Smooth Skinning Decomposition with Rigid Bones

Binh Huy Le and Zhigang Deng

UNIVERSITY of HOUSTON

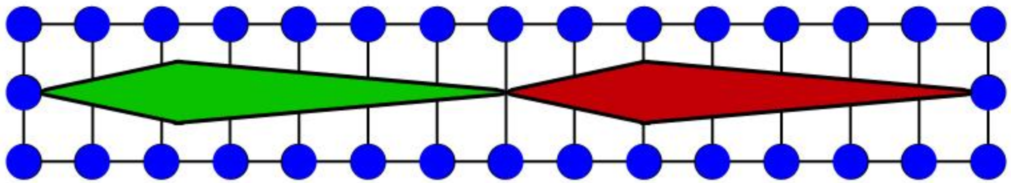
Sponsored by ACM SIGGRAPH

SIGGRAPH ASIA 2012

Motivation

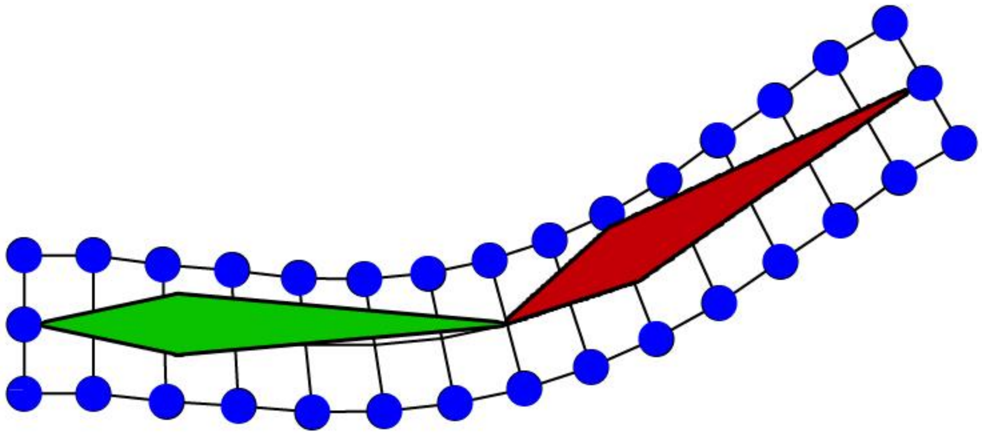
Linear Blend Skinning (LBS)

- A.k.a. skeleton subspace deformation, enveloping, vertex blending, smooth skinning, bones skinning, etc.



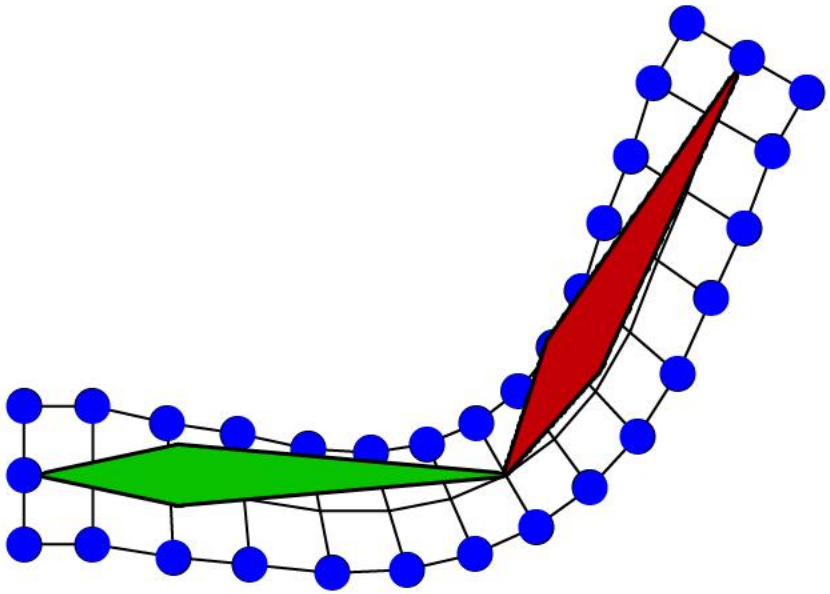
Linear Blend Skinning (LBS)

- A.k.a. skeleton subspace deformation, enveloping, vertex blending, smooth skinning, bones skinning, etc.



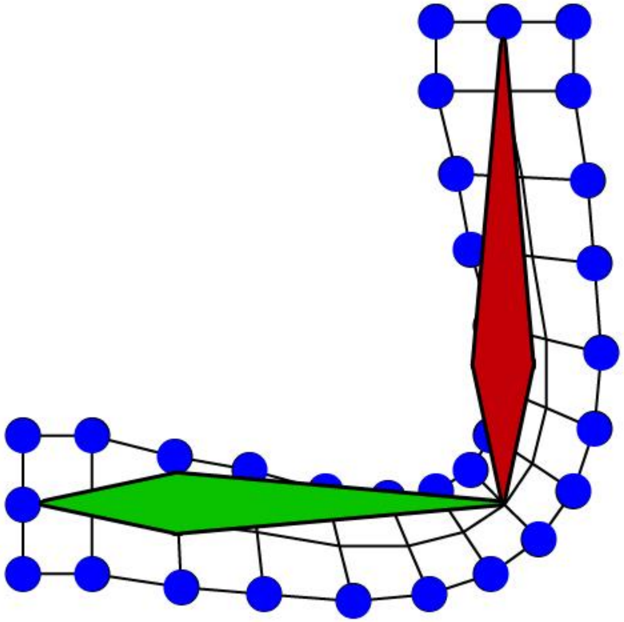
Linear Blend Skinning (LBS)

- A.k.a. skeleton subspace deformation, enveloping, vertex blending, smooth skinning, bones skinning, etc.



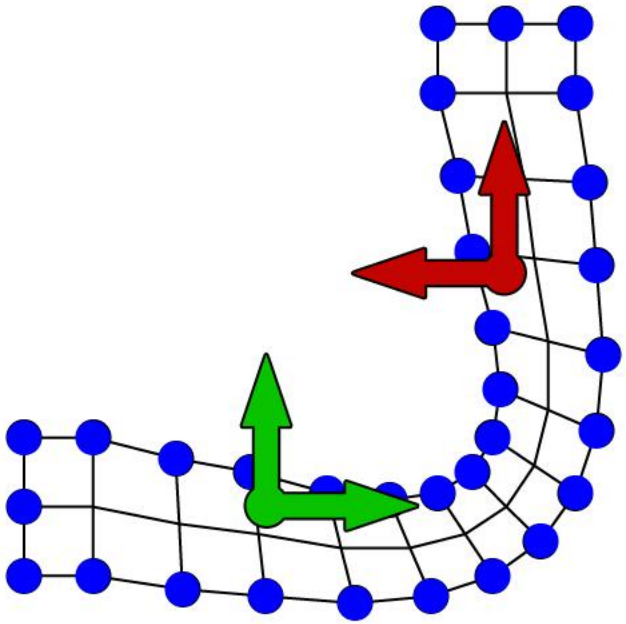
Linear Blend Skinning (LBS)

- A.k.a. skeleton subspace deformation, enveloping, vertex blending, smooth skinning, bones skinning, etc.



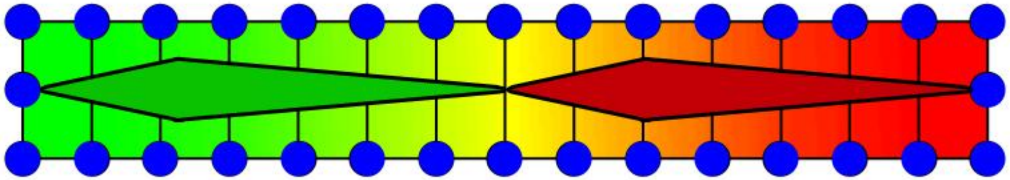
Linear Blend Skinning (LBS)

- A.k.a. skeleton subspace deformation, enveloping, vertex blending, smooth skinning, bones skinning, etc.



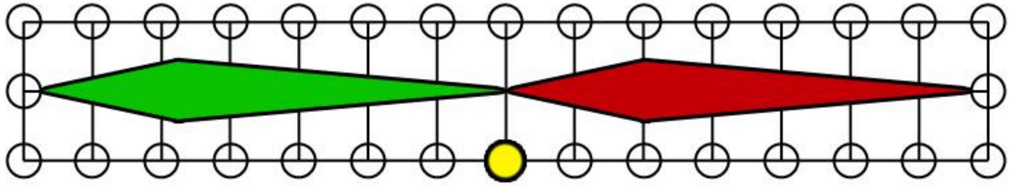
Linear Blend Skinning (LBS)

- A.k.a. skeleton subspace deformation, enveloping, vertex blending, smooth skinning, bones skinning, etc.



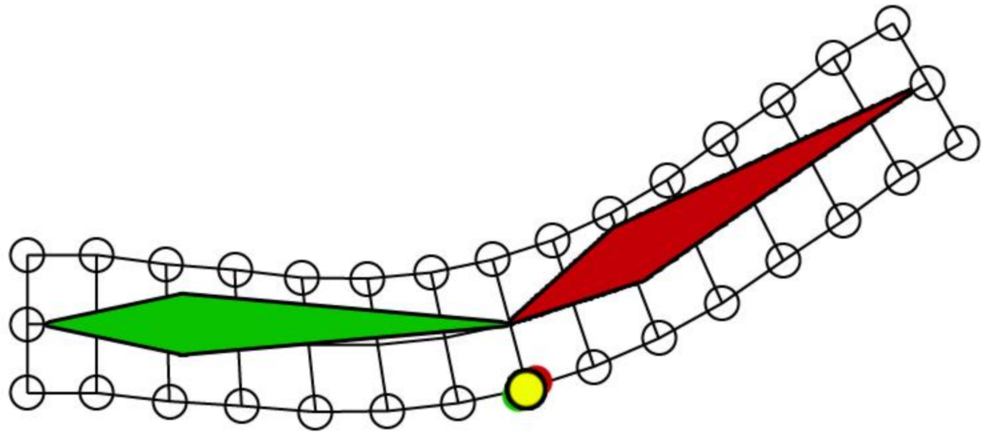
Linear Blend Skinning (LBS)

- A.k.a. skeleton subspace deformation, enveloping, vertex blending, smooth skinning, bones skinning, etc.



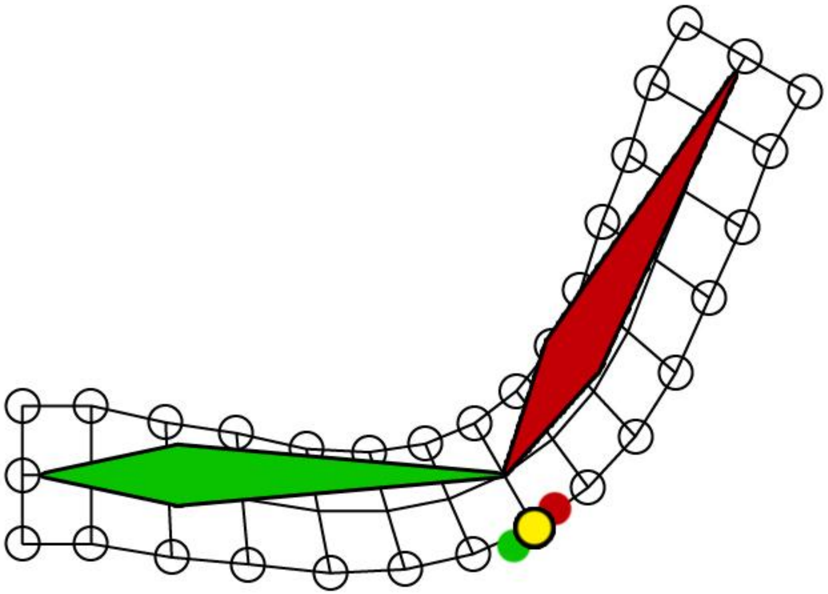
Linear Blend Skinning (LBS)

- A.k.a. skeleton subspace deformation, enveloping, vertex blending, smooth skinning, bones skinning, etc.



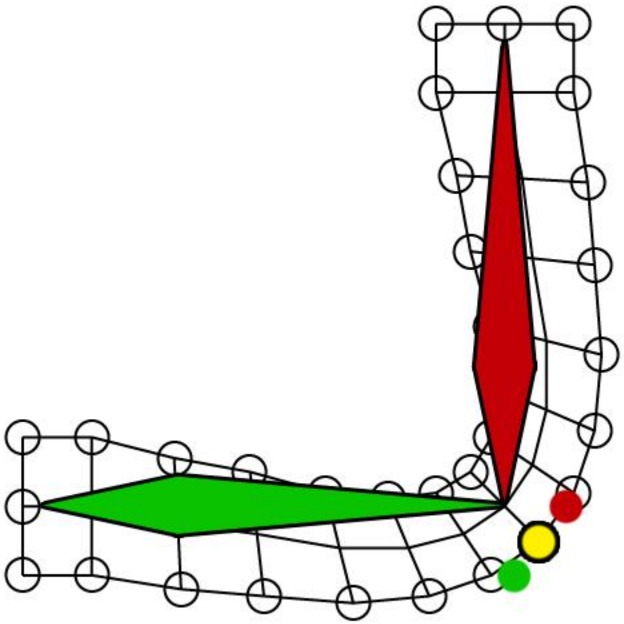
Linear Blend Skinning (LBS)

- A.k.a. skeleton subspace deformation, enveloping, vertex blending, smooth skinning, bones skinning, etc.



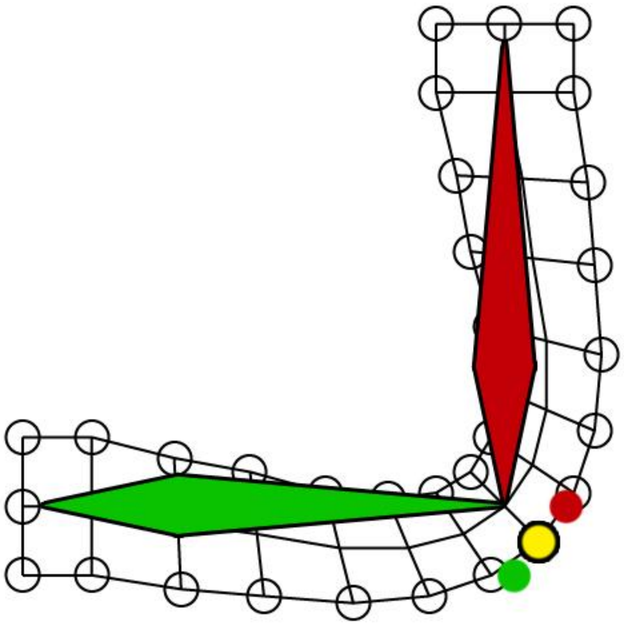
Linear Blend Skinning (LBS)

- A.k.a. skeleton subspace deformation, enveloping, vertex blending, smooth skinning, bones skinning, etc.



Linear Blend Skinning (LBS)

- A.k.a. skeleton subspace deformation, enveloping, vertex blending, smooth skinning, bones skinning, etc.



Number of bones

Rest pose

$$v_i = \sum_{j=1}^{|B|} w_{ij} (R_j p_i + T_j)$$

Weight

Bone rotation

Bone translation

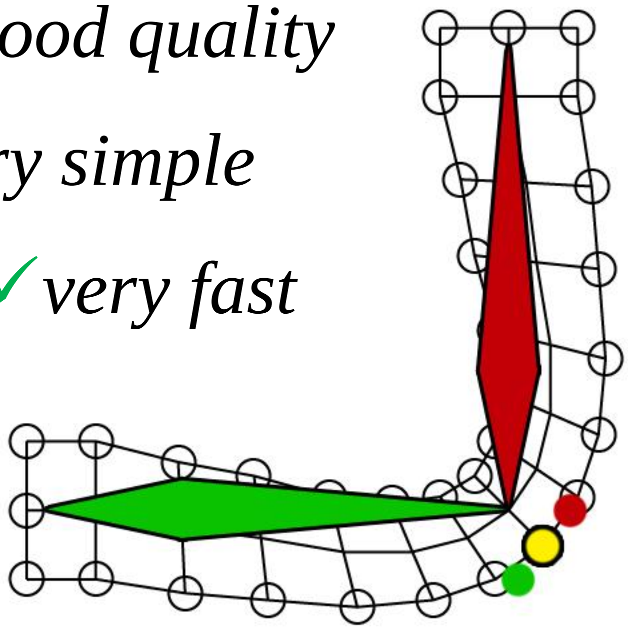
Linear Blend Skinning (LBS)

- A.k.a. skeleton subspace deformation, enveloping, vertex blending, smooth skinning, bones skinning, etc.

✓ *fairly good quality*

✓ *very simple*

✓ *very fast*



$$v_i = \sum_{j=1}^{|B|} w_{ij} (R_j p_i + T_j)$$

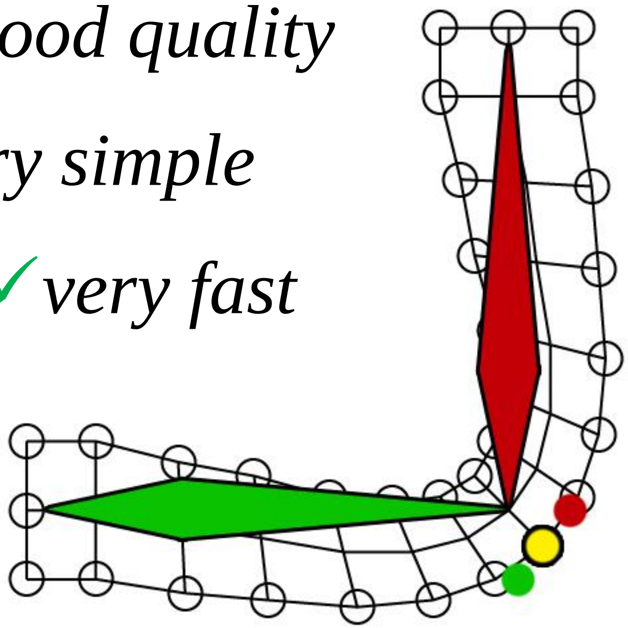
Linear Blend Skinning (LBS)

- A.k.a. skeleton subspace deformation, enveloping, vertex blending, smooth skinning, bones skinning, etc.

✓ *fairly good quality*

✓ *very simple*

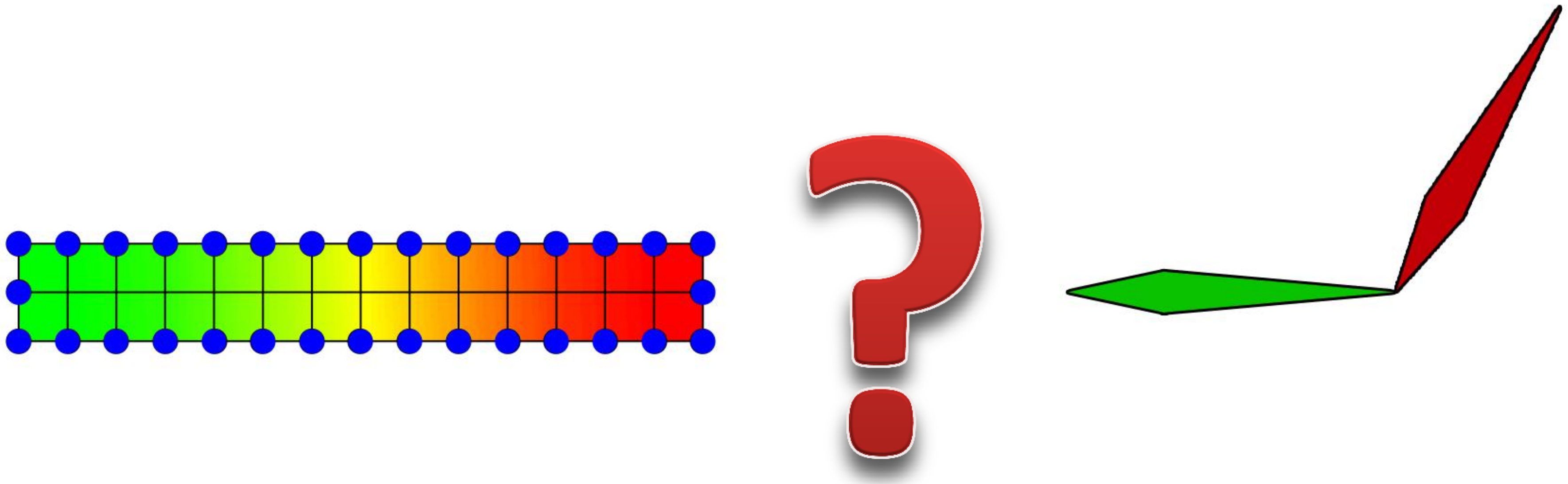
✓ *very fast*



$$v_i = \sum_{j=1}^{|B|} w_{ij} (R_j p_i + T_j)$$

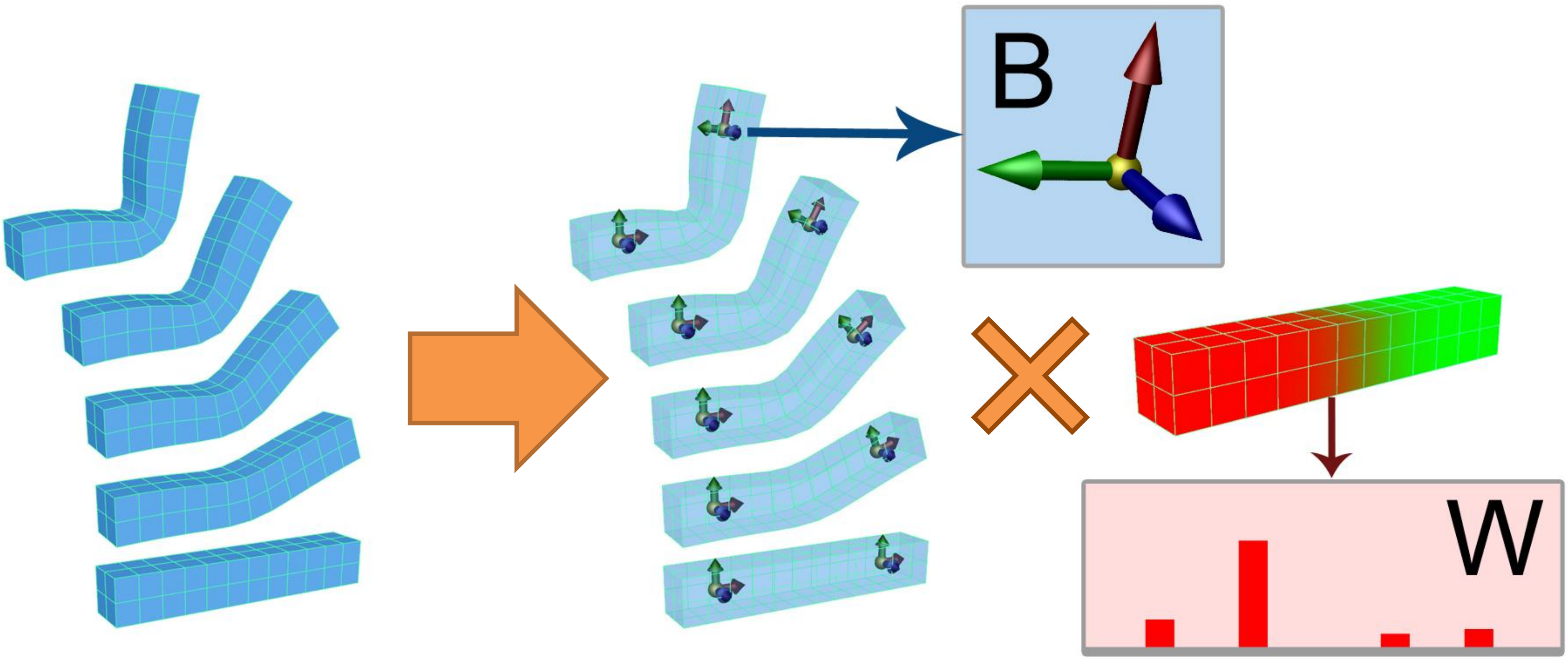
→ *most popular skinning model*

Linear Blend Skinning (LBS)

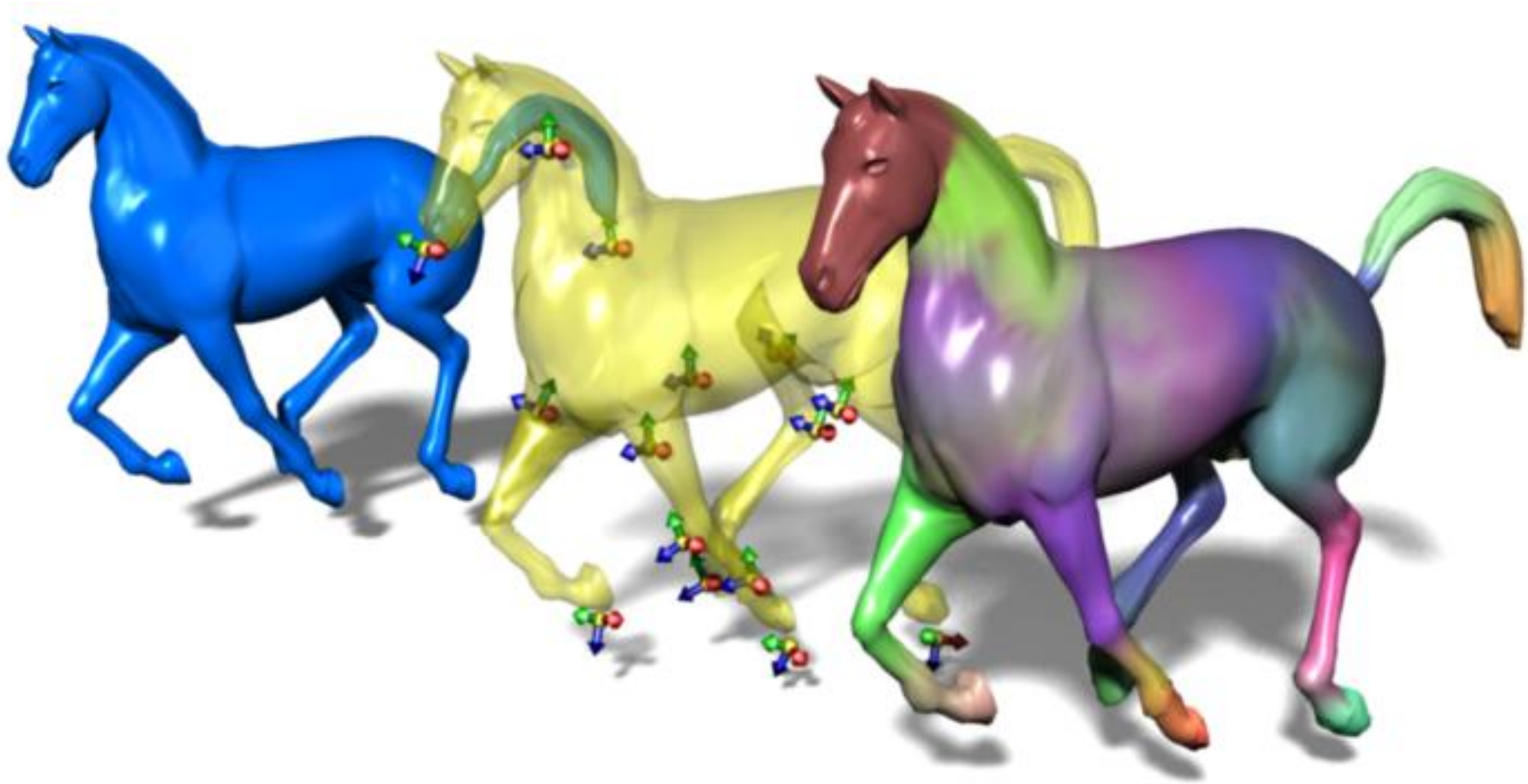


Skinning Decomposition

Skinning Decomposition

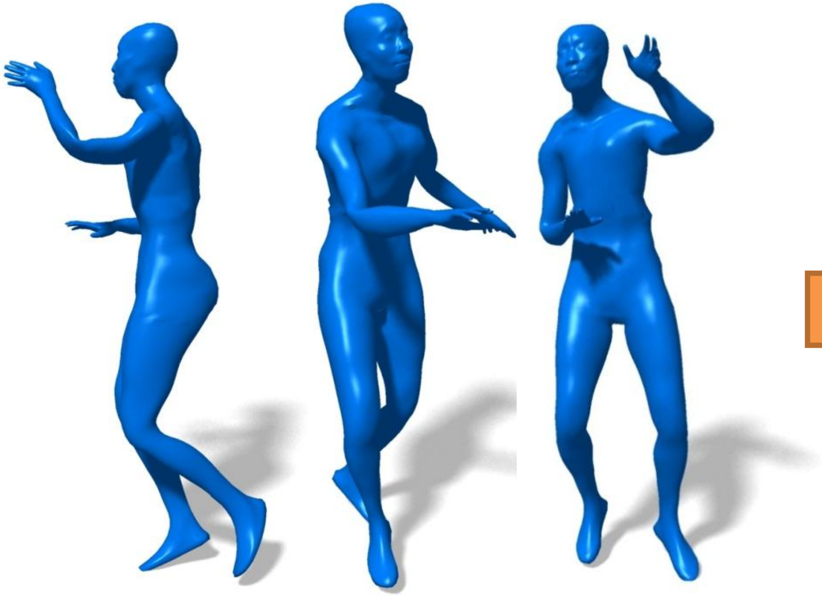


Skinning Decomposition



Applications

- Rigging, animation editing



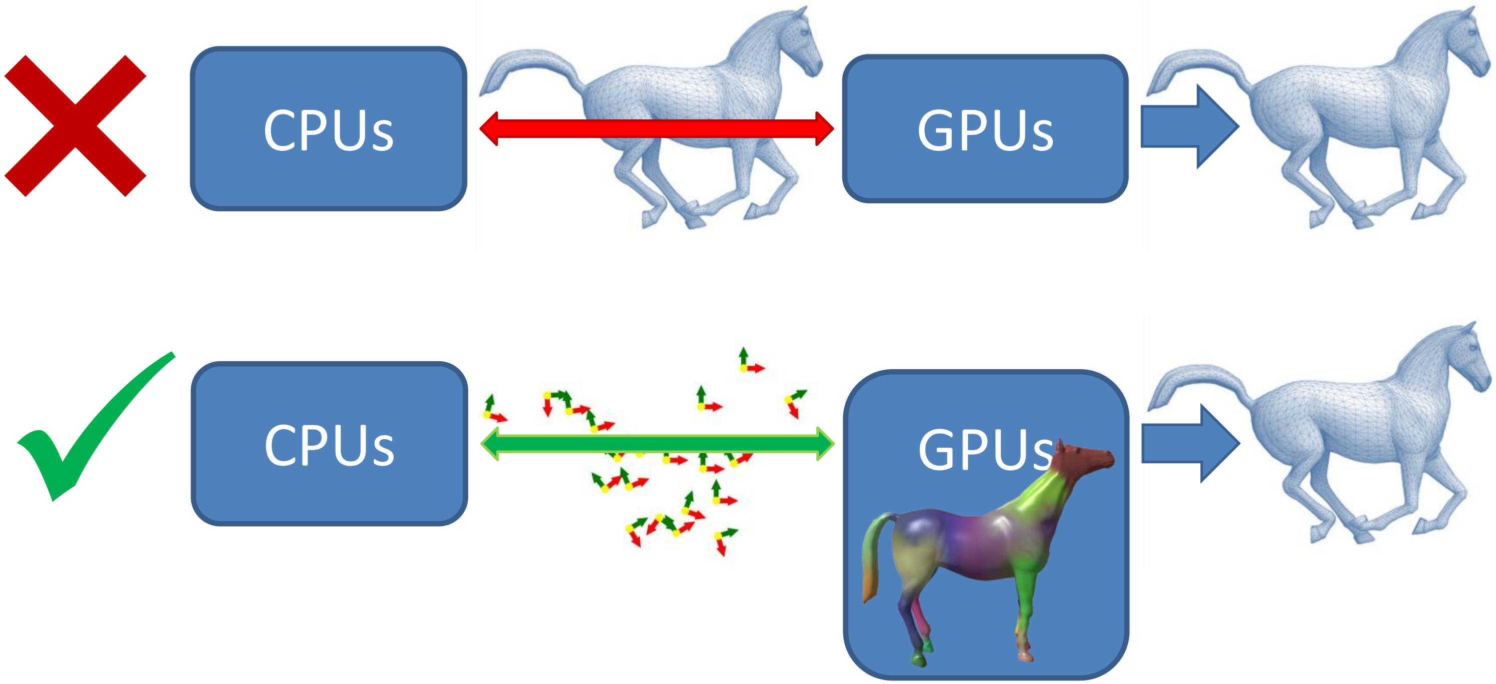
Performance capture seq.

Skinning Decomposition

Skeleton Extraction

Applications

- Rigging, animation editing
- Compression, hardware accelerated rendering



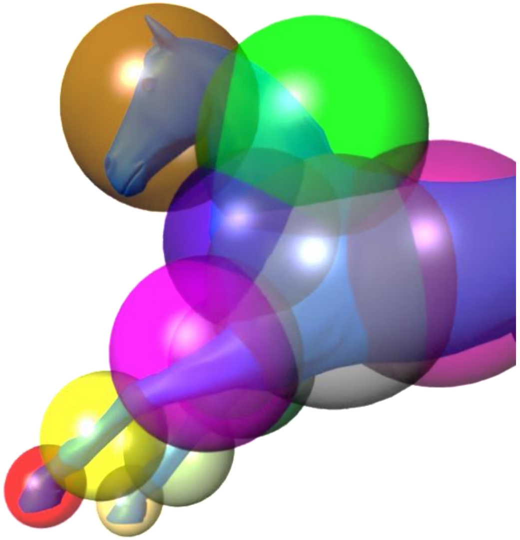
Applications

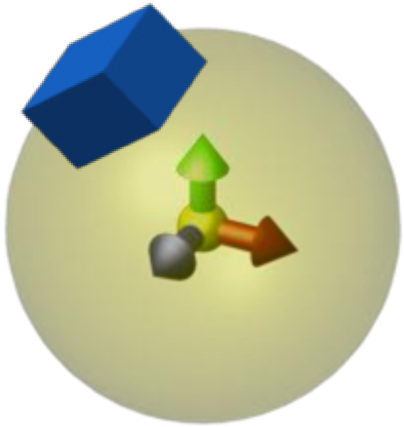
- Rigging, animation editing
- Compression, hardware accelerated rendering
- Segmentation, meshes simplification

Skinning Weights

Applications

- Rigging, animation editing
- Compression, hardware accelerated rendering
- Segmentation, meshes simplification
- Collision detection





Applications

- Rigging, animation editing
- Compression, hardware accelerated rendering
- Segmentation, meshes simplification
- Collision detection

Skinning Decomposition

Smooth Skinning Decomposition with Rigid Bones

Input: Example poses

Output: Linear Blend Skinning model

- Sparse, convex weights
- **Rigid bone transformations**
- No skeleton hierarchy

Smooth Skinning Decomposition with Rigid Bones

Input: Example poses

Output: Linear Blend Skinning model

- Sparse, convex weights
- **Rigid bone transformations**
- No skeleton hierarchy

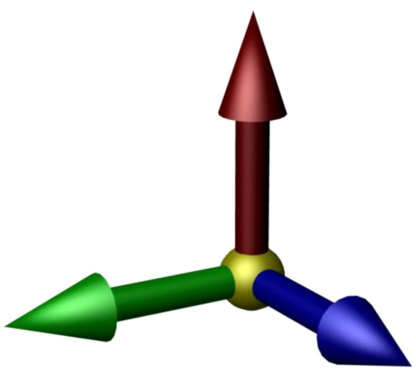
Goals:

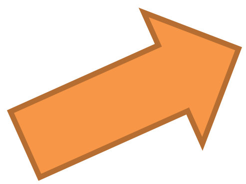
✓ Approximate highly deformation models

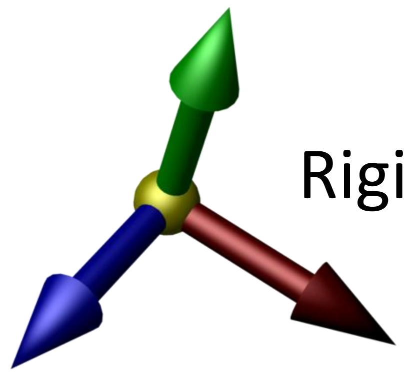
✓ Fast performance

✓ Simple implementation

Rigid Bones v.s. Flexible Bones







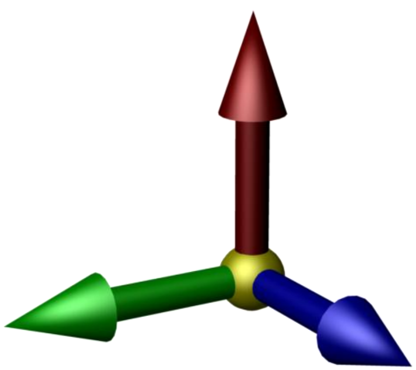
Rigid transformation
(orthogonal)

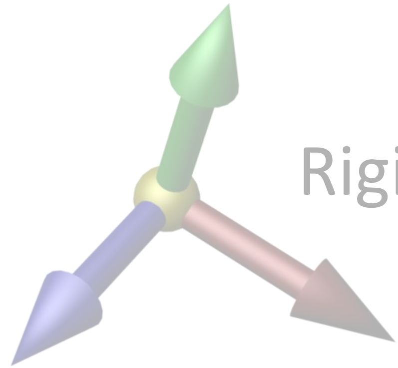
$$\begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$R^{\mathrm{T}}R = I, \det R = 1$$

Non-rigid transformation
(non-orthogonal)

Rigid Bones v.s. Flexible Bones

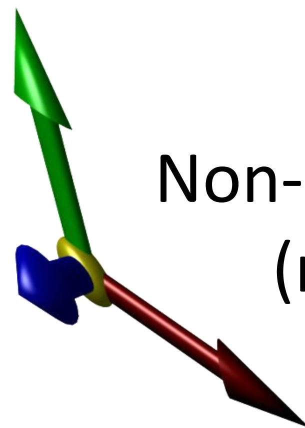




Rigid transformation
(orthogonal)

$$\begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

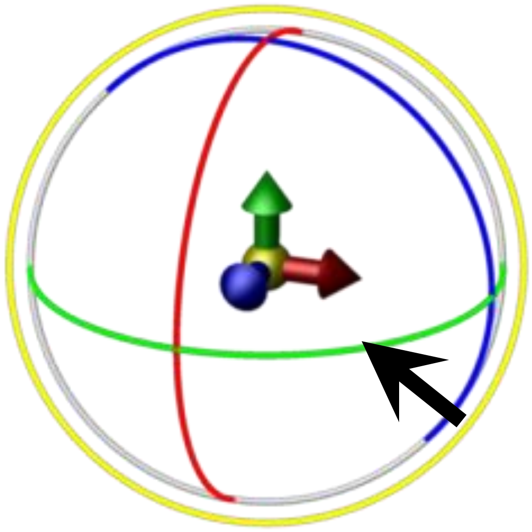
$R^{\mathrm{T}}R = I, \det R = 1$

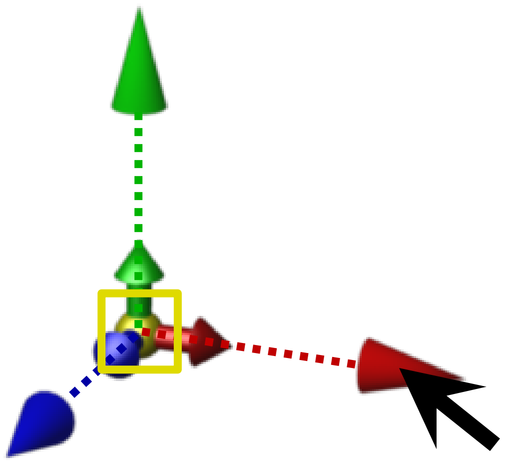


Non-rigid transformation
(non-orthogonal)

Benefits of Rigid Bones

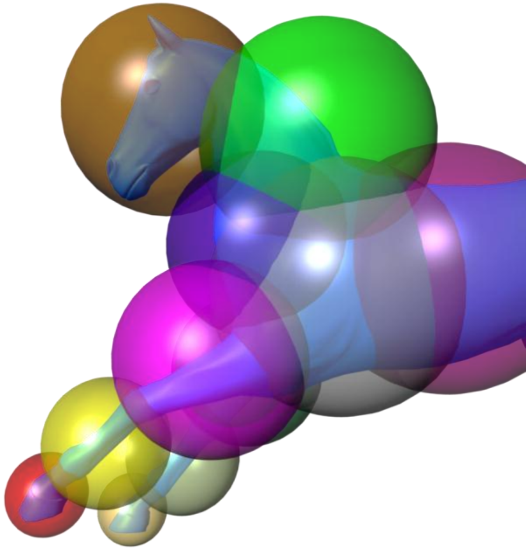
- ✓ Animation editing

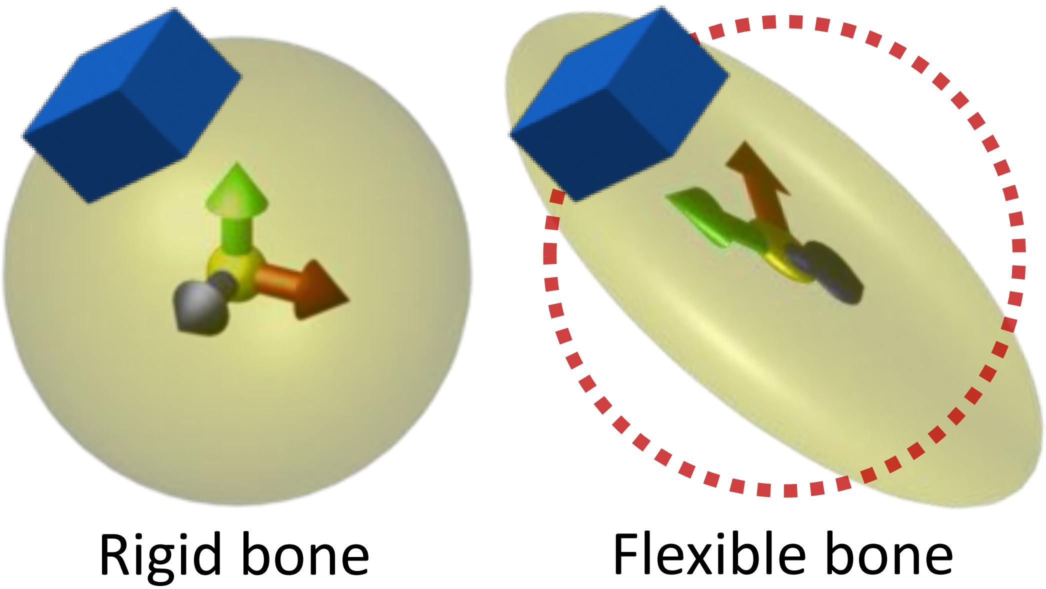




Benefits of Rigid Bones

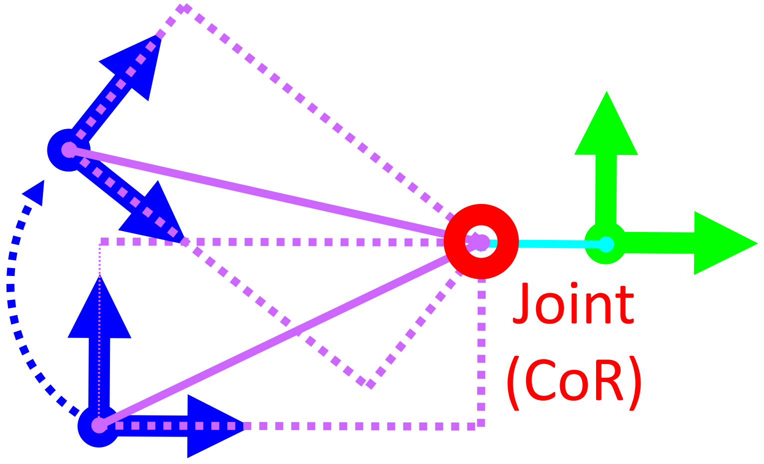
- ✓ Animation editing
- ✓ Collision detection



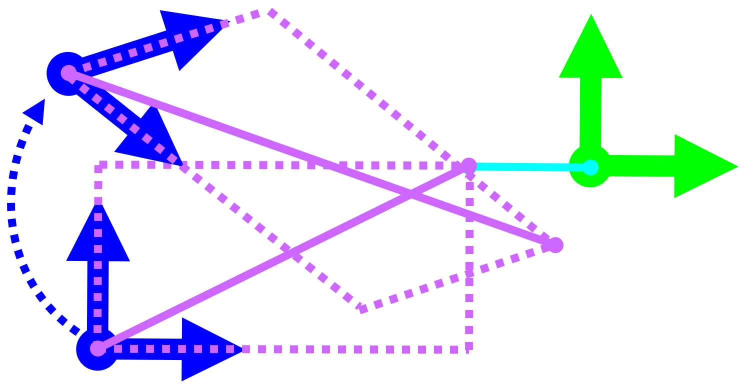


Benefits of Rigid Bones

- ✓ Animation editing
- ✓ Collision detection
- ✓ Skeleton extraction



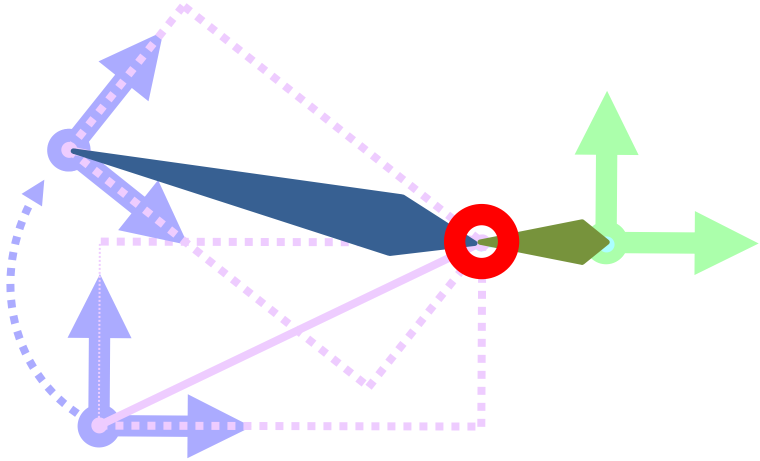
Rigid bones



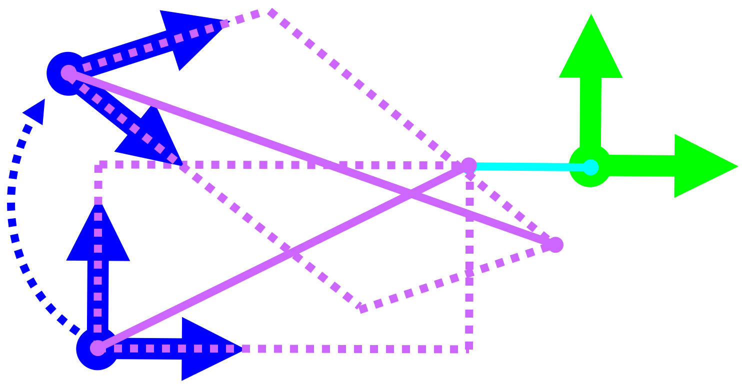
Flexible bones

Benefits of Rigid Bones

- ✓ Animation editing
- ✓ Collision detection
- ✓ Skeleton extraction



Rigid bones



Flexible bones

Benefits of Rigid Bones

- ✓ Animation editing
- ✓ Collision detection
- ✓ Skeleton extraction
- ✓ Compact representation

$$(r_1, r_2, r_3, t_1, t_2, t_3) \quad \text{v.s.} \quad \begin{bmatrix} r_{11} & r_{12} & r_{13} & t_1 \\ r_{21} & r_{22} & r_{23} & t_2 \\ r_{31} & r_{32} & r_{33} & t_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Rigid bone
6 DOFs

Flexible bone
12 DOFs

Benefits of Rigid Bones

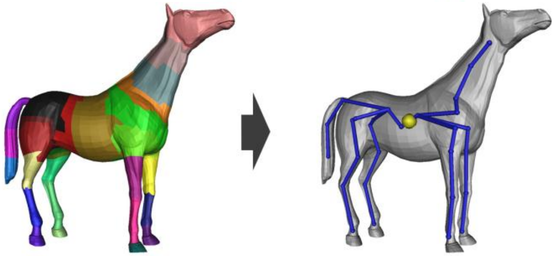
- ✓ Animation editing
- ✓ Collision detection
- ✓ Skeleton extraction
- ✓ Compact representation

Rigid Bones

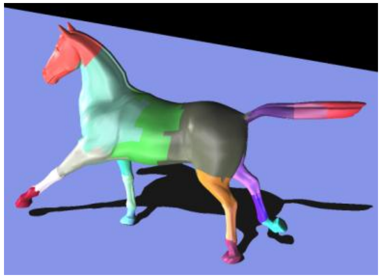
Previous Work

- Cluster triangles with similar deformations to get bones, then optimize skinning weights
  - Skinning Mesh Animations [James and Twigg 2005]

  - Example-Based Skeleton Extraction [Schaefer and Yuksel 2007]



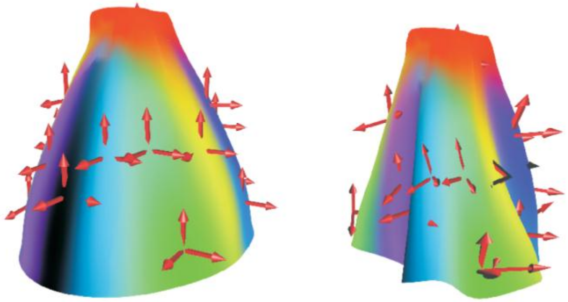
  - Automatic Conversion of Mesh Animations into Skeleton-based Animations [de Aguiar et al. 2008]



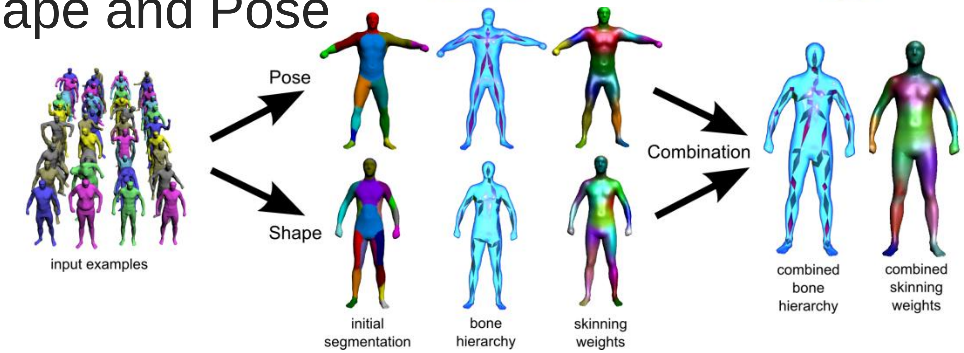
✗ Not consider skin blending, only good for nearly articulated models

Previous Work

- Joint optimize bone transformations and skinning weights
  - Fast and Efficient Skinning of Animated Meshes [Kavan et al. 2010]
    - ✓ Linear solvers
    - ✗ Flexible bones



  - Learning Skeletons for Shape and Pose [Hasler et al. 2010]
    - ✓ Rigid bones
    - ✗ Non linear solver



✓ Good approximation of highly deformable models

! Non-convex optimization, possibly with non-linear constraints

Smooth Skinning Decomposition with Rigid Bones

[Le and Deng 2012]

✓ Rigid bones
✓ Highly deformable models
✓ Linear solvers

Problem Formulation

$$\min_{w,R,T} E = \min_{w,R,T} \sum_{t=1}^{|t|} \sum_{i=1}^{|V|} \left\| v_i^t - \sum_{j=1}^{|B|} w_{ij} (R_j^t p_i + T_j^t) \right\|^2$$

Approximation Error

Subject to: $w_{ij} \geq 0, \forall i, j$

$$\sum_{j=1}^{|B|} w_{ij} = 1, \forall i$$

$$|\{w_{ij} | w_{ij} \neq 0\}| \leq |K|, \forall i$$

$${R_j^t}^{\top} R_j^t = I, \det R_j^t = 1, \forall t, j$$

Problem Formulation

$$\min_{w,R,T} E = \min_{w,R,T} \sum_{t=1}^{|t|} \sum_{i=1}^{|V|} \left\| v_i^t - \sum_{j=1}^{|B|} w_{ij} (R_j^t p_i + T_j^t) \right\|^2$$

Subject to: $w_{ij} \geq 0, \forall i, j$

$$\sum_{j=1}^{|B|} w_{ij} = 1, \forall i$$

$$|\{w_{ij} | w_{ij} \neq 0\}| \leq |K|, \forall i$$

$${R_j^t}^\top R_j^t = I, \det R_j^t = 1, \forall t, j$$

Skinning Weights

Problem Formulation

$$\min_{w,R,T} E = \min_{w,R,T} \sum_{t=1}^{|t|} \sum_{i=1}^{|V|} \left\| v_i^t - \sum_{j=1}^{|B|} w_{ij} \left(\boxed{R_j^t} p_i + \boxed{T_j^t} \right) \right\|^2$$

Bone Transformations

Subject to: $w_{ij} \geq 0, \forall i, j$

$$\sum_{j=1}^{|B|} w_{ij} = 1, \forall i$$

$$|\{w_{ij} | w_{ij} \neq 0\}| \leq |K|, \forall i$$

$${R_j^t}^\top R_j^t = I, \det R_j^t = 1, \forall t, j$$

Problem Formulation

$$\min_{w,R,T} E = \min_{w,R,T} \sum_{t=1}^{|t|} \sum_{i=1}^{|V|} \left\| v_i^t - \sum_{j=1}^{|B|} w_{ij} (R_j^t p_i + T_j^t) \right\|^2$$

Subject to: $w_{ij} \geq 0, \forall i, j$ → Non-negativity

$$\sum_{j=1}^{|B|} w_{ij} = 1, \forall i$$ → Affinity

$$|\{w_{ij} | w_{ij} \neq 0\}| \leq |K|, \forall i$$ → Sparseness

$${R_j^t}^{\mathsf{T}} R_j^t = I, \det R_j^t = 1, \forall t, j$$

Problem Formulation

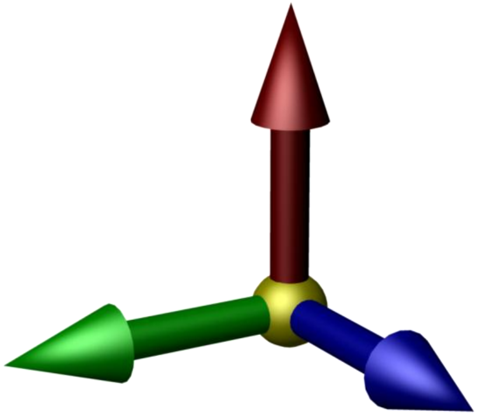
$$\min_{w,R,T} E = \min_{w,R,T} \sum_{t=1}^{|t|} \sum_{i=1}^{|V|} \left\| v_i^t - \sum_{j=1}^{|B|} w_{ij} (R_j^t p_i + T_j^t) \right\|^2$$

Subject to: $w_{ij} \geq 0, \forall i, j$

$$\sum_{j=1}^{|B|} w_{ij} = 1, \forall i$$

$$|\{w_{ij} | w_{ij} \neq 0\}| \leq |K|, \forall i$$

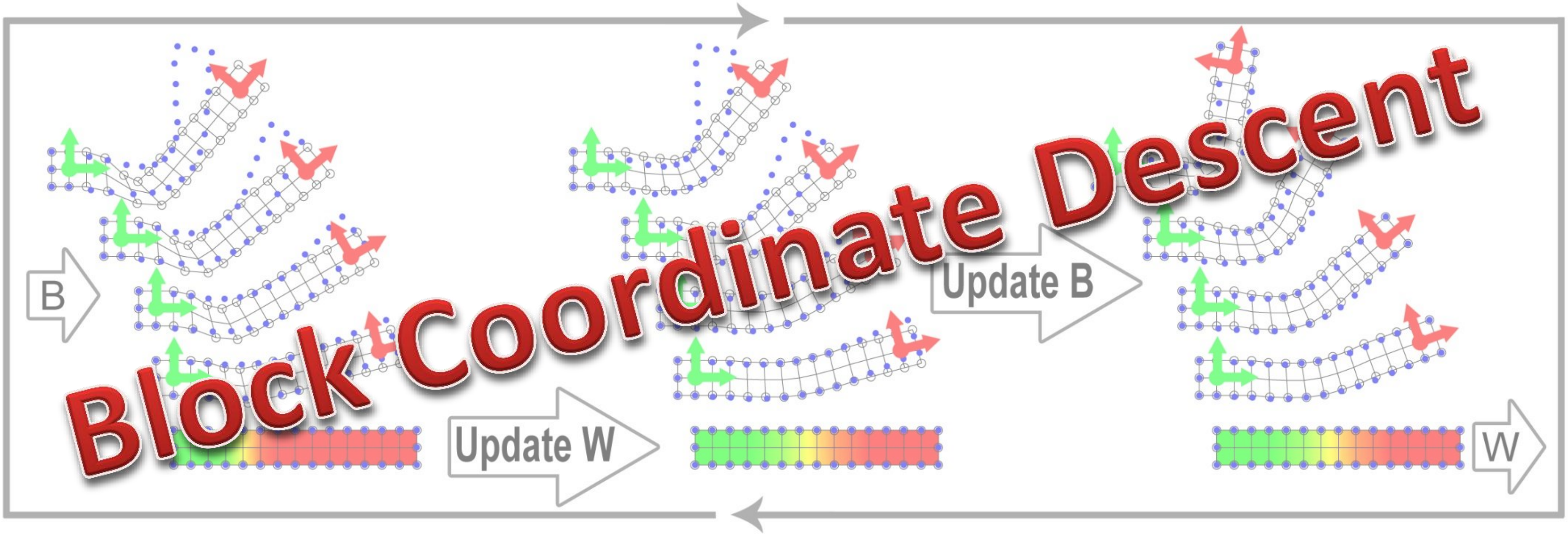
$${R_j^t}^{\mathsf{T}} R_j^t = I, \det R_j^t = 1, \forall t, j$$ → Orthogonal



! Non-linear

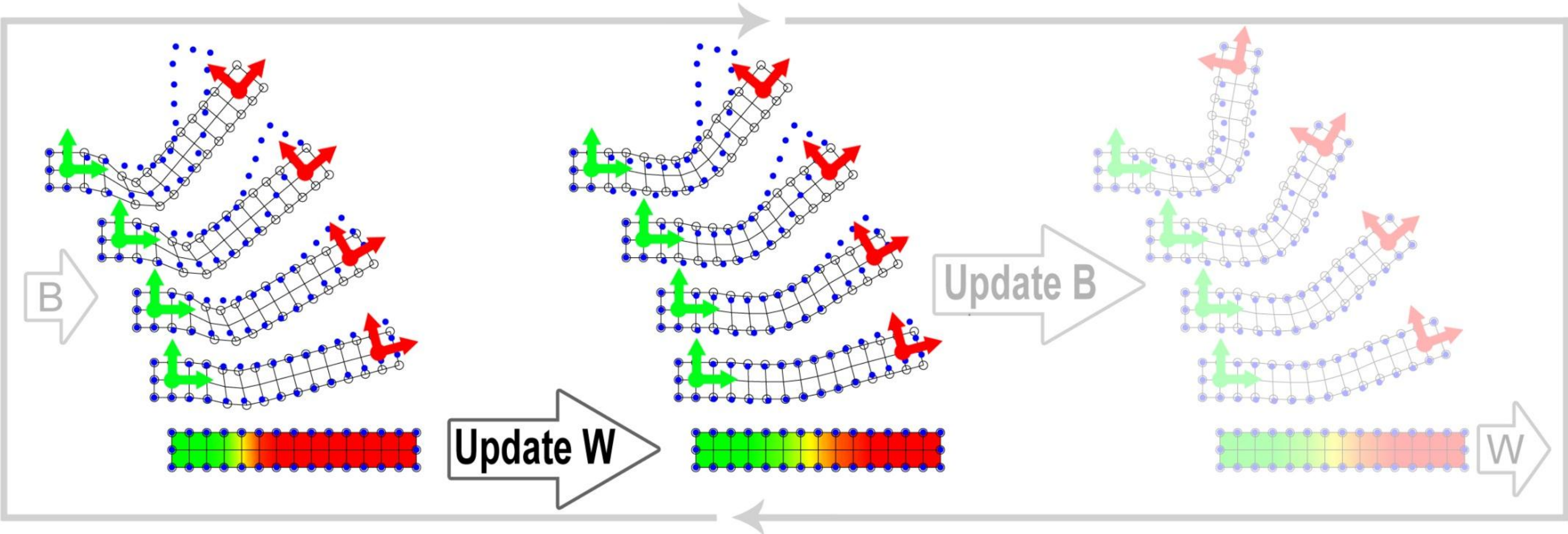
Skinning Decomposition Algorithm

$$\min_{w,R,T} E = \min_{w,R,T} \sum_{t=1}^{|t|} \sum_{i=1}^{|V|} \left\| v_i^t - \sum_{j=1}^{|B|} w_{ij} (R_j^t p_i + T_j^t) \right\|^2$$



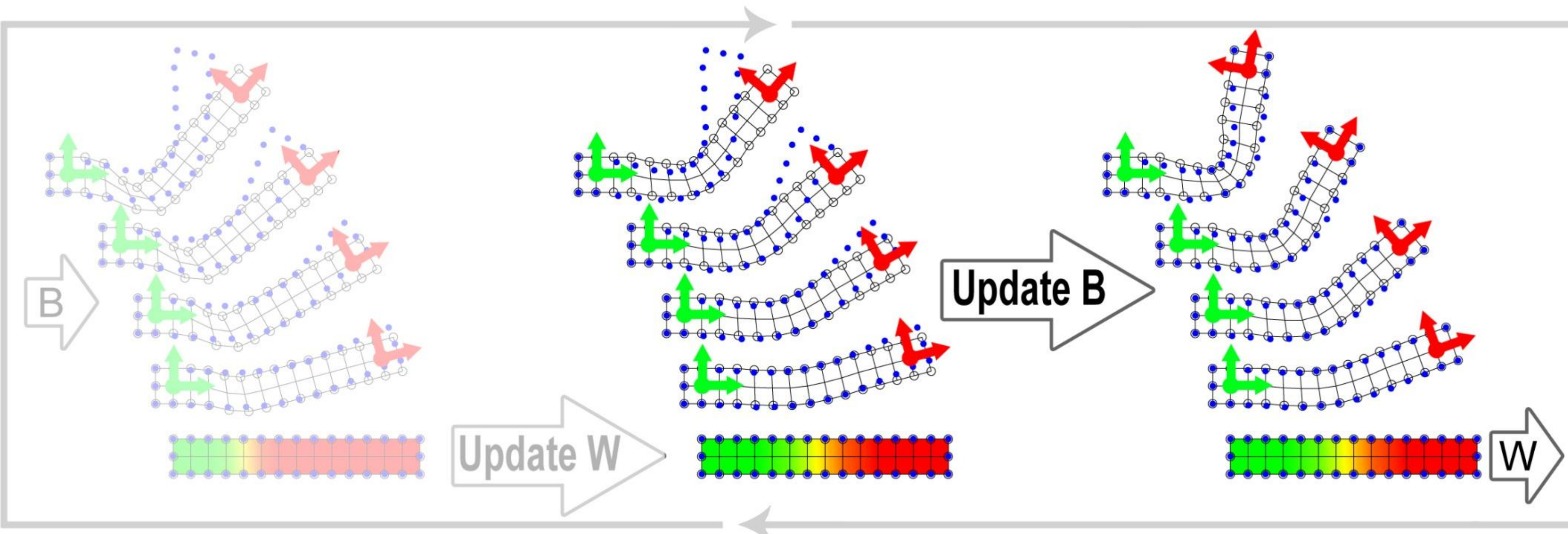
Skinning Decomposition Algorithm

$$\min_{w,R,T} E = \min_{w,R,T} \sum_{t=1}^{|t|} \sum_{i=1}^{|V|} \left\| v_i^t - \sum_{j=1}^{|B|} w_{ij} (R_j^t p_i + T_j^t) \right\|^2$$



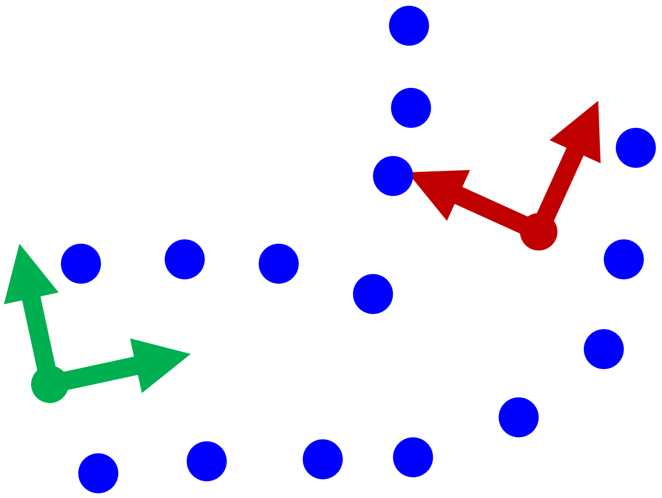
Skinning Decomposition Algorithm

$$\min_{w,R,T} E = \min_{w,R,T} \sum_{t=1}^{|t|} \sum_{i=1}^{|V|} \left\| v_i^t - \sum_{j=1}^{|B|} w_{ij} \left(R_j^t p_i + T_j^t \right) \right\|^2$$



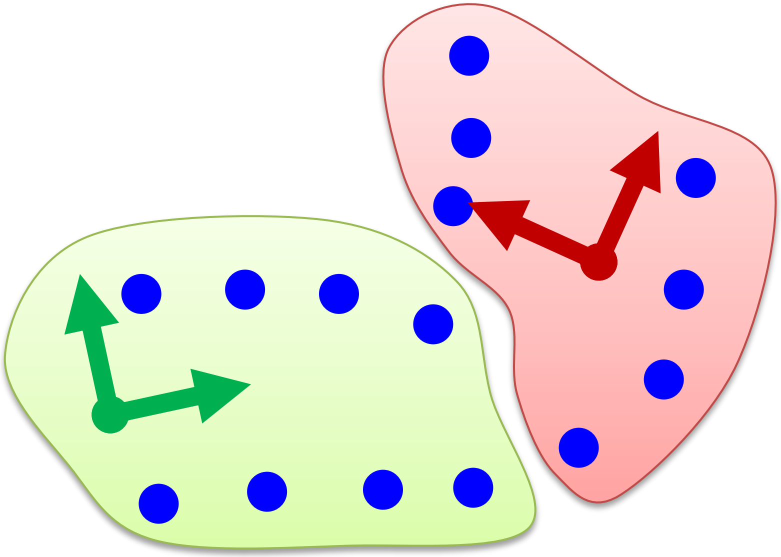
Initialization

- No blending (rigid binding): each vertex is driven by exactly one bone
- Assign |V| vertices into |B| clusters
- K-means clustering



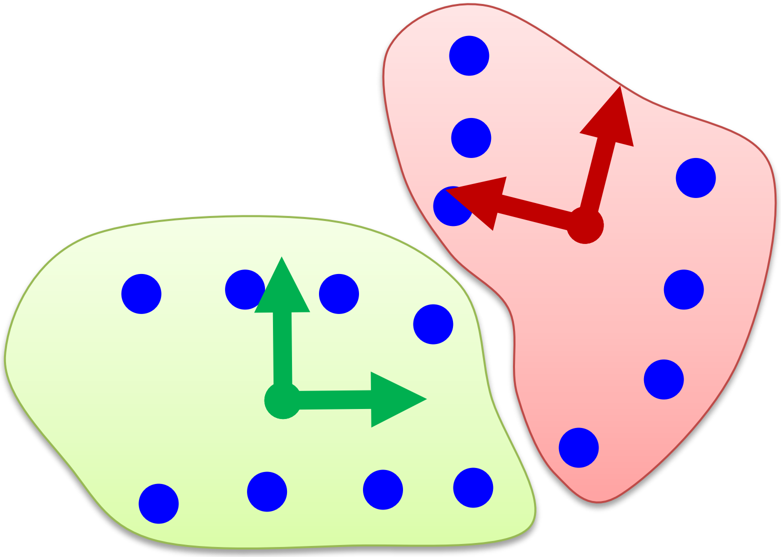
Initialization

- No blending (rigid binding): each vertex is driven by exactly one bone
- Assign |V| vertices into |B| clusters
- K-means clustering



Initialization

- No blending (rigid binding): each vertex is driven by exactly one bone
- Assign |V| vertices into |B| clusters
- K-means clustering



Skinning Weights Solver

- Per vertex solver: Constrained Linear Least Squares

$$W_i{}^{\mathsf{T}} = \arg\min_x \|Ax - b\|^2$$

$$\text{Subject to: } x \geq 0$$

$$\|x\|_1 = 1$$

$$\|x\|_0 \leq |K|$$

Skinning Weights Solver

- Per vertex solver: Constrained Linear Least Squares

$$W_i^{\mathsf{T}} = \arg\min_x \|Ax - b\|^2$$

$$\text{Subject to: } \boxed{x \geq 0} \rightarrow \text{Bound Constraint}$$

$$\boxed{\|x\|_1 = 1} \rightarrow \text{Equality Constraint}$$

$$\|x\|_0 \leq |K|$$

- Active Set Method [Lawson and Hanson]
  – Pre-compute LU factorization of $A^{\mathsf{T}}A$ and $A^{\mathsf{T}}b$
  – Pre-compute QR decomposition of $\begin{bmatrix}1 & 1 & \cdots & 1\end{bmatrix}^{\mathsf{T}}$

Skinning Weights Solver

- Per vertex solver: Constrained Linear Least Squares

$$W_i^{\mathsf{T}} = \arg\min_x \|Ax - b\|^2$$

$$\text{Subject to: } x \geq 0$$

$$\|x\|_1 = 1$$

$$\|x\|_0 \leq |K|$$ → Sparseness Constraint

- Weight pruning of bones with small contribution

$$e_{ij} = \left\| w_{ij}(R_j^t p_i + T_j^t) \right\|^2$$

Keep $|K|$ bones with largest e_{ij} and solve the LS again

Bone Transformations Solver

- Per example pose solver:

$$\min_{R^t, T^t} E^t = \min_{R^t, T^t} \sum_{i=1}^{|V|} \left\| v_i^t - \sum_{j=1}^{|B|} w_{ij} (R_j^t p_i + T_j^t) \right\|^2$$

$$\text{Subject to: } \boxed{{R_j^t}^\top R_j^t = I,} \det R_j^t = 1$$

Bone Transformations Solver

- Per example pose solver:

$$\min_{R^t,T^t} E^t = \min_{R^t,T^t} \sum_{i=1}^{|V|} \left\| v_i^t - \sum_{j=1}^{|B|} w_{ij} (R_j^t p_i + T_j^t) \right\|^2$$

$$\text{Subject to: } \boxed{{R_j^t}^{\top} R_j^t = I}, \det R_j^t = 1$$

? Levenberg-Marquardt optimization

✓ Optimized solution ✗ Slow

? Absolute Orientation (a.k.a. Procrustes Analysis) [Kabsch 1978; Horn 1987]

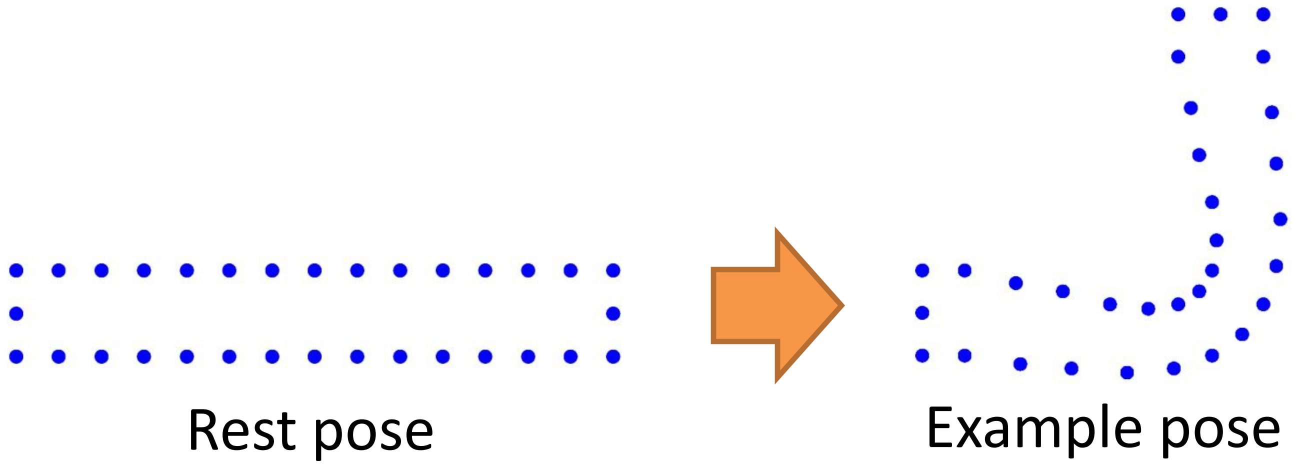
✓ Fast ✗ Approximate solution

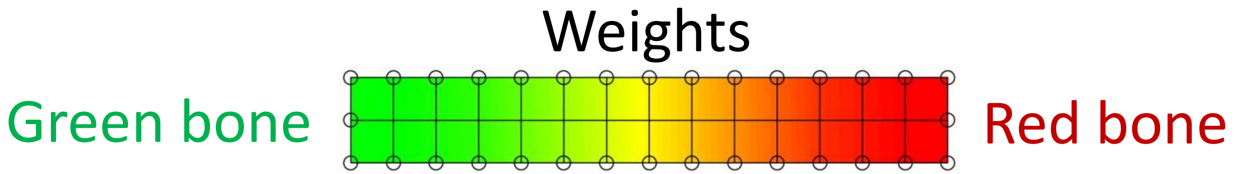
Bone Transformations Solver

- Our solution: Solve bone transformation **one-by-one** to minimize the deformation residual of remaining bones
  - ✓ Linear solver, fast, and simple
  - ✓ Near optimized solution

Bone Transformations Solver

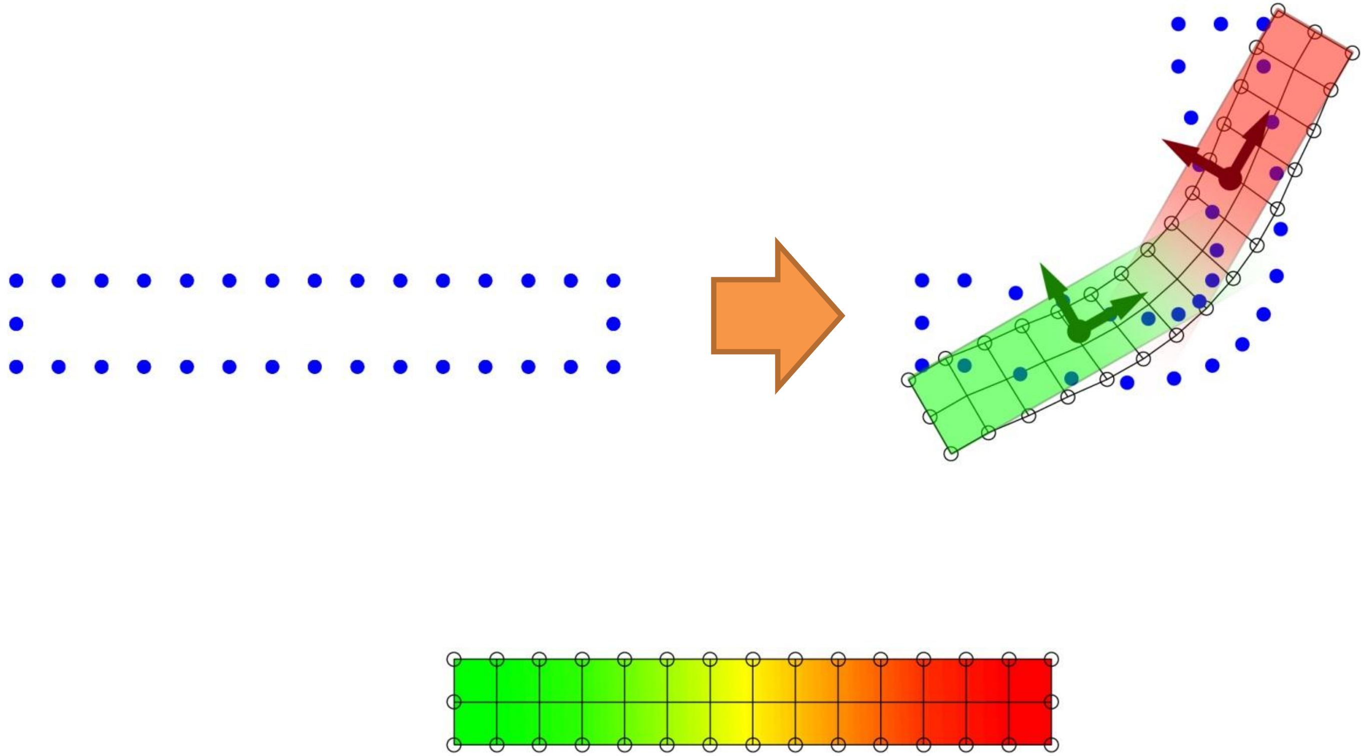
- Our solution: Solve bone transformation **one-by-one** to minimize the deformation residual of remaining bones





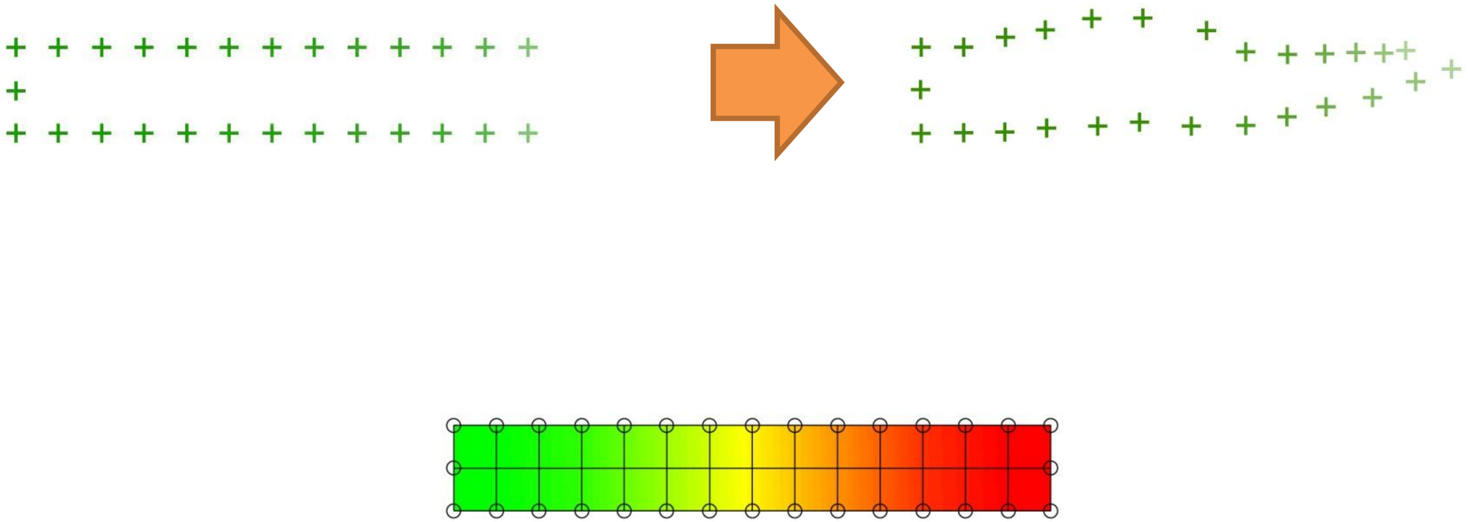
Bone Transformations Solver

- Our solution: Solve bone transformation **one-by-one** to minimize the deformation residual of remaining bones



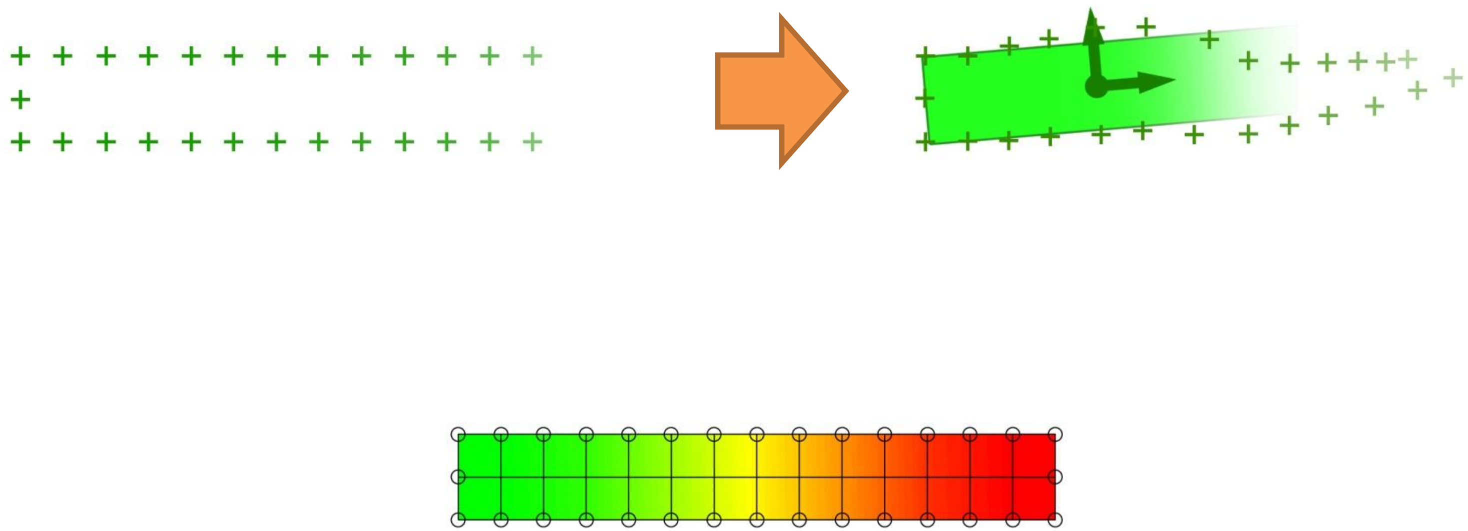
Bone Transformations Solver

- Our solution: Solve bone transformation **one-by-one** to minimize the deformation residual of remaining bones



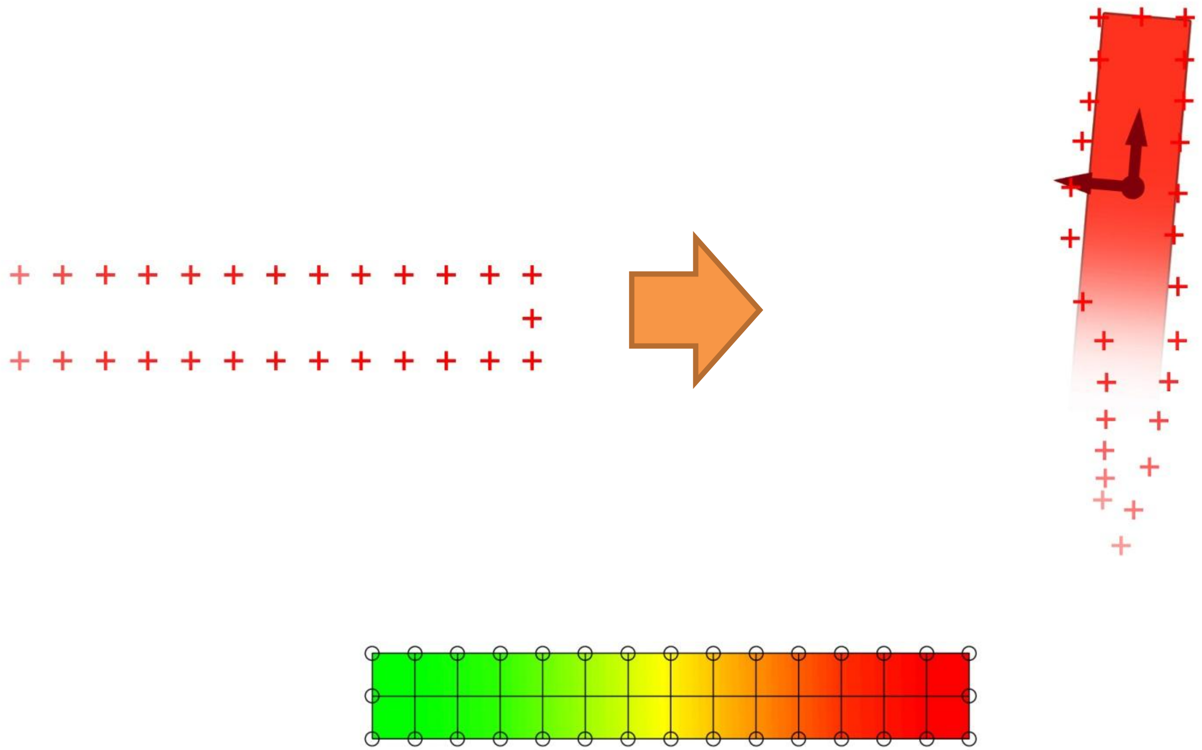
Bone Transformations Solver

- Our solution: Solve bone transformation **one-by-one** to minimize the deformation residual of remaining bones



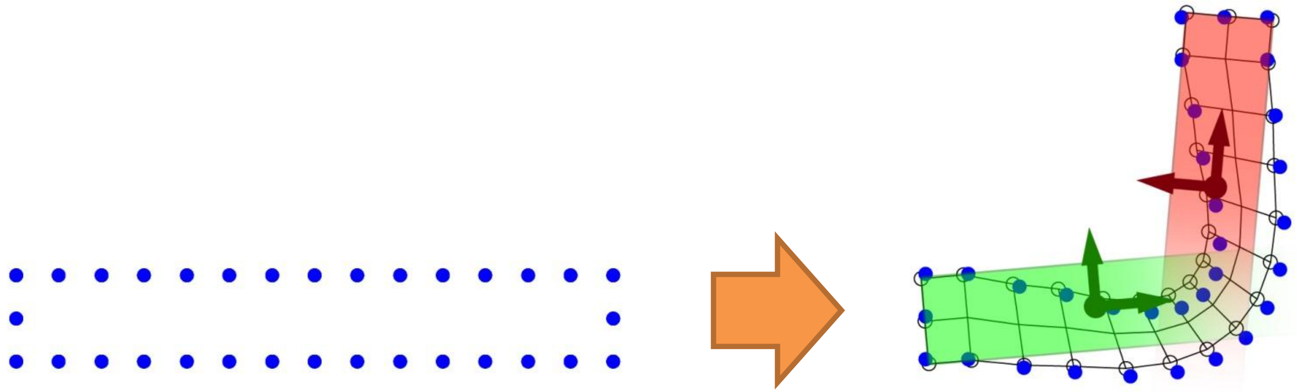
Bone Transformations Solver

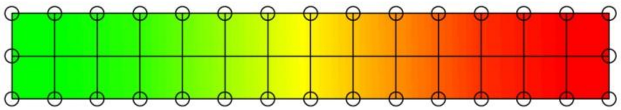
- Our solution: Solve bone transformation **one-by-one** to minimize the deformation residual of remaining bones



Bone Transformations Solver

- Our solution: Solve bone transformation **one-by-one** to minimize the deformation residual of remaining bones

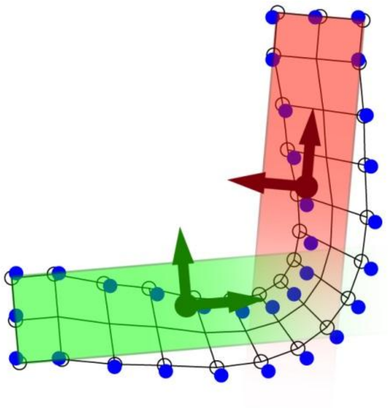




Bone Transformations Solver

- Our solution: Solve bone transformation **one-by-one** to minimize the deformation residual of remaining bones

Before



After

Bone Transformations Solver

- The residual q_i^t for bone $\hat{j}$

$$E^t = \left\| v_i^t - \sum_{j=1}^{|B|} w_{ij}(R_j^t p_i + T_j^t) \right\|^2$$

$$E_{\hat{j}}^t = \sum_{i=1}^{|V|} \left\| \underbrace{v_i^t - \sum_{j=1, j\neq\hat{j}}^{|B|} w_{ij}(R_j^t p_i + T_j^t)}_{q_i^t} - \boxed{w_{i\hat{j}}(R_{\hat{j}}^t p_i + T_{\hat{j}}^t)} \right\|^2$$

Bone $\hat{j}$ out

Bone Transformations Solver

- The residual q_i^t for bone $\hat{j}$

$$E^t = \left\| v_i^t - \sum_{j=1}^{|B|} w_{ij}(R_j^t p_i + T_j^t) \right\|^2$$

$$E_{\hat{j}}^t = \sum_{i=1}^{|V|} \left\| \underbrace{v_i^t - \sum_{j=1, j \neq \hat{j}}^{|B|} w_{ij}(R_j^t p_i + T_j^t)}_{q_i^t} - \boxed{w_{i\hat{j}}(R_{\hat{j}}^t p_i + T_{\hat{j}}^t)} \right\|^2$$

Bone $\hat{j}$ out

- Now find rigid transformation

$$p_i \xrightarrow{(R_{\hat{j}}^t,\, T_{\hat{j}}^t)} q_i^t$$

Bone Transformations Solver

- Remove the translation

$$\overline{p}_i = p_i - p_*$$
$$\overline{q}_i^t = q_i^t - w_{i\hat{j}} q_*^t$$

Center of Rotation:

$$p_* = \frac{\sum_{i=1}^{|V|} w_{i\hat{j}}^2 p_i}{\sum_{i=1}^{|V|} w_{i\hat{j}}^2}$$

$$q_*^t = \frac{\sum_{i=1}^{|V|} w_{i\hat{j}} q_i^t}{\sum_{i=1}^{|V|} w_{i\hat{j}}^2}$$

- Calculate the rotation by Singular Value Decomposition

Compare Equations

- Remove the translation

Our method	Weighted Absolute Orientation
$\overline{p}_i = p_i - p_*$	$\overline{p}_i = p_i - p_*$
$\overline{q}_i^t = q_i^t - w_{i\hat{j}} q_*^t$	$\overline{q}_i^t = q_i^t - q_*^t$
Center of Rotation:	Center of Rotation:
$p_* = \frac{\sum_{i=1}^{\vert V\vert} w_{i\hat{j}}^2 p_i}{\sum_{i=1}^{\vert V\vert} w_{i\hat{j}}^2}$	$p_* = \frac{\sum_{i=1}^{\vert V\vert} w_{i\hat{j}} p_i}{\sum_{i=1}^{\vert V\vert} w_{i\hat{j}}}$
$q_*^t = \frac{\sum_{i=1}^{\vert V\vert} w_{i\hat{j}} q_i^t}{\sum_{i=1}^{\vert V\vert} w_{i\hat{j}}^2}$	$v_*^t = \frac{\sum_{i=1}^{\vert V\vert} w_{i\hat{j}} v_i^t}{\sum_{i=1}^{\vert V\vert} w_{i\hat{j}}}$

Why there are differences?

Compare Equations

Our method	Weighted Absolute Orientation
$E^t = \left\lVert v_i^t - \sum_{j=1}^{\lvert B \rvert} w_{ij} (R_j^t p_i + T_j^t) \right\rVert^2$	$E^t = \sum_{j=1}^{\lvert B \rvert} \sum_{i=1}^{\lvert V \rvert} w_{ij} \left\lVert v_i^t - (R_j^t p_i + T_j^t) \right\rVert^2$

Different objective functions!

Compare Equations

Our method	Weighted Absolute Orientation
$E^t = \left\| v_i^t - \sum_{j=1}^{\lvert B \rvert} w_{ij}(R_j^t p_i + T_j^t) \right\|^2$	$E^t = \sum_{j=1}^{\lvert B \rvert} \sum_{i=1}^{\lvert V \rvert} w_{ij} \left\| v_i^t - (R_j^t p_i + T_j^t) \right\|^2$
Bone blending	No blending

Different objective functions!

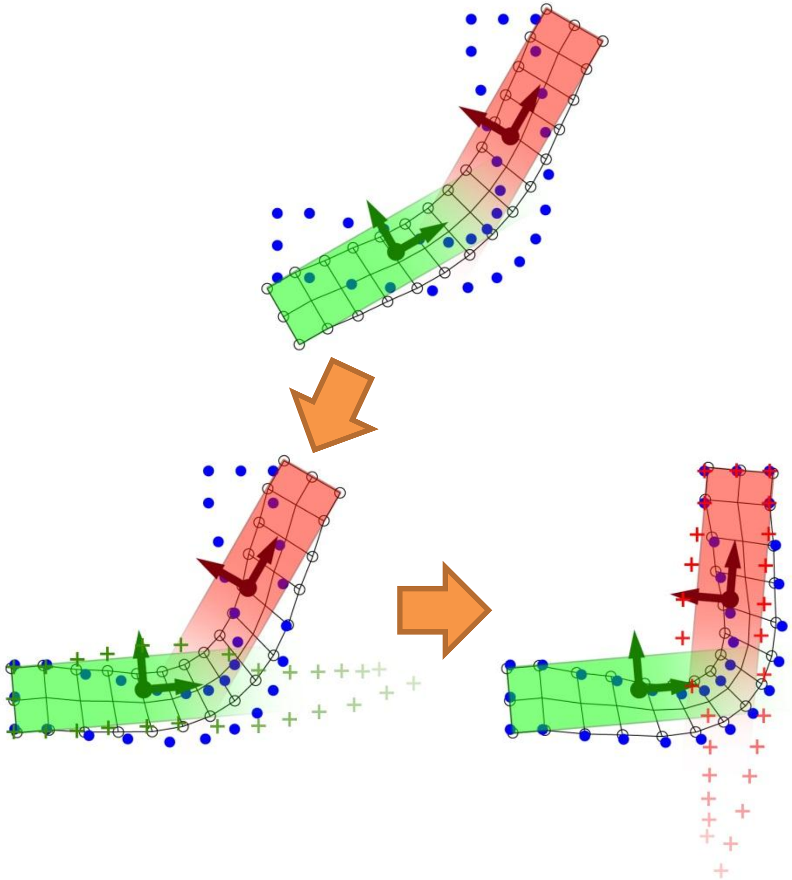
Toy Example

Our method	Weighted Absolute Orientation
	

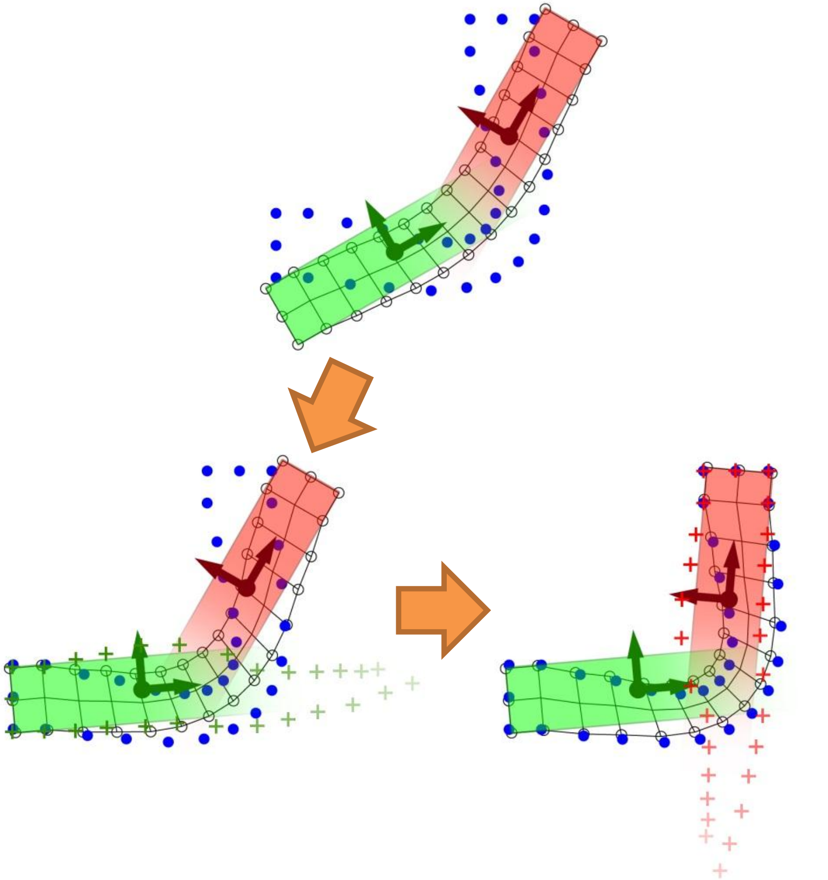
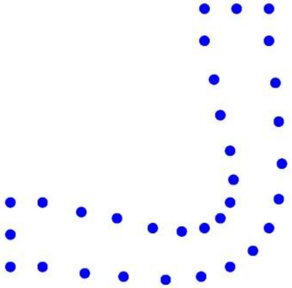
Toy Example

Our method	Weighted Absolute Orientation
	

Toy Example

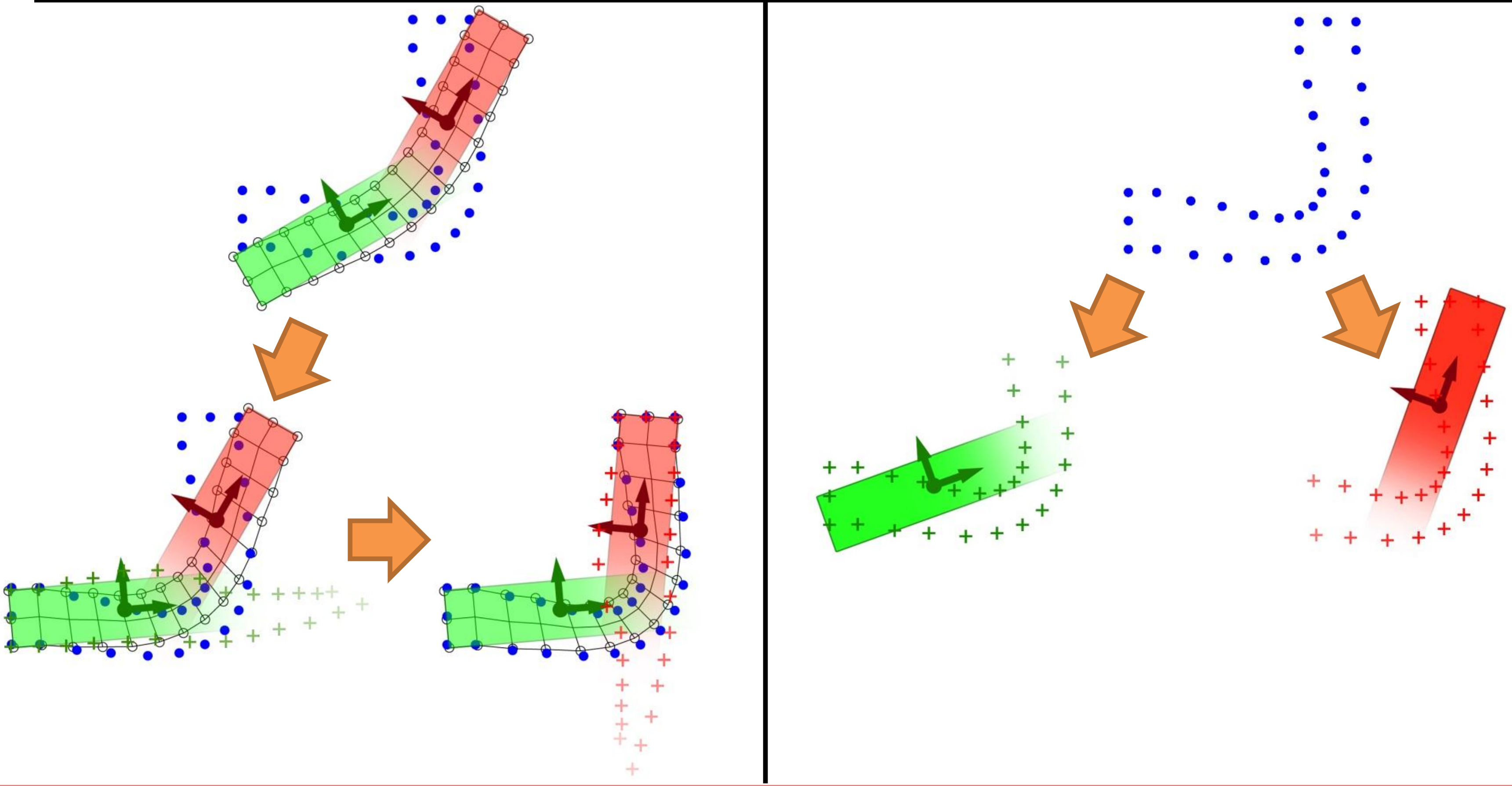
Our method	Weighted Absolute Orientation
	

Toy Example

Our method	Weighted Absolute Orientation
	

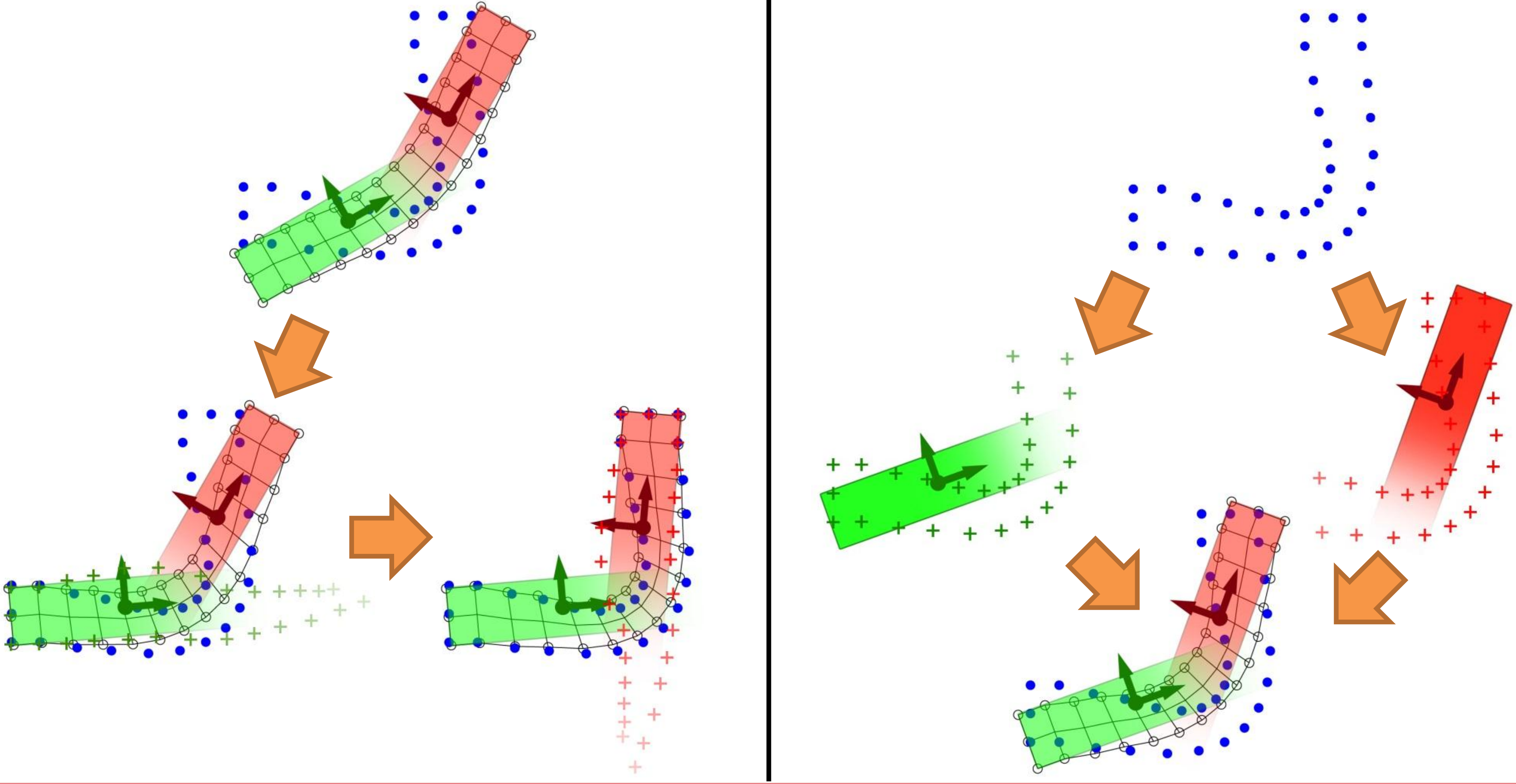
Toy Example

Our method	Weighted Absolute Orientation

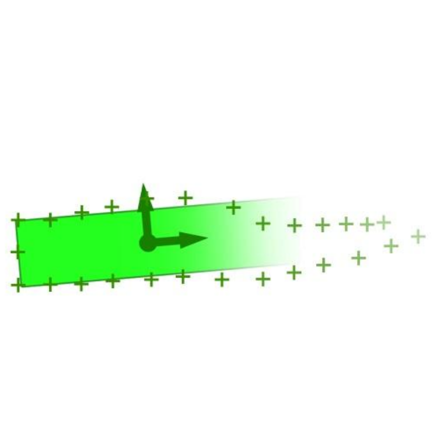
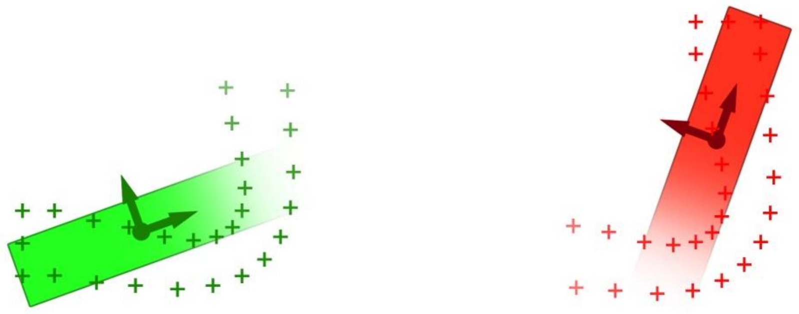


Toy Example

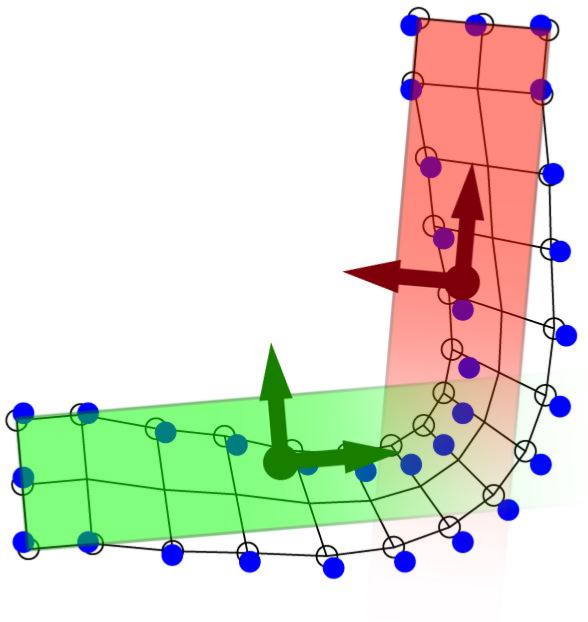
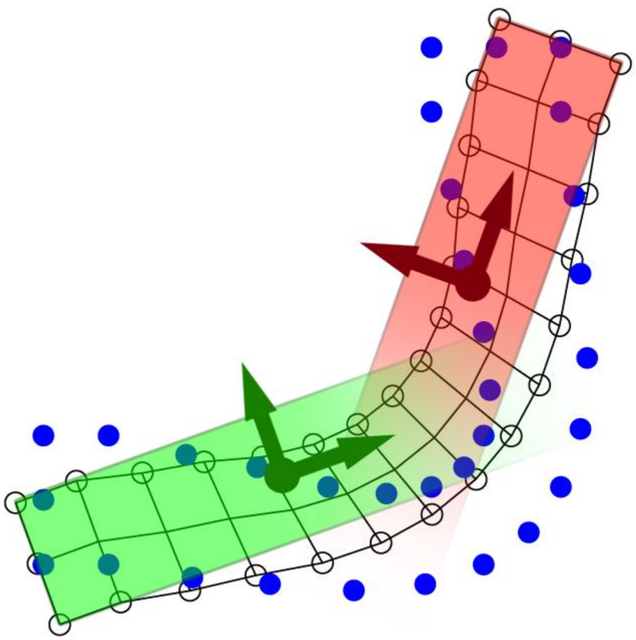
Our method	Weighted Absolute Orientation



Toy Example

Our method	Weighted Absolute Orientation
	

Toy Example

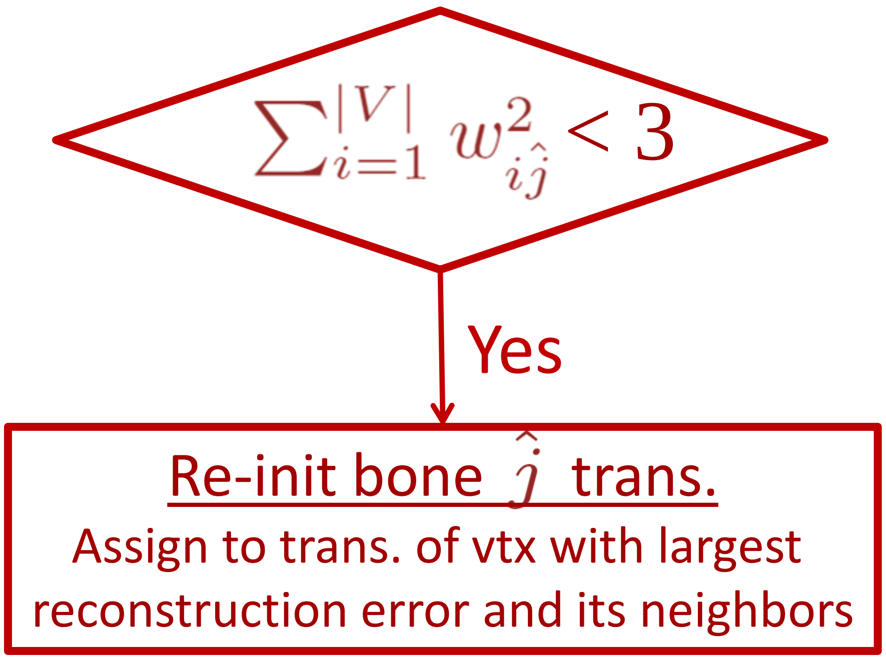
Our method	Weighted Absolute Orientation
	

Bone Transformations Re-Initialization

- Recall: Center of Rotation

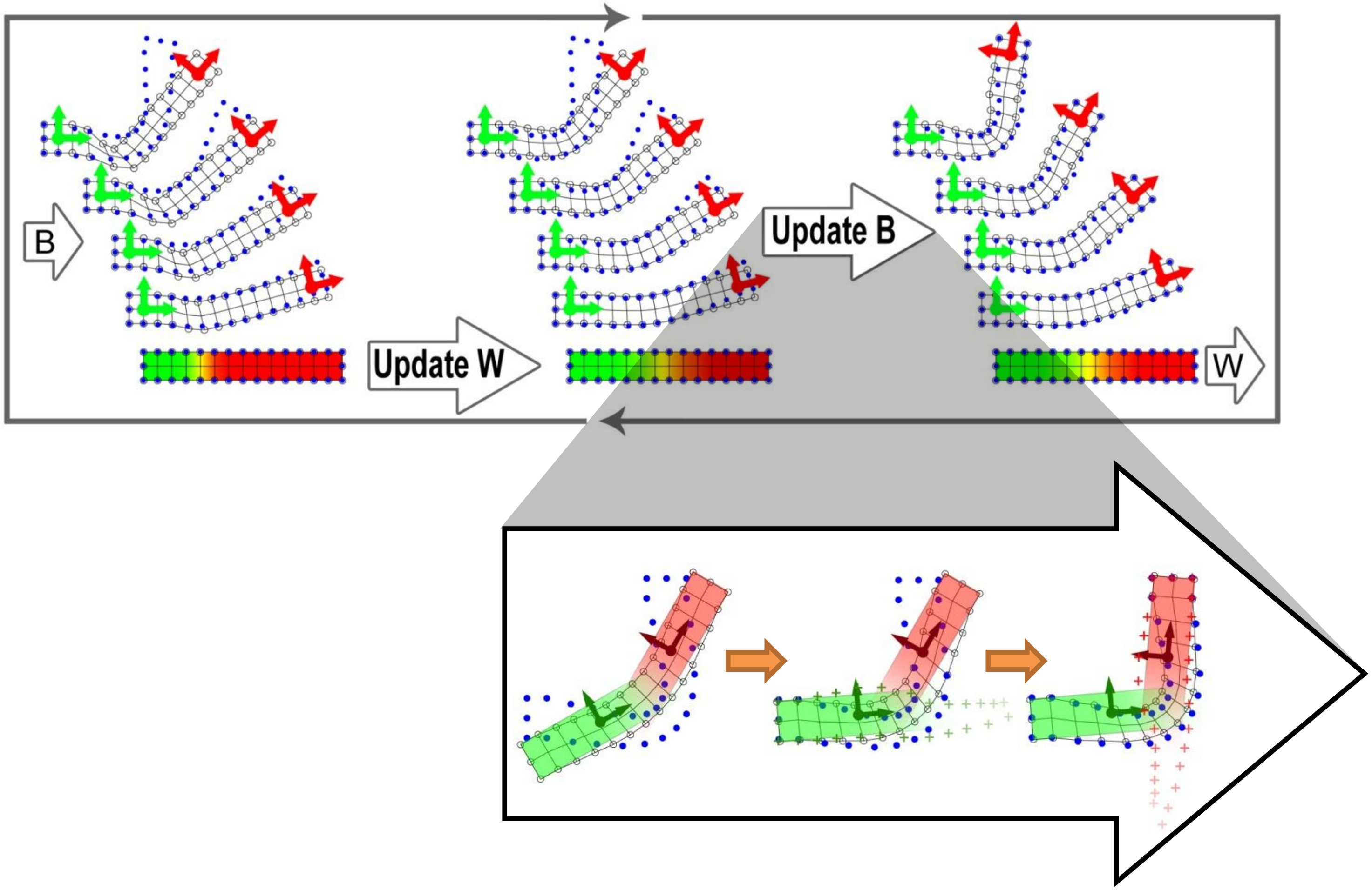
$$p_* = \frac{\sum_{i=1}^{|V|} w_{i\hat{j}}^2 p_i}{\boxed{\sum_{i=1}^{|V|} w_{i\hat{j}}^2}}$$

$$q_*^t = \frac{\sum_{i=1}^{|V|} w_{i\hat{j}} q_i^t}{\boxed{\sum_{i=1}^{|V|} w_{i\hat{j}}^2}}$$

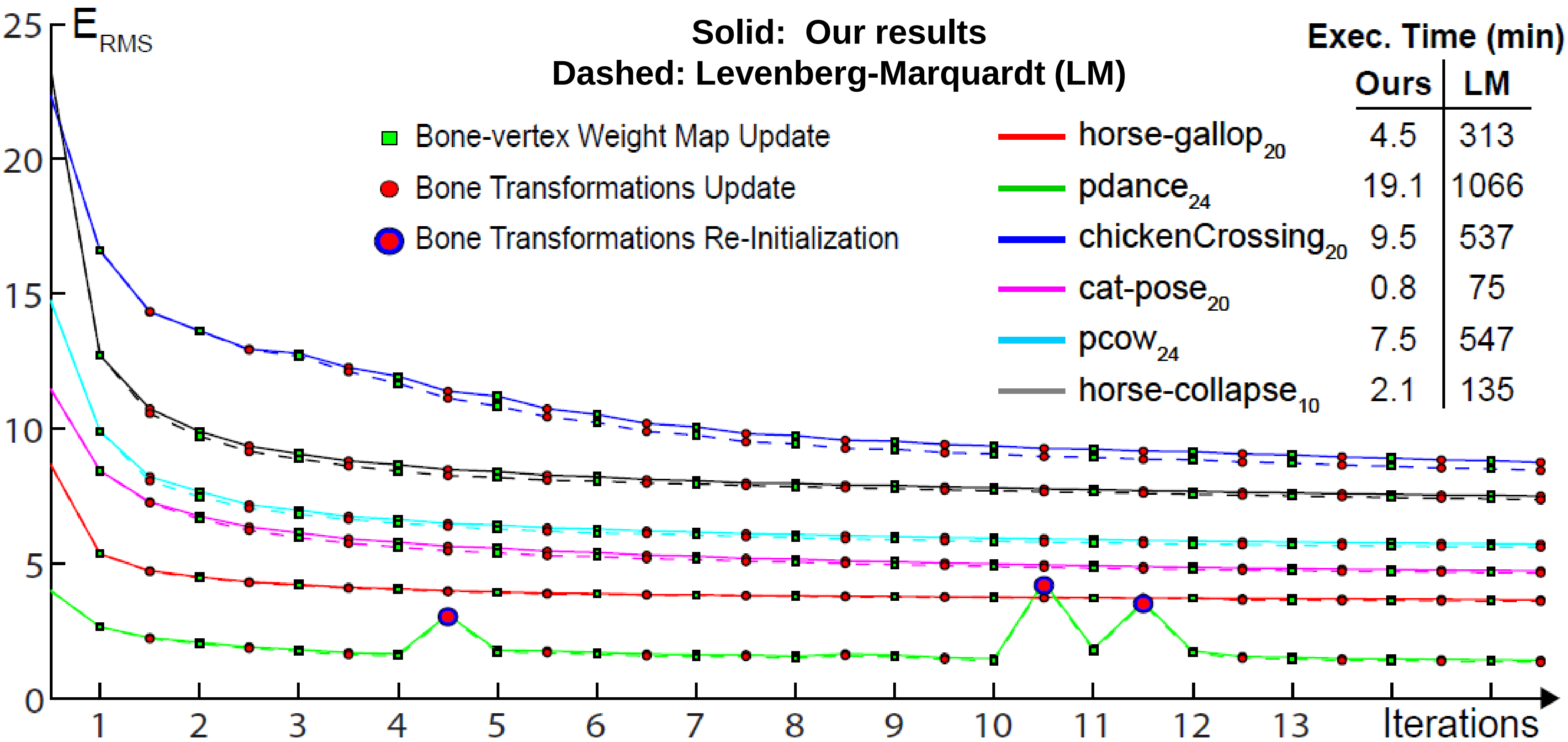


- Improve stability
- Jump out of local minimums

Summary of Our Algorithm



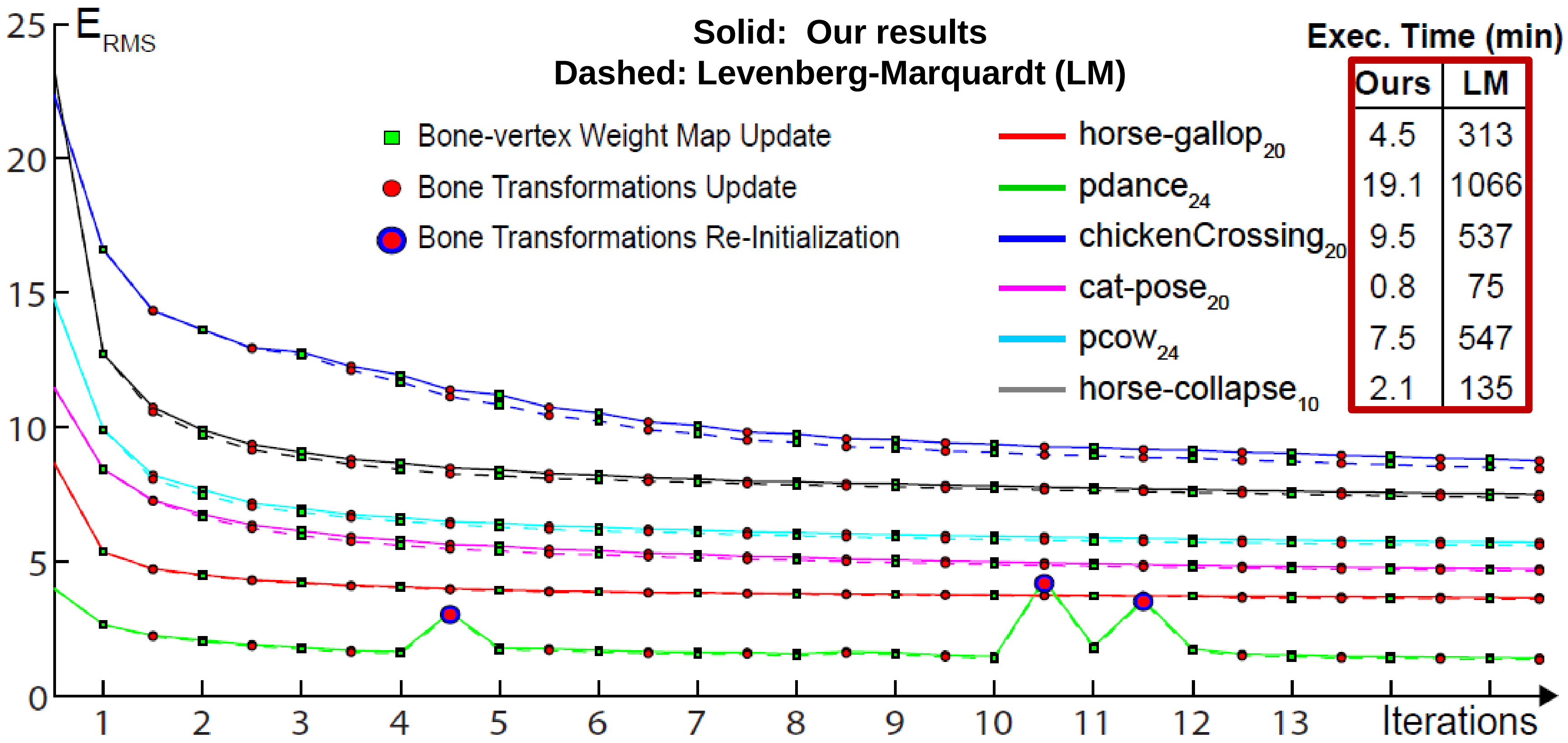
Convergence



	Ours	LM
horse-gallop$_{20}$	4.5	313
pdance$_{24}$	19.1	1066
chickenCrossing$_{20}$	9.5	537
cat-pose$_{20}$	0.8	75
pcow$_{24}$	7.5	547
horse-collapse$_{10}$	2.1	135

- Error decreases monotonically (without re-init bone transformations)

Convergence

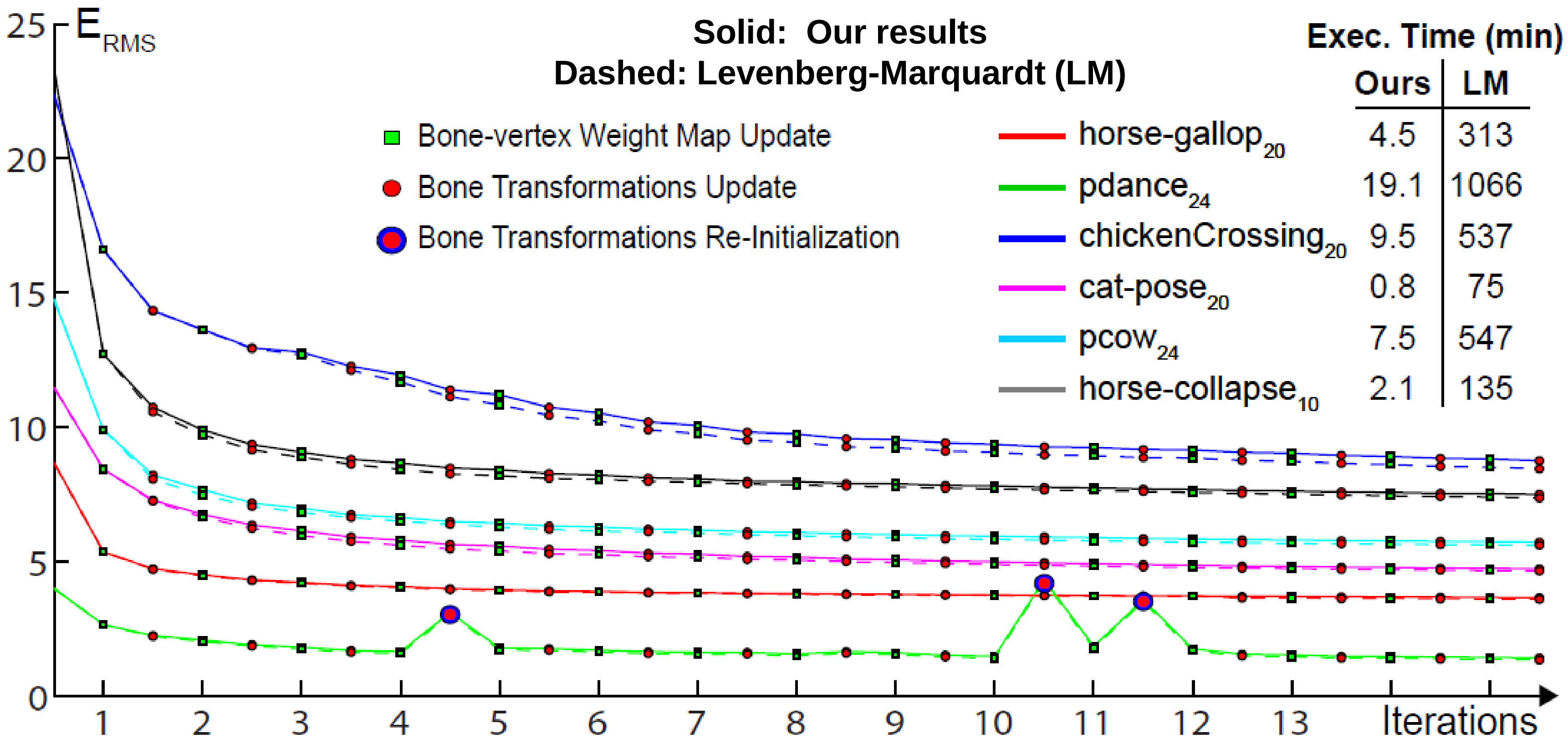


Exec. Time (min)

Ours	LM
4.5	313
19.1	1066
9.5	537
0.8	75
7.5	547
2.1	135

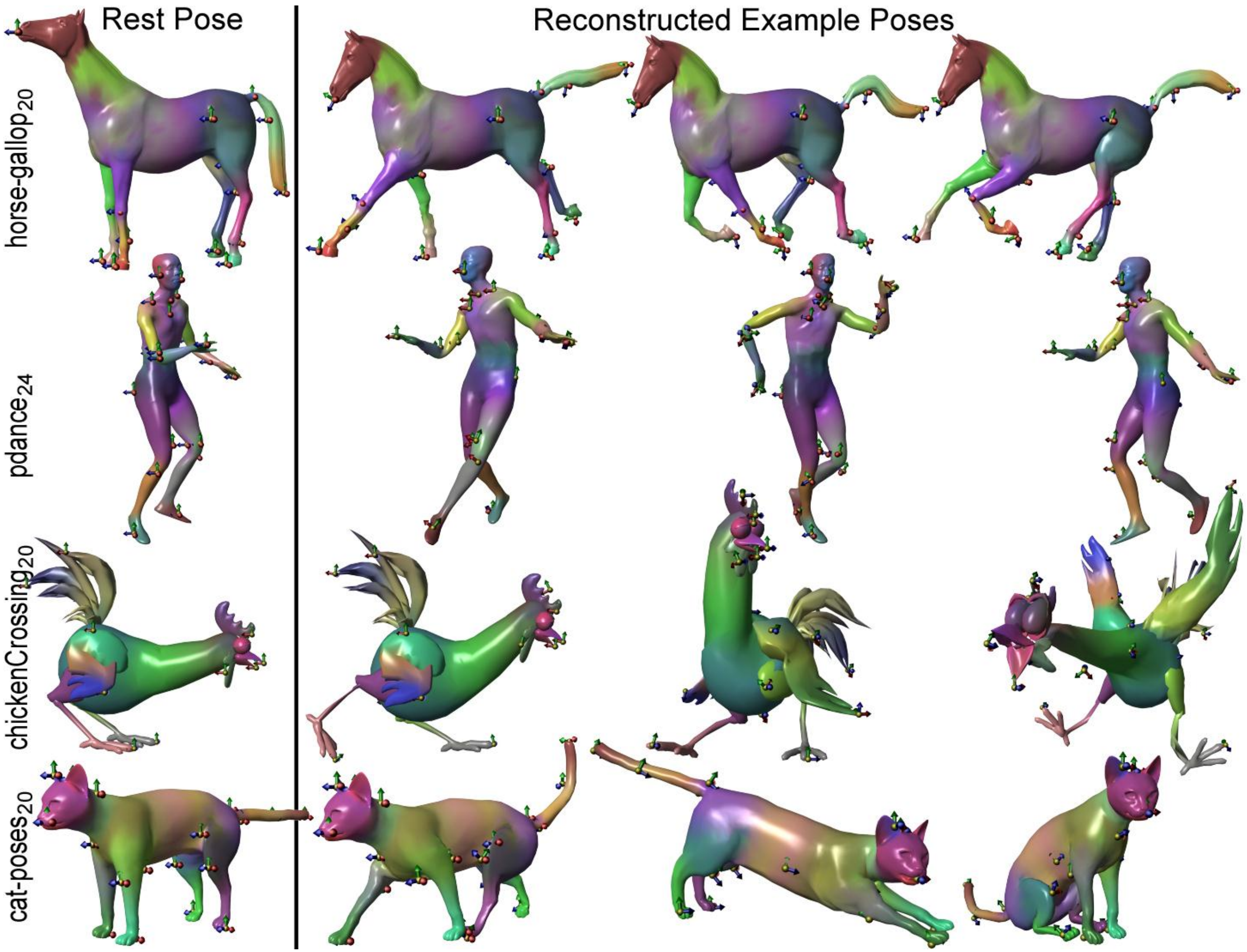
- Error decreases monotonically (without re-init bone transformations)
- Our algorithm converges much faster than LM (~50 times)

Convergence

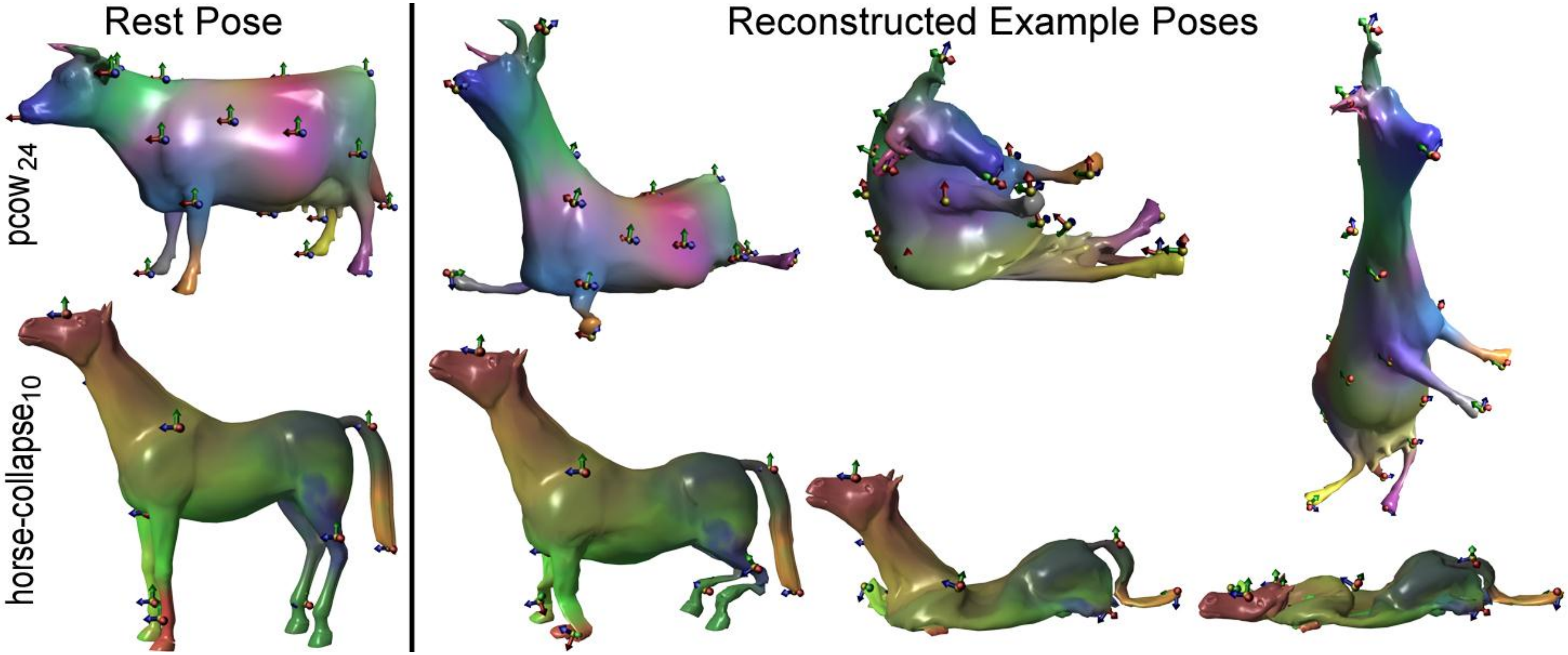


- Error decreases monotonically (without re-init bone transformations)
- Our algorithm converges much faster than LM (~50 times)
- One pass is enough for bone transformations update

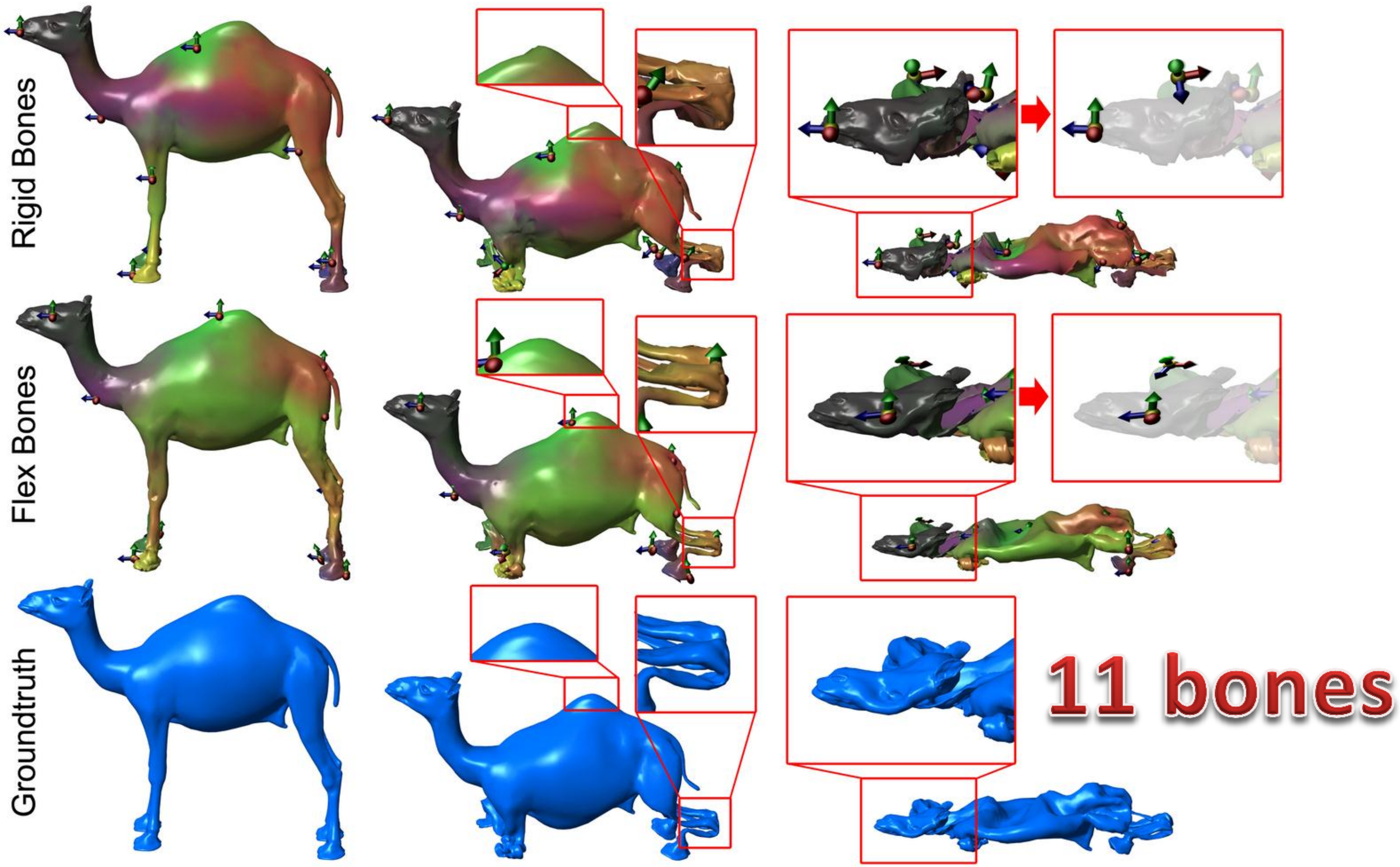
Results – Articulated models



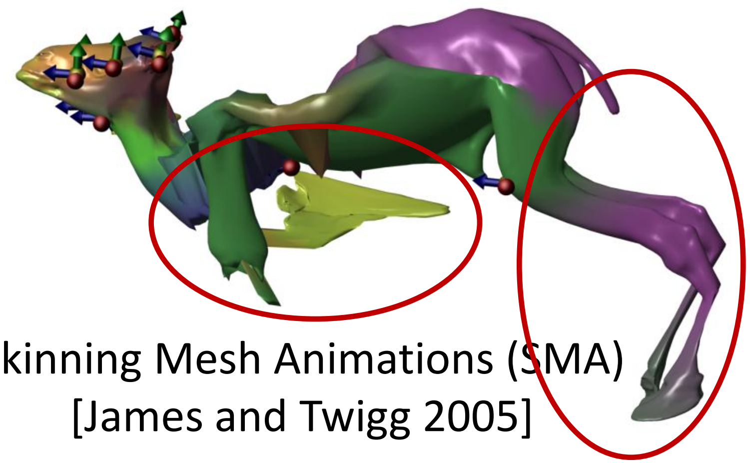
Results – Highly deformable models



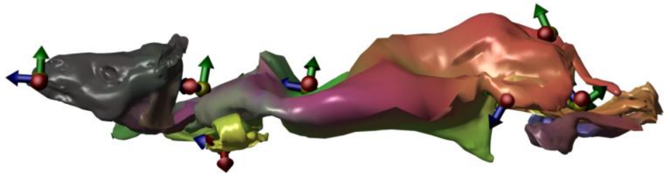
Rigid Bones vs. Flexible Bones



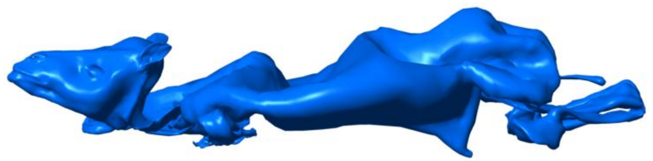
Comparison



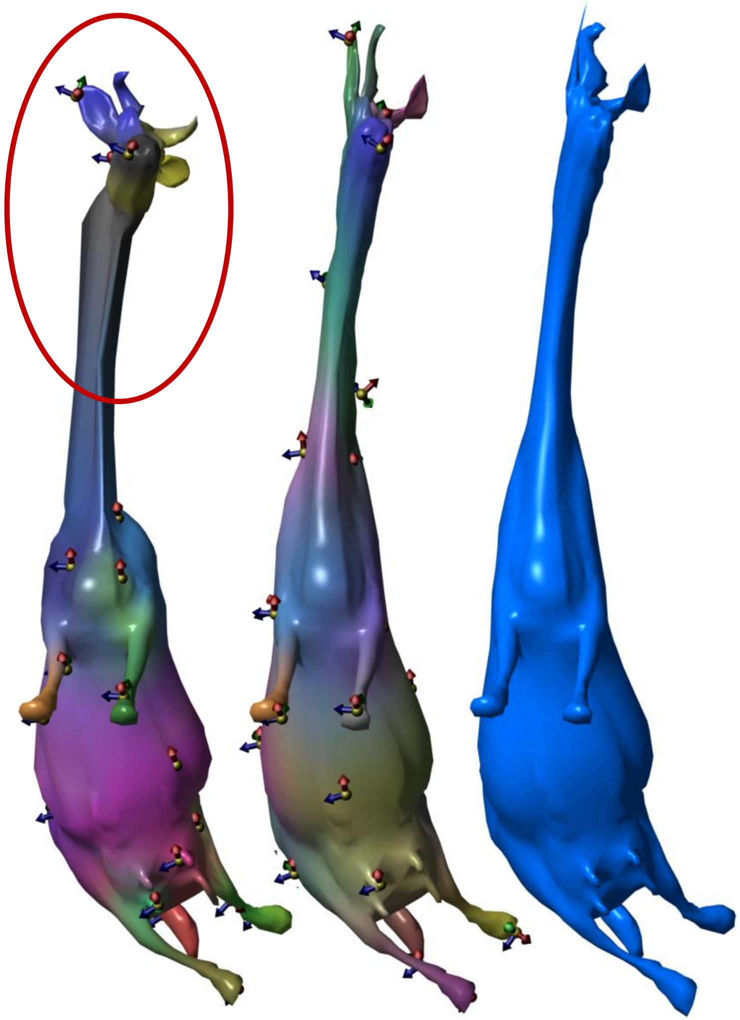
Skinning Mesh Animations (SMA)
[James and Twigg 2005]



Our method



Ground truth



SMA Ours Ground truth

Comparison

Dataset$_{[\text{No. of bones}]}$	Approximation error E_{RMS}			Execution time (minutes)		
	SMA	LSSP	SSDR	SMA	LSSP	SSDR
camel-collapse$_{11}$	125.3 (4)	-	5.4(1.7)	13.8	-	7.4
cat-poses$_{25}$	8.5 (3.1)	6.2(3.3)	3.4(1.4)	0.7	371.7	1.5
chickenCrossing$_{28}$	12.5 (4.2)	6.2(5.1)	8.1(5.4)	14.1	1165.4	24
horse-gallop$_{33}$	9.5 (1.5)	12.5(4.6)	2.2(1.1)	3.8	911	9.8
lion-poses$_{21}$	62.8 (5.7)	7.7(3.9)	4.4(2.2)	0.6	360.2	0.8
pcow$_{24}$	24.8 (13.2)	7.2(6.7)	5.7(4.8)	3.8	564.5	8.9
pdance$_{24}$	3.8 (1.6)	3.4(2.3)	1.3(0.8)	22	2446.8	28.3

SMA: Skinning Mesh Animations [James and Twigg 2005]
LSSP: Learning Skeletons for Shape and Pose [Hasler et al. 2010]
SSDR: Smooth Skinning Decomposition with Rigid Bones (our method)
Result in parentheses: rank-5 EigenSkin correction [Kry et al. 2002]

Comparison

Dataset$_{\text{[No. of bones]}}$	Approximation error E_{RMS}			Execution time (minutes)		
	SMA	LSSP	SSDR	SMA	LSSP	SSDR
camel-collapse$_{11}$	125.3 (4)	-	5.4(1.7)	13.8	-	7.4
cat-poses$_{25}$	8.5 (3.1)	6.2(3.3)	3.4(1.4)	0.7	371.7	1.5
chickenCrossing$_{28}$	12.5 (4.2)	6.2(5.1)	8.1(5.4)	14.1	1165.4	24
horse-gallop$_{33}$	9.5 (1.5)	12.5(4.6)	2.2(1.1)	3.8	911	9.8
lion-poses$_{21}$	62.8 (5.7)	7.7(3.9)	4.4(2.2)	0.6	360.2	0.8
pcow$_{24}$	24.8 (13.2)	7.2(6.7)	5.7(4.8)	3.8	564.5	8.9
pdance$_{24}$	3.8 (1.6)	3.4(2.3)	1.3(0.8)	22	2446.8	28.3

SMA: Skinning Mesh Animations [James and Twigg 2005]
LSSP: Learning Skeletons for Shape and Pose [Hasler et al. 2010]
SSDR: Smooth Skinning Decomposition with Rigid Bones (our method)
Result in parentheses: rank-5 EigenSkin correction [Kry et al. 2002]

Comparison

$\text{Dataset}_{[\text{No. of bones}]}$	Approximation error E_{RMS}			Execution time (minutes)		
	SMA	LSSP	SSDR	SMA	LSSP	SSDR
camel-collapse$_{11}$	125.3 (4)	-	5.4(1.7)	13.8	-	7.4
cat-poses$_{25}$	8.5 (3.1)	6.2(3.3)	3.4(1.4)	0.7	371.7	1.5
chickenCrossing$_{28}$	12.5 (4.2)	6.2(5.1)	8.1(5.4)	14.1	1165.4	24
horse-gallop$_{33}$	9.5 (1.5)	12.5(4.6)	2.2(1.1)	3.8	911	9.8
lion-poses$_{21}$	62.8 (5.7)	7.7(3.9)	4.4(2.2)	0.6	360.2	0.8
pcow$_{24}$	24.8 (13.2)	7.2(6.7)	5.7(4.8)	3.8	564.5	8.9
pdance$_{24}$	3.8 (1.6)	3.4(2.3)	1.3(0.8)	22	2446.8	28.3

SMA: Skinning Mesh Animations [James and Twigg 2005]
LSSP: Learning Skeletons for Shape and Pose [Hasler et al. 2010]
SSDR: Smooth Skinning Decomposition with Rigid Bones (our method)
Result in parentheses: rank-5 EigenSkin correction [Kry et al. 2002]

Comparison

$\text{Dataset}_{[\text{No. of bones}]}$	Approximation error E_{RMS}			Execution time (minutes)		
	SMA	LSSP	SSDR	SMA	LSSP	SSDR
$\text{camel-collapse}_{11}$	125.3 (4)	-	5.4(1.7)	13.8	-	7.4
cat-poses_{25}	8.5 (3.1)	6.2(3.3)	3.4(1.4)	0.7	371.7	1.5
$\text{chickenCrossing}_{28}$	12.5 (4.2)	6.2(5.1)	8.1(5.4)	14.1	1165.4	24
horse-gallop_{33}	9.5 (1.5)	12.5(4.6)	2.2(1.1)	3.8	911	9.8
lion-poses_{21}	62.8 (5.7)	7.7(3.9)	4.4(2.2)	0.6	360.2	0.8
pcow_{24}	24.8 (13.2)	7.2(6.7)	5.7(4.8)	3.8	564.5	8.9
pdance_{24}	3.8 (1.6)	3.4(2.3)	1.3(0.8)	22	2446.8	28.3

SMA: Skinning Mesh Animations [James and Twigg 2005]
LSSP: Learning Skeletons for Shape and Pose [Hasler et al. 2010]
SSDR: Smooth Skinning Decomposition with Rigid Bones (our method)
Result in parentheses: rank-5 EigenSkin correction [Kry et al. 2002]

We are about 100 times faster!

Conclusion

Linear Blend Skinning Decomposition Model

- Convex, sparse weights
- ✓ Rigid bone transformations
- ✓ Iterative bone transformation linear solvers
  - ✓ Nearly optimized, working well with highly deformation models
  - ✓ Fast
  - ✓ Simple

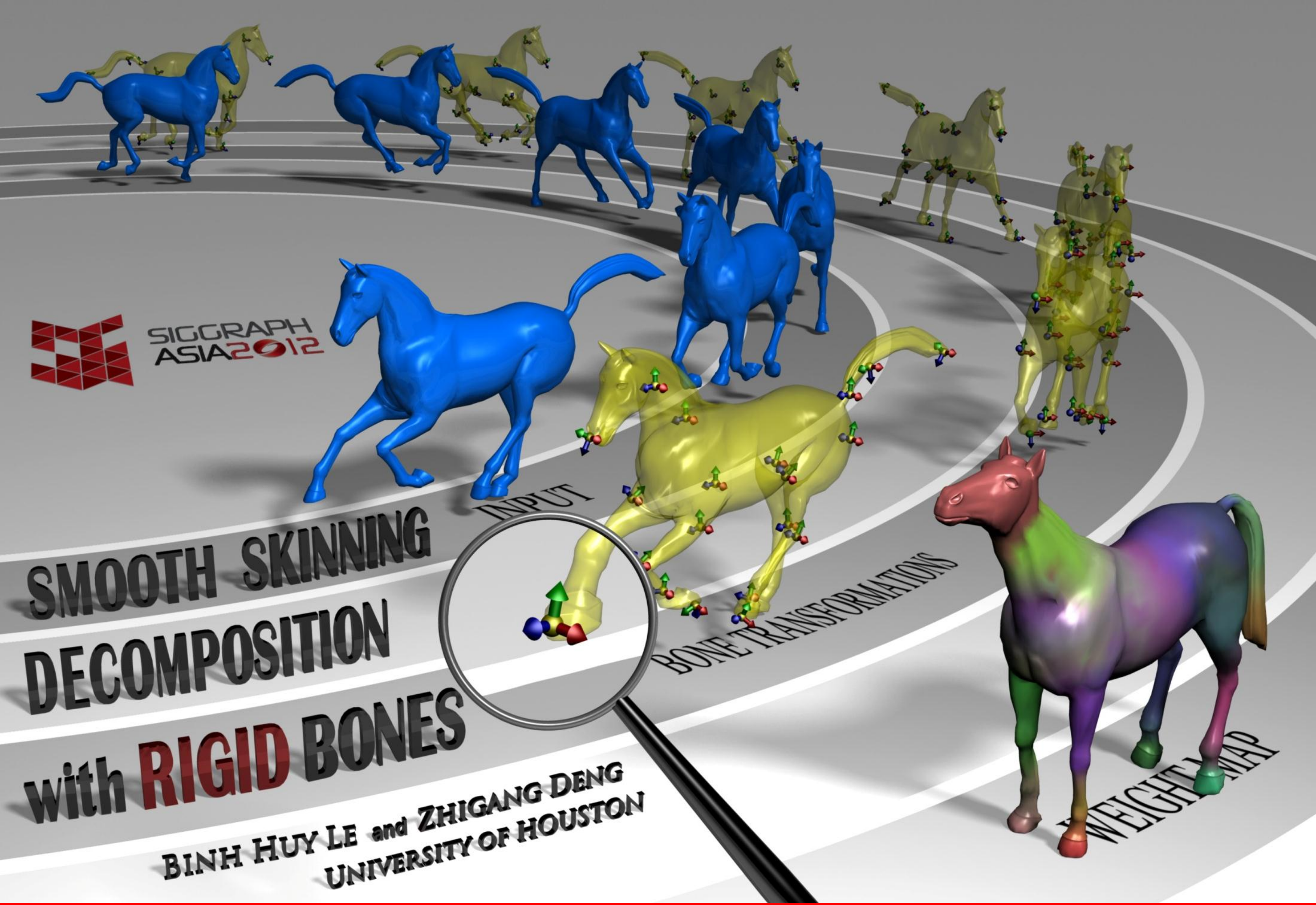
Conclusion

Linear Blend Skinning Decomposition Model

- Convex, sparse weights
- ✓ Rigid bone transformations
- ✓ Iterative bone transformation linear solvers
  - ✓ Nearly optimized, working well with highly deformation models
  - ✓ Fast
  - ✓ Simple
- ✗ Considering skeleton hierarchy
- ✗ Utilizing other information: Mesh topology or anatomy

Acknowledgements

- NSF IIS-0915965
- Vietnam Education Foundation (VEF)
- Google and Nokia for research gifts
- Robert Sumner, Jovan Popovic, Hugues Hoppe, Doug James, and Igor Guskov for publishing the mesh sequences
- Anonymous reviewers for giving insightful comments



http://graphics.cs.uh.edu/ble/papers/2012sa-ssdr/