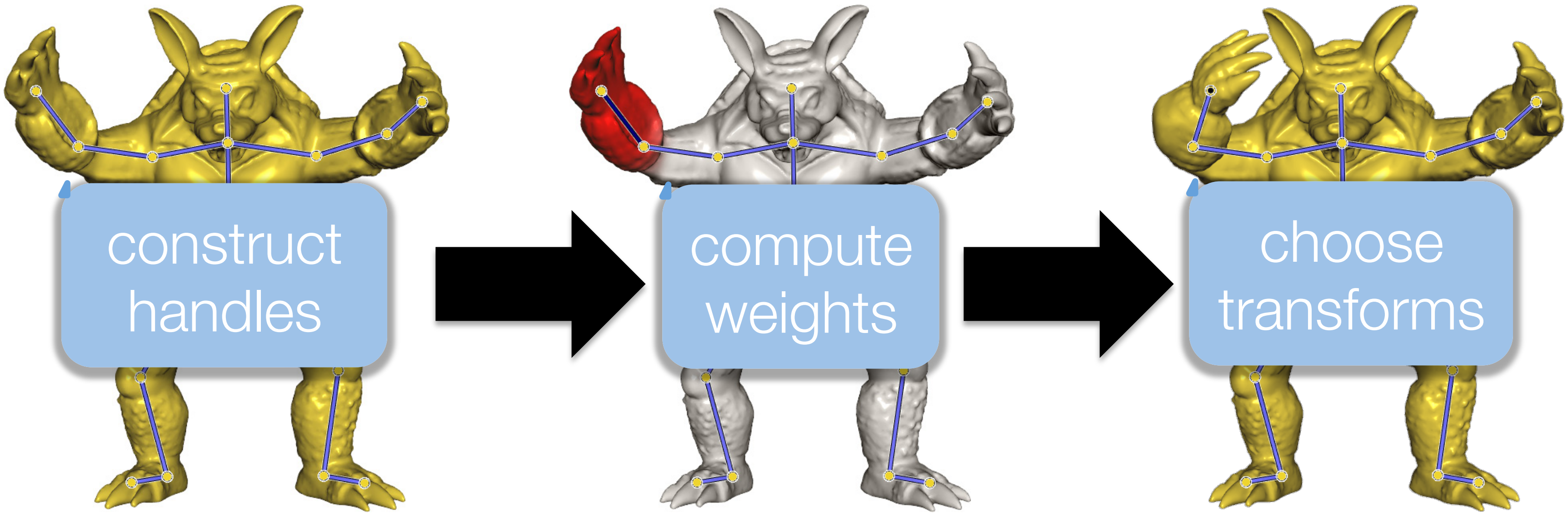


[Faure et al. 2011, Jacobson 2013, Liu et al. 2013, Bouaziz et al. 2014]

Posing still requires more research

- Safe contacts, collisions in real time
- Leverage amassed data: semantics
- Better virtual and physical interfaces

Recent research automates each step



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Automatic Skinning via Constrained Energy Optimization

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