Animation et déformation

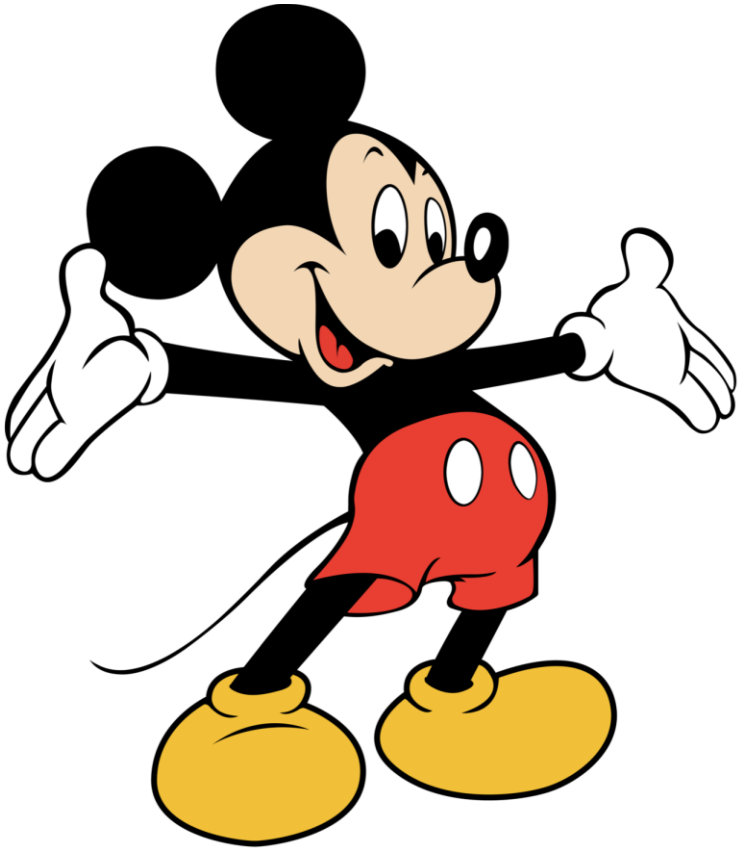
Master IMAGINA

Plan

- Introduction
- Animation
  - Images clés
  - Squelette
  - Skinning
- Deformation
  - Surface
  - Volume

Double héritage

Dessin animé

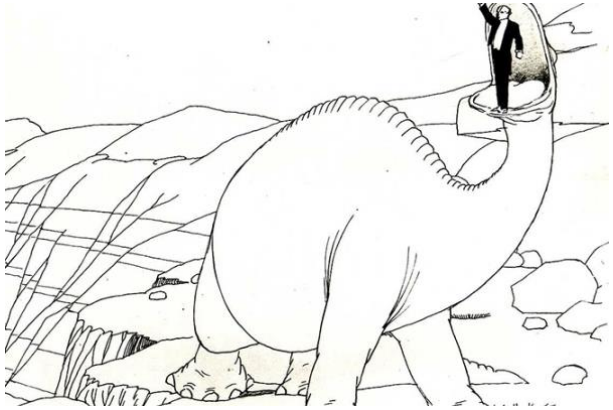


Robotique

Dessin animé

- Animation

Gertie le dinosaure (1914)

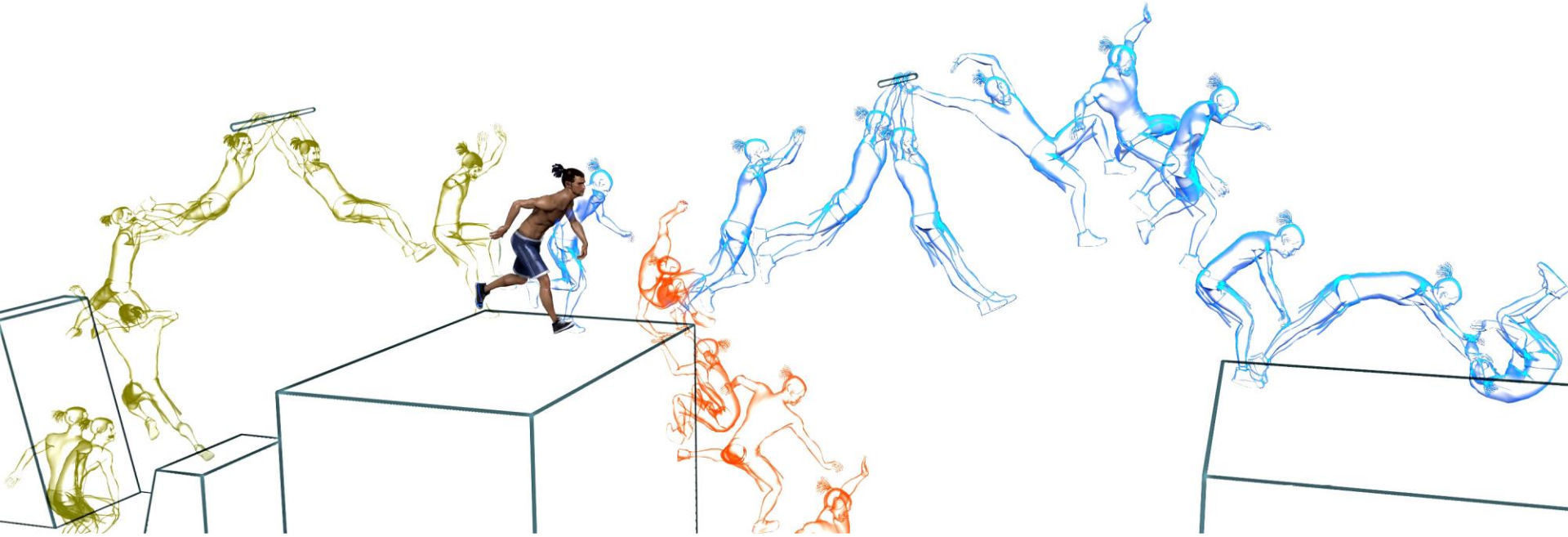


1ère animation par **image clés**

- Données par un animateur et dessin des images intermédiaires par des « petites mains »

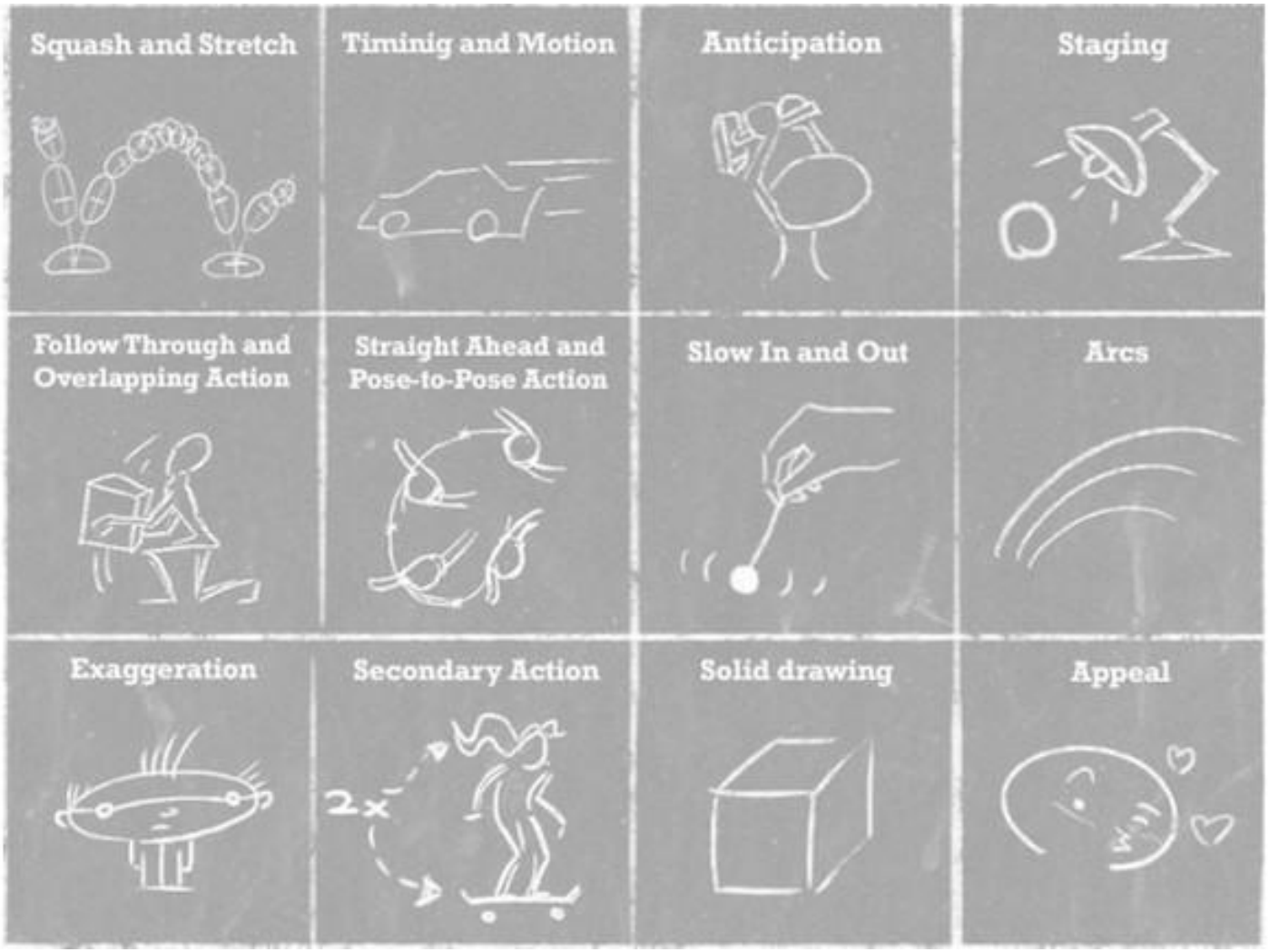
Animation par ordinateur

- Automatiser ce processus



12 principes d'animation

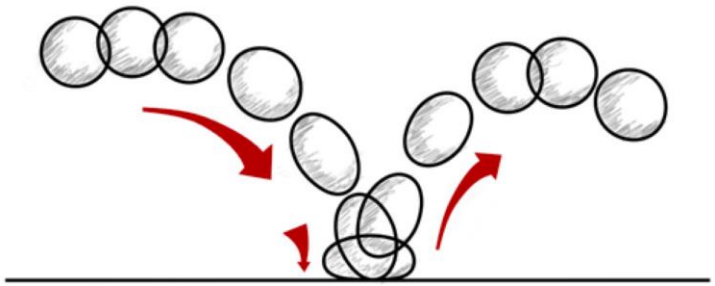
Disney Studios, 1930s



Voir vidéo…

1. Squash and stretch

- Distorsion de la forme pour accentuer le mouvement (avec préservation du volume)



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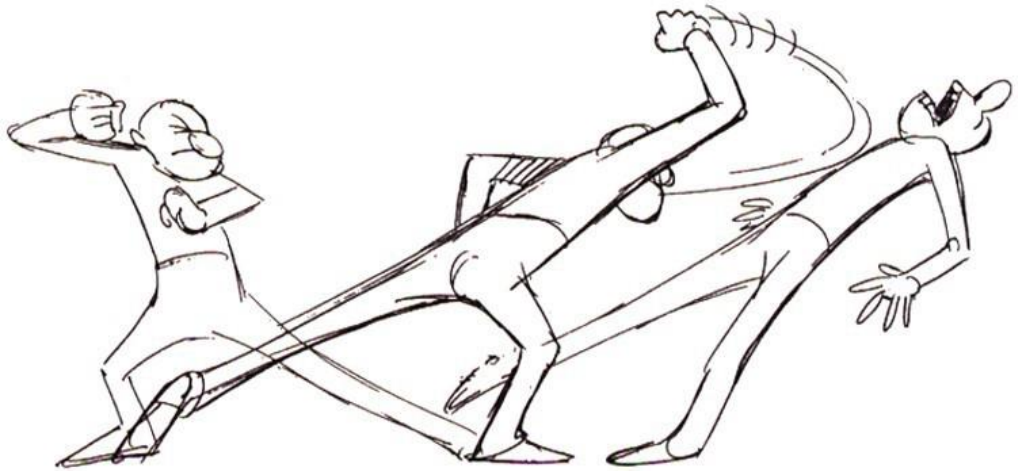
4. Anticipation

- Action inverse au mouvement pour l’accentuer



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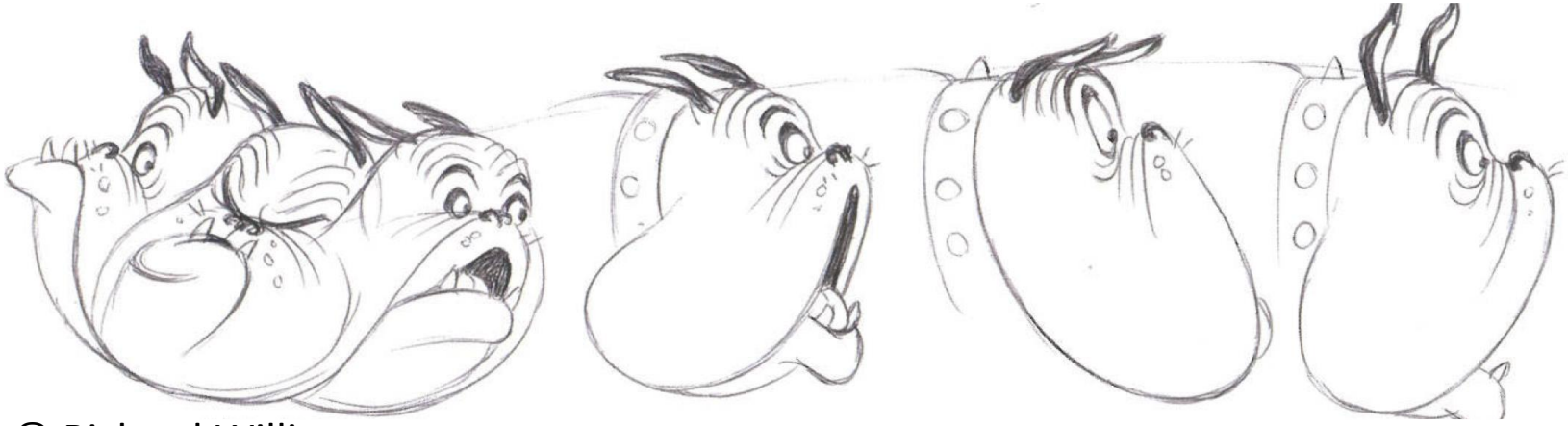
5. Follow through & Overlapping

- Retards et anticipations de certaines parties de la forme



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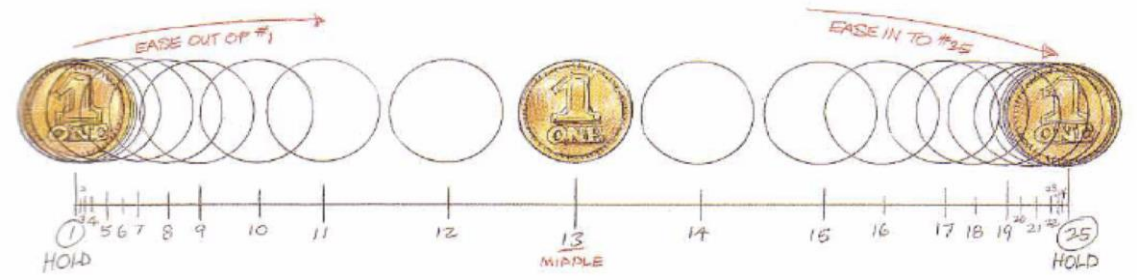
6. Slow in, slow out

- Exagération de l'accélération et de la décélération aux extrémités de la trajectoire



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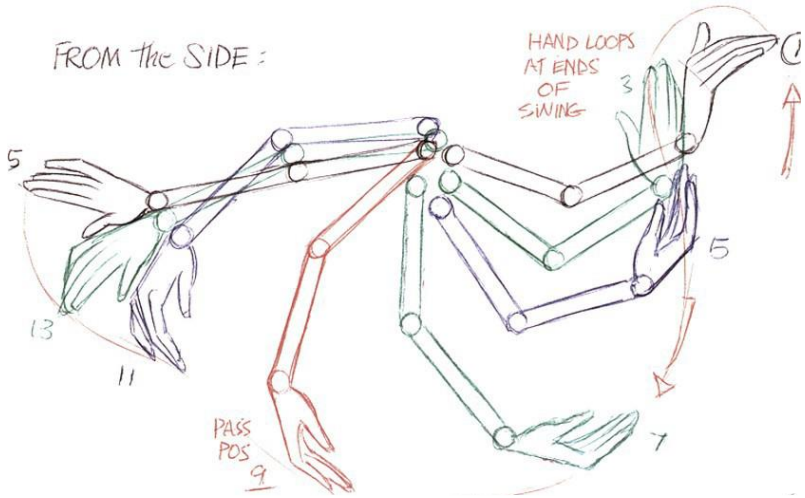
7. Arcs

- Rien ne bouge en ligne droite mais selon un arc



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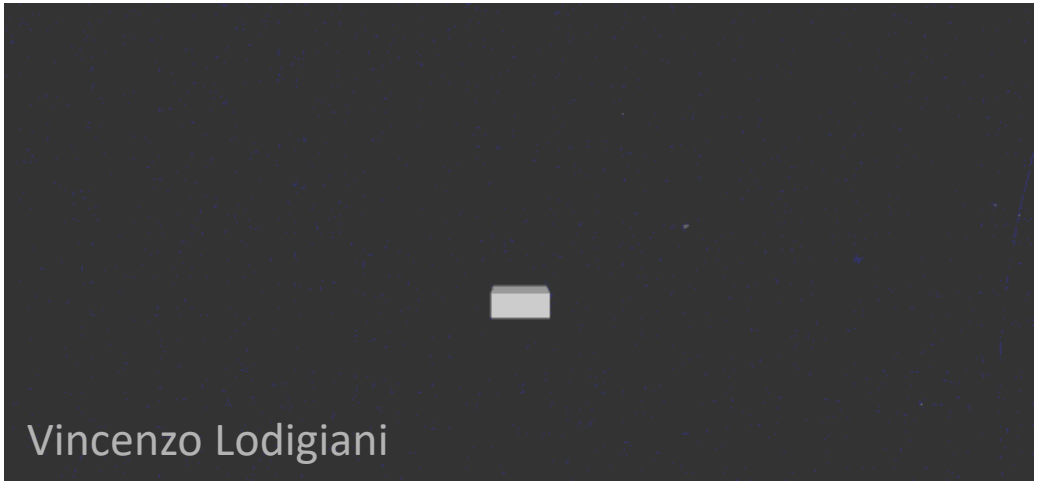


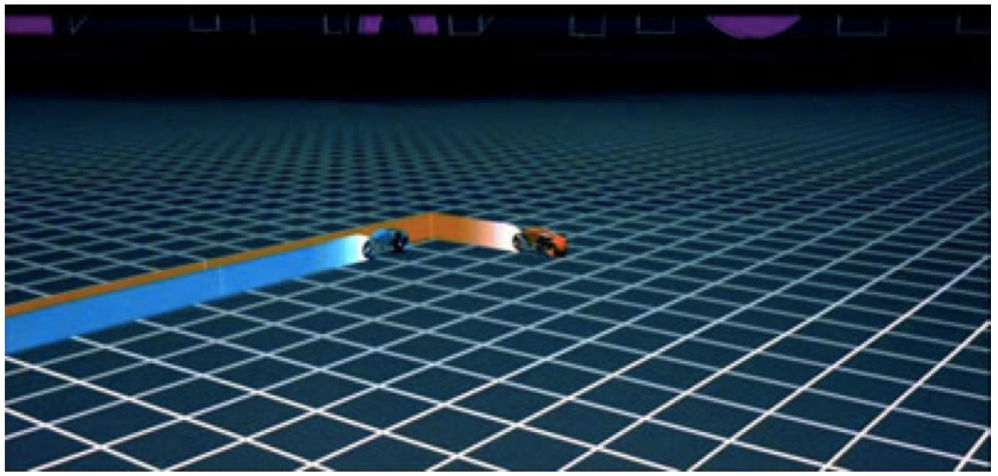
Débuts de l’animation 3D

- Recherche académique

A Computer Animated Hand (1972)
Ed Catmull - **Fred Parke**

Débuts de l'animation 3D

- Effets spéciaux



Tron (1986)

Abysse (1989)

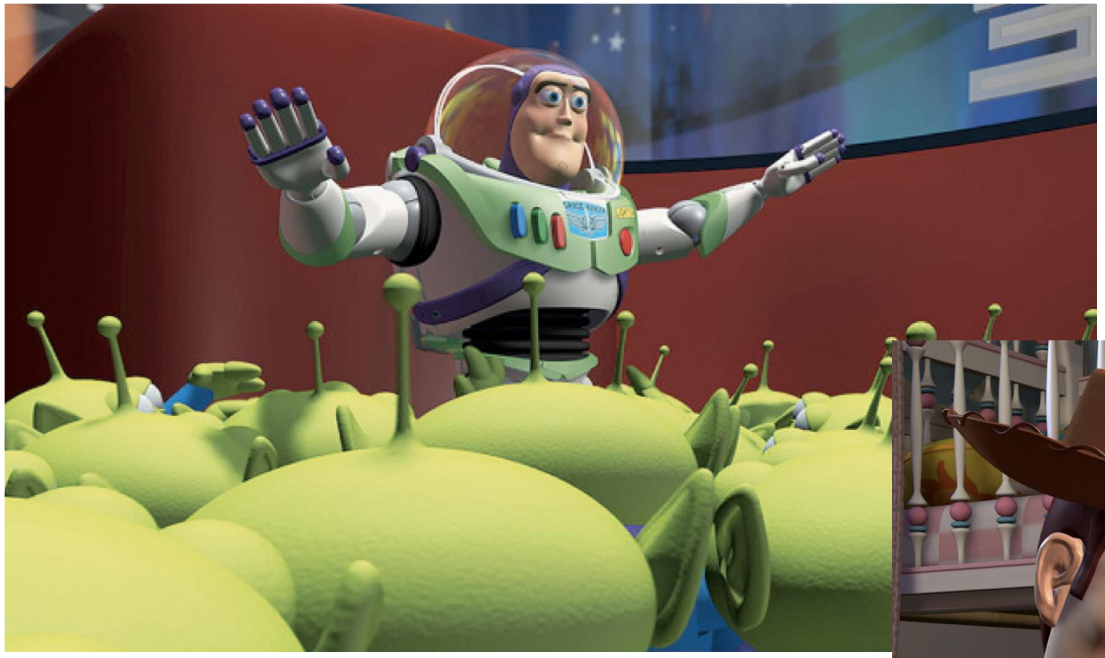
Débuts de l’animation 3D

- Court métrage d’animation 3D

Luxo Jr. (Pixar 1986)

Débuts de l'animation 3D

- Premier long métrage d'animation 3D



Toy Story, (Pixar 1995)

Animation par ordinateur

- Les modèles ont des paramètres :
  - Position de sommets
  - Normales
  - Points de contrôles de courbes
  - Angle de jointures
  - Couleurs,
  - Lumières…
- n paramètres définissent un espace d'état de n dimension
- Un jeu de valeurs de ces n paramètres = point dans cet espace

Animation par ordinateur

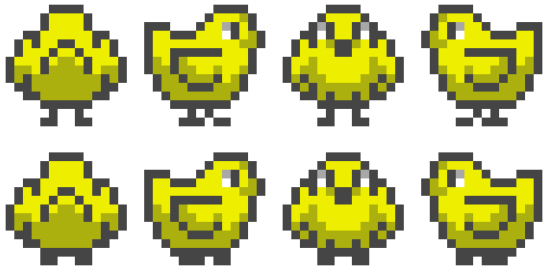
- Une animation est définie par un chemin dans cet espace d'état
- Pour produire une animation :
  1. Commencer au début du chemin
  2. Fixer les paramètres de votre modèle
  3. Rendre une image
  4. Bouger au point suivant du chemin dans l'espace d'état
  5. Aller à 2
- Le chemin est défini par un ensemble de courbe de mouvement (une pour chaque parameter)
- Animation = spécifier la trajectoire dans l'espace d'état

Techniques d’animation

- Traditionnelle (image par image)
- Par image clés (keyframing)
- Techniques procédurales
- Techniques comportementales (e.g., flocking)
- Basées sur la performance (motion capture)
- Basées sur la physique (dynamique)

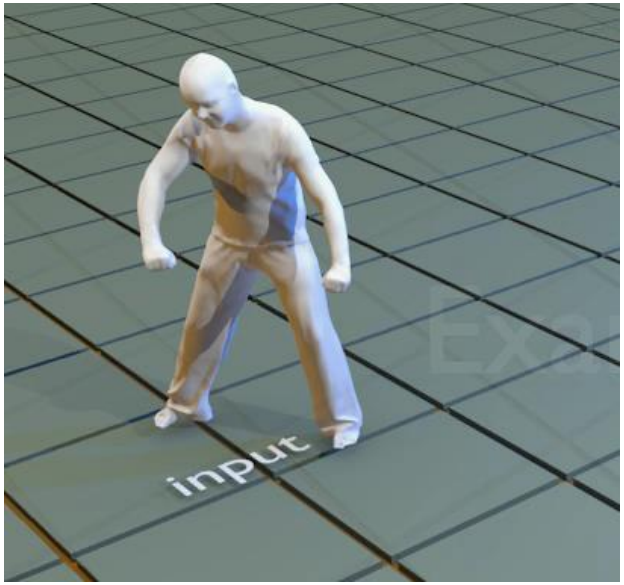
Animation classique

- Chaque image de notre animation est stockée dans une unité complète, séparée du reste.



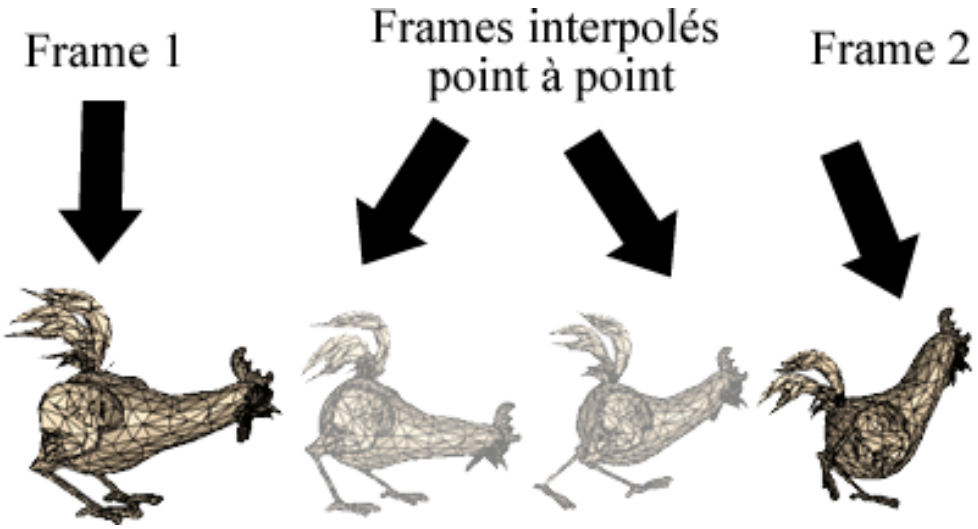
- En 2D on parle de “Sprite”
  - Images 2D affichées en séquence.

- En 3D on parle d’une suite de maillages (mesh)
  - Suite de modèles 3D
  - rendus en séquence.



Animation par images clés

- Variation pour l'animation par **key-frame** classique en 3D :
  - Le modèle contient un nombre de frame réduit pour l'animation.
  - Chaque vertex est interpolé un à un entre les images pour combler les trous

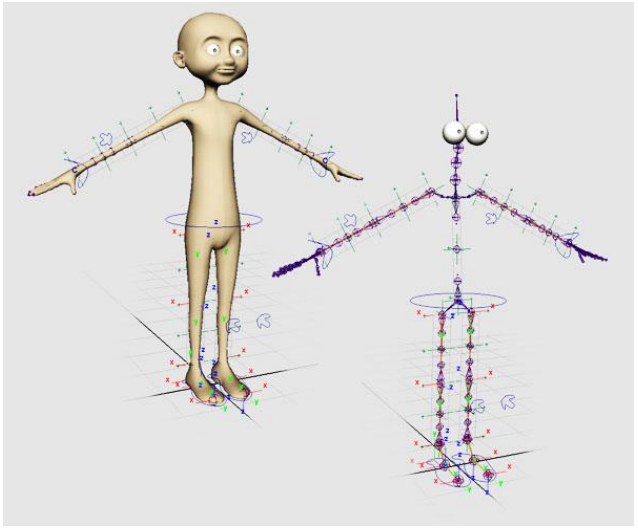


Pourquoi utiliser les squelettes ?

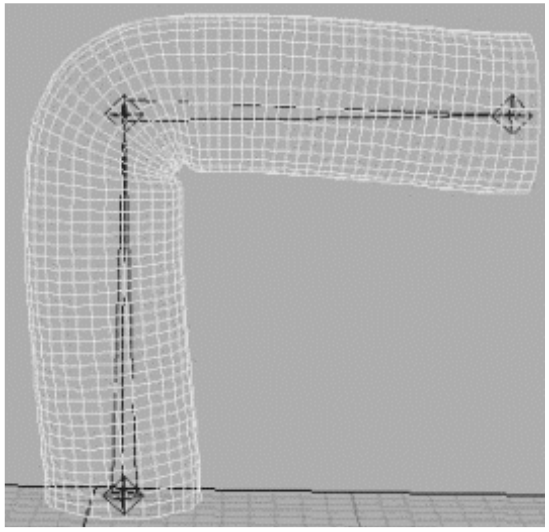
- Beaucoup plus simple à animer.
  - Manipulation d'articulations (sinon chaque vertex indépendamment)
- Beaucoup plus compact que l'animation par keyframe classique.
  - Modèle + squelette stocké 1 fois en mémoire → animation du squelette.
- Assez simple pour permettre l'interaction avec l'environnement
- Possibilité de réutiliser le même squelette pour plusieurs modèles 3D. (Mêmes animations, apparences différentes.)
- Utilisation de méthodes d'interpolation de complexité supérieure à linéaire.
  - Rendu possible puisque l'interpolation se fait sur les articulations, moins nombreuses que les points qui composent le modèle.

Squelette d'animation

- Le modèle 3D contenant la hiérarchie peut être perçu comme une **enveloppe**.
  - Les différents points (vertices) qui composent le modèle sont reliés à différents nœuds de la hiérarchie.
  - L'association d'un point à un élément de la hiérarchie est appelé **"skinning"**



"Lucien", Mathias Aubry, 2008

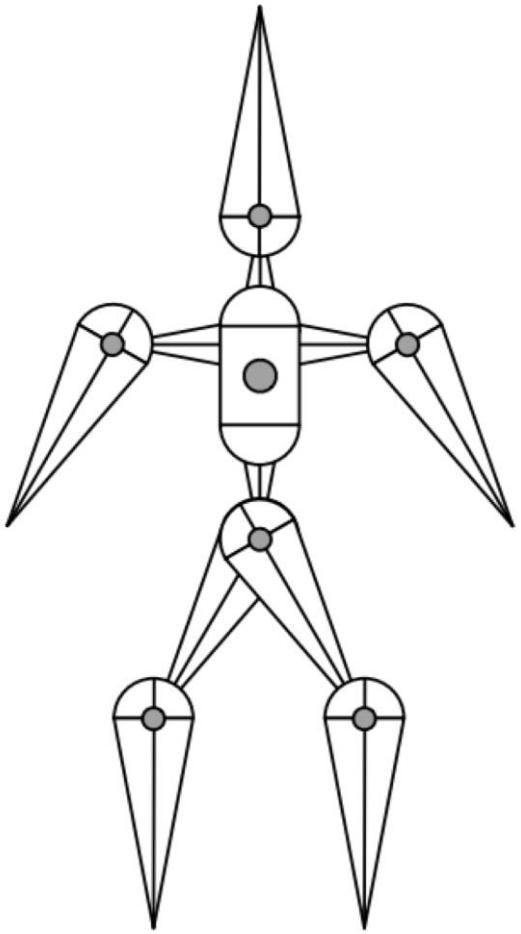


David Lanier, 2002

Squelette d’animation

- Modèle décomposé en une **hiérarchie de repères contraints**

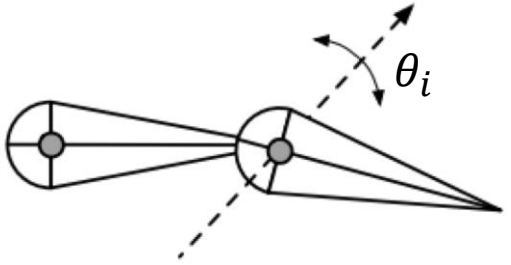
- Pas de géométrie, que des solides appelés **os (*bones*)** et des liaisons appelés **articulations (*joins*)**

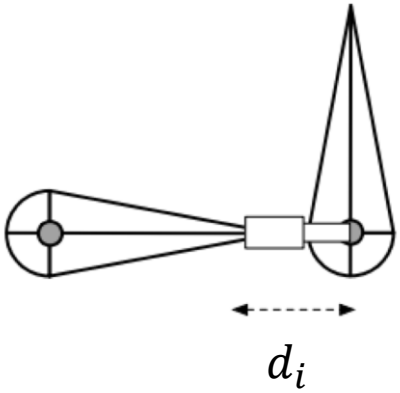


Articulations

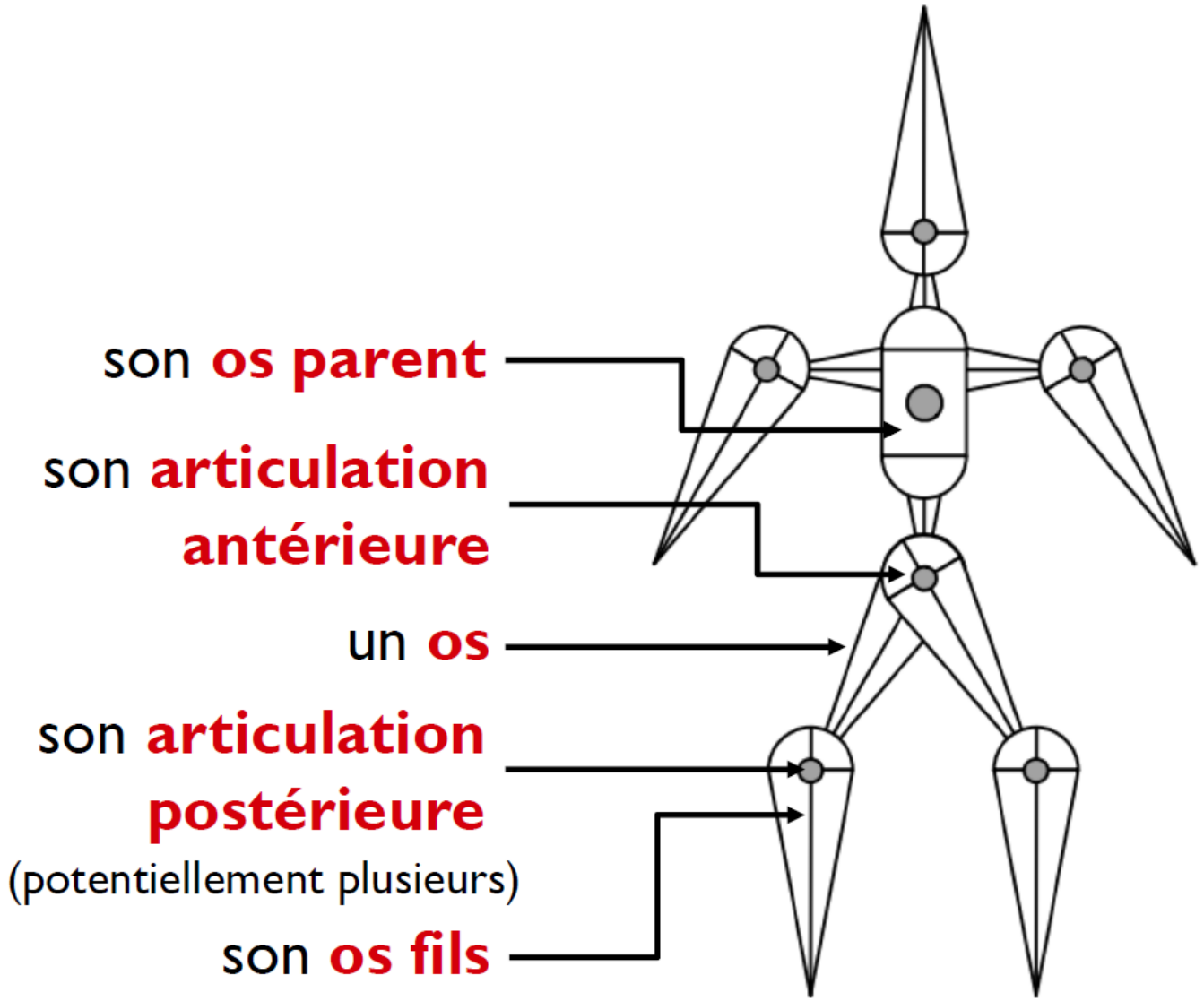
- En général **6 degrés de liberté (DOF)** :
  - 3 translations
  - 3 rotations

- En pratique, souvent des **contraintes** :
- ***Pin*** – rotation autour d'un axe (1 DOF)
- ***Ball*** – rotation arbitraire (3 DOF)
- ***Prism*** – translation selon un axe (1 DOF)

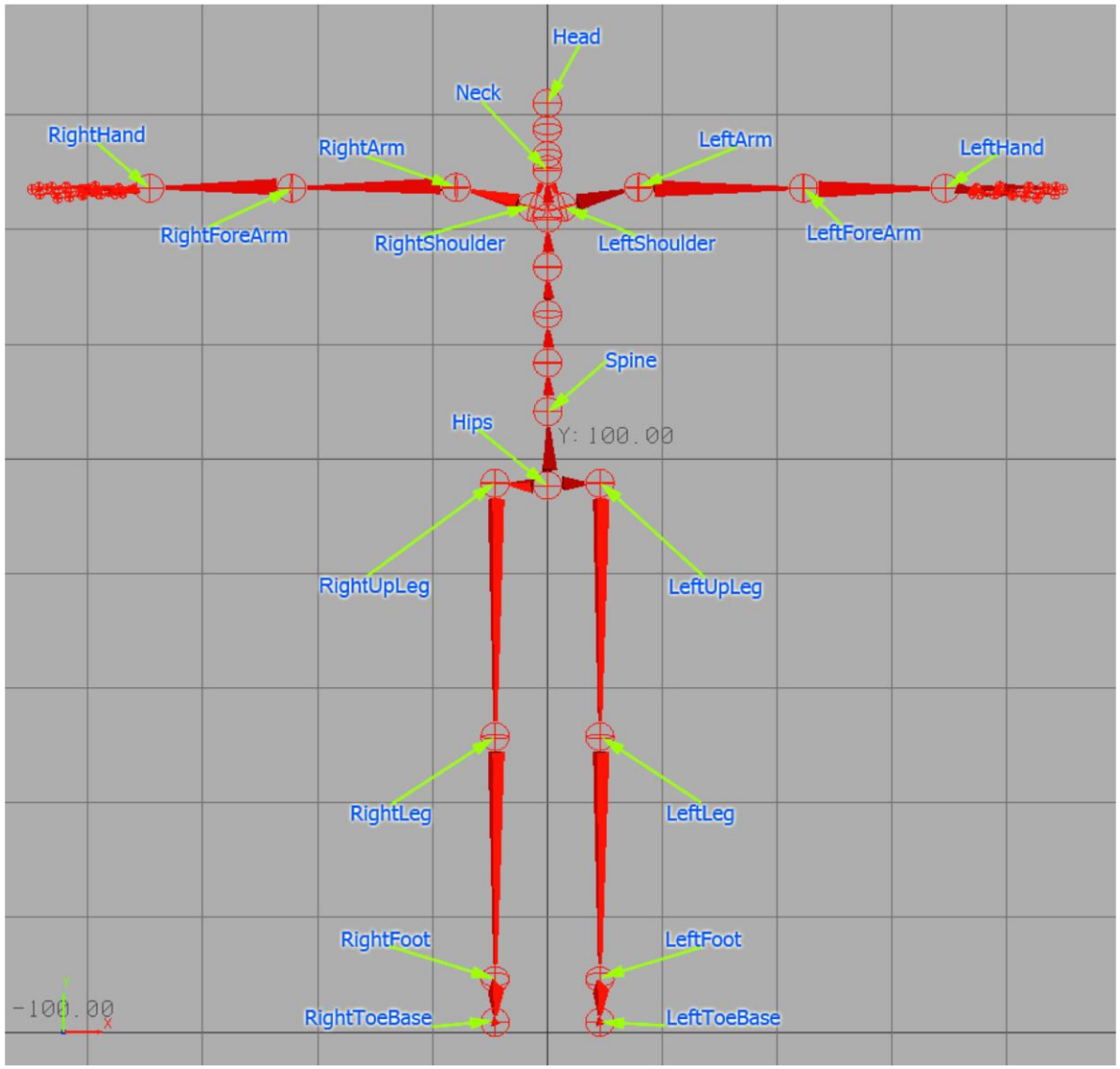




Chaîne articulée

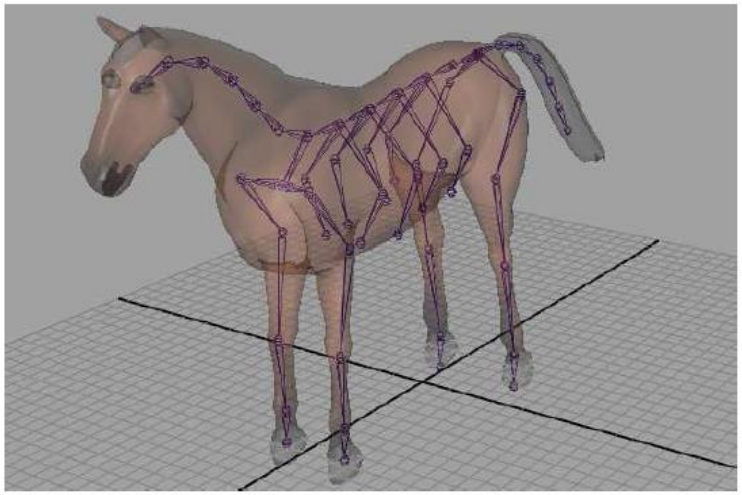


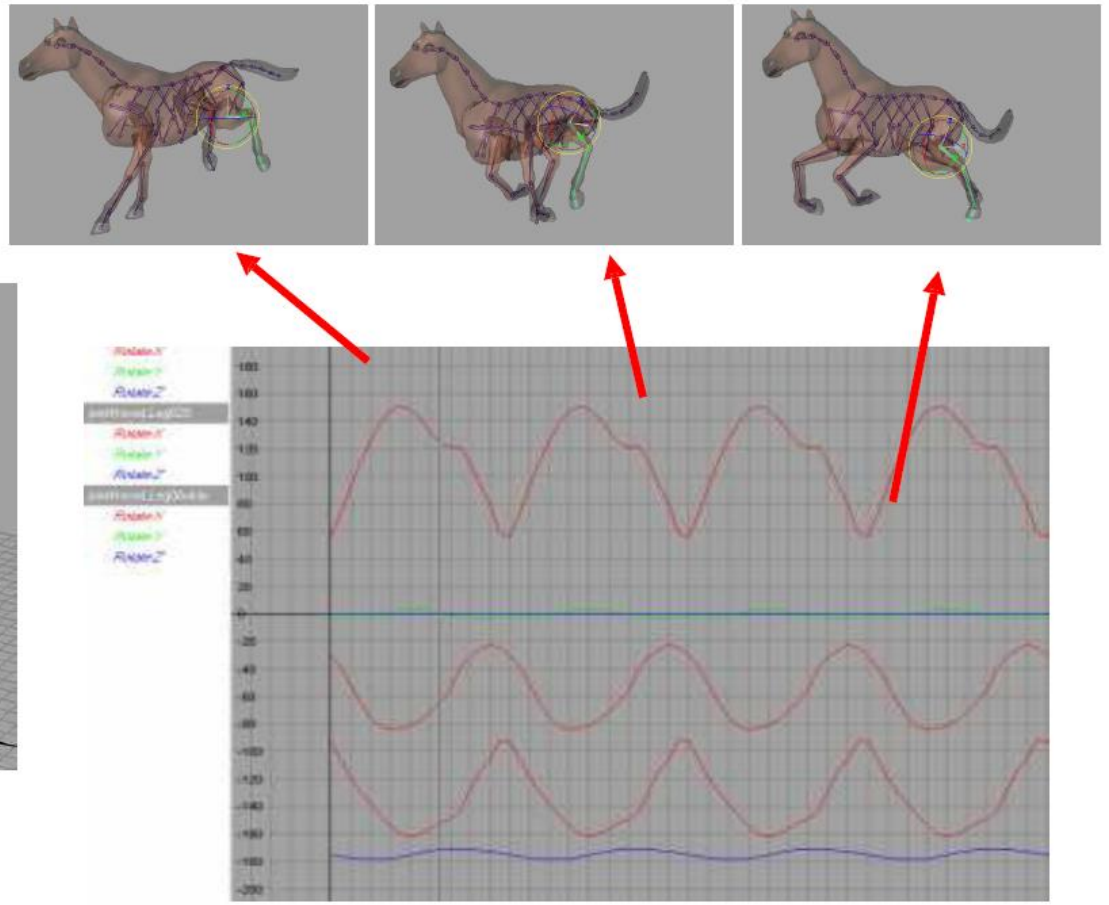
Squelette d’animation



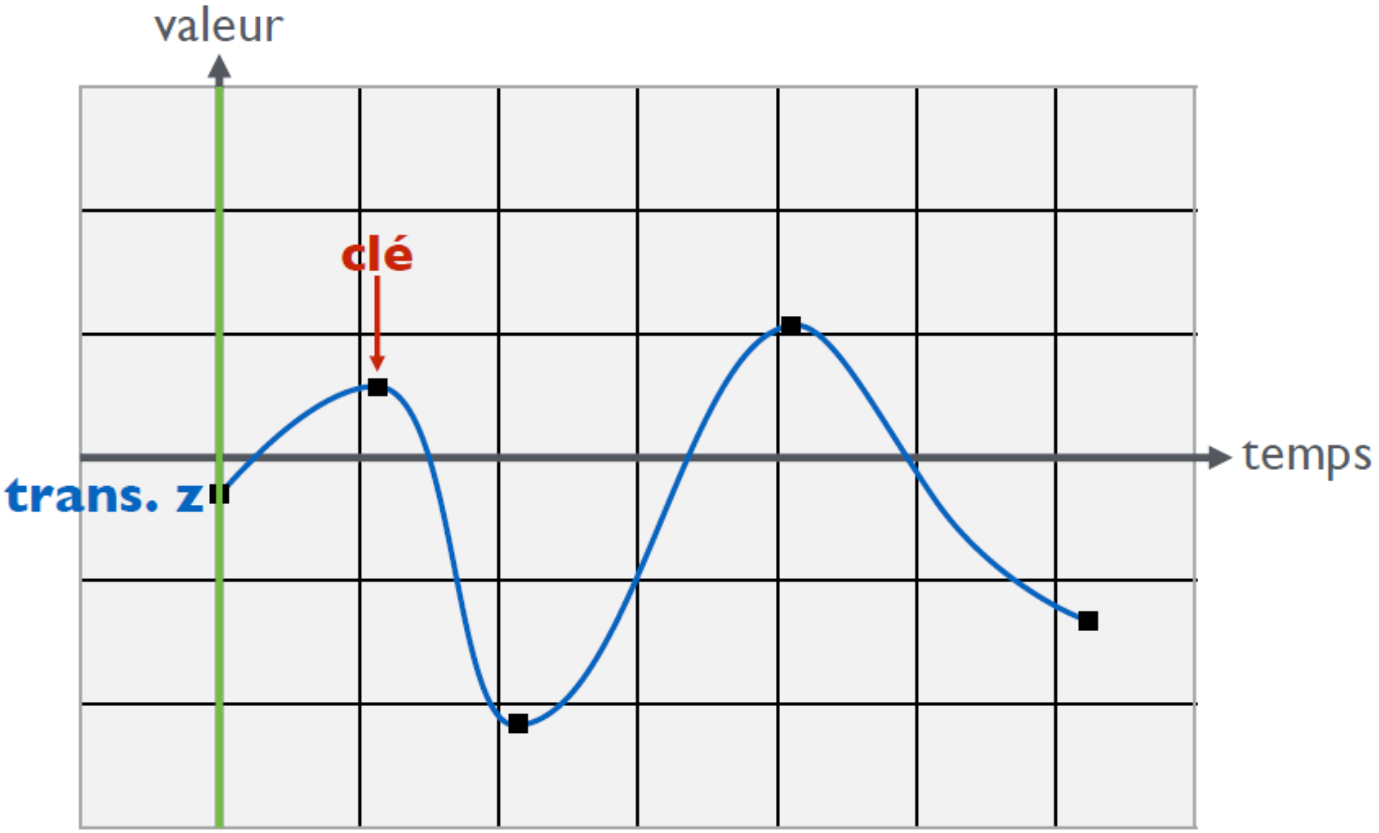
Animation 3D

- **Squelette + interpolation** selon une courbe





Courbe d’animation



Interpolation

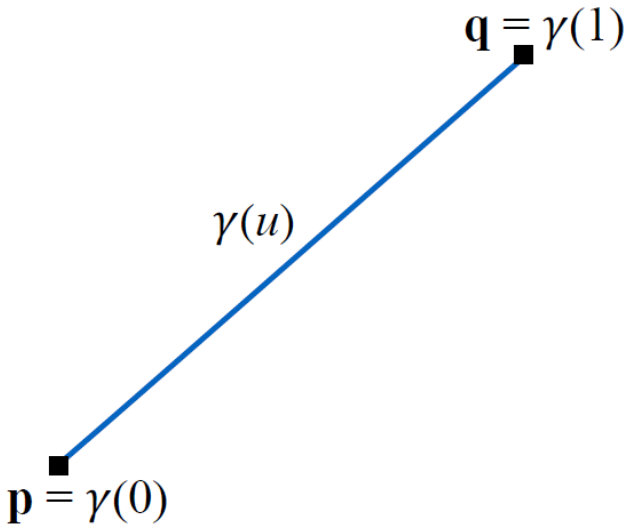
- **Entrées :** valeurs clés (positions)
- **Objectif :** interpoler ces valeurs clés par une fonction continue $\Longrightarrow$courbes d'animation

- **Fonction linéaire :**

$$\gamma(u) = (1-u)\,\mathbf{p} + u\,\mathbf{q}$$

Continuité C^0

(position)



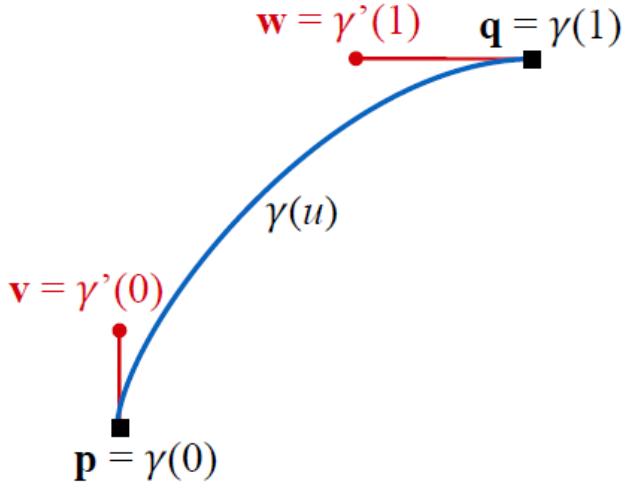
Interpolation

- **Entrées :** valeurs clés (positions et vitesses)
- **Objectif :** interpoler ces valeurs clés par une fonction continue ⟹courbes d'animation
- **Polynôme de degré 3** de la forme :

$$\gamma(u) = \sum_{n=0\ldots3} a_n u^n$$

Continuité C^1 entre deux clés

(positions et tangentes)



- Déterminer les paramètres en interpolant (ou approximant) au mieux les valeurs clés
- Degré 3 ⟹4 contraintes suffisantes pour résolution exacte

Interpolation

- Polynômes d’Hermitte
- Splines de Catmull-Rom
- Interpolation de Bézier cubique
- Comme vu aux cours précédents…

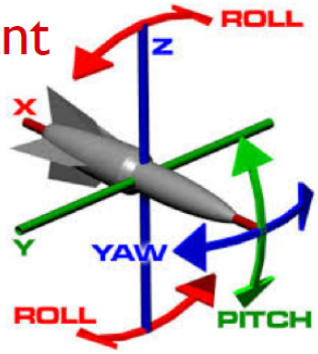
Interpolation des rotations

Angles d'Euler

- 1 angle par axe : $(\theta_x , \theta_y , \theta_z)$
- $$M = R_{x,\theta x}\, R_{y,\theta y}\, R_{z,\theta z} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & cos\theta_x & -sin\theta_x \\ 0 & sin\theta_x & cos\theta_x \end{bmatrix} \begin{bmatrix} cos\theta_y & 0 & sin\theta_y \\ 0 & 1 & 0 \\ -sin\theta_y & 0 & cos\theta_y \end{bmatrix} \begin{bmatrix} cos\theta_z & -sin\theta_z & 0 \\ sin\theta_z & cos\theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

  $\Longrightarrow$ attention, l'ordre des multiplications est important
- Interpoler chaque angle

  $\Longrightarrow$ intuitif et peu couteux



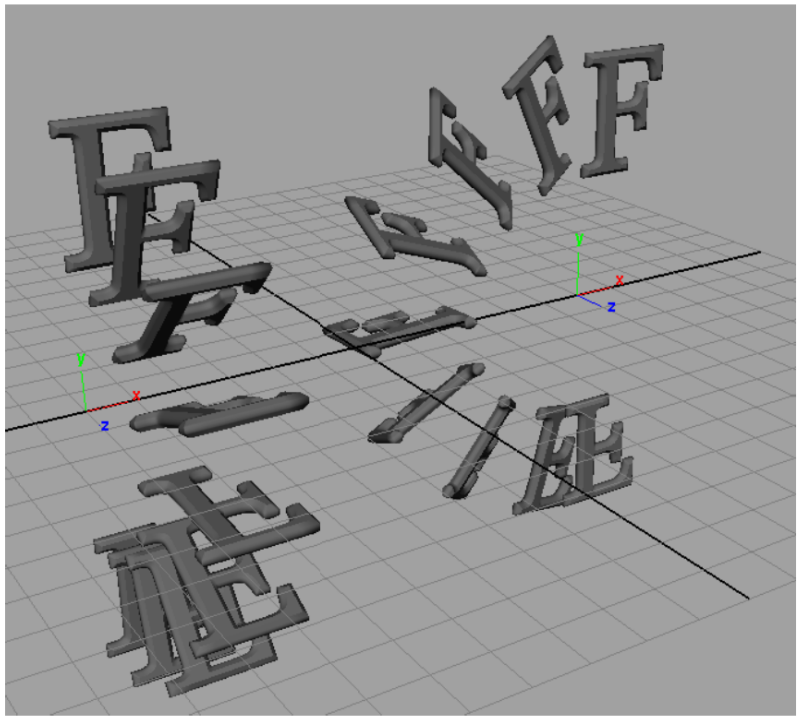
Limitation

Non-unicité de la trajectoire

$[\theta_x,\theta_y,\theta_z] = [0,0,0]$

$[\theta_x,\theta_y,\theta_z] = [\pi,0,0]$

$$M = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}$$



$[\theta_x,\theta_y,\theta_z] = [0,0,0]$

$[\theta_x,\theta_y,\theta_z] = [0,\pi,\pi]$

$$M = \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}$$

Quaternions

Méthode la plus populaire pour représenter une orientation dans le domaine de.

- Composé de 4 nombres, soient 1 angle et 3 nombres qui composent un vecteur.

Se note:

$$q = [s, x, y, z]$$

Ou

$q = [s, \boldsymbol{v}]$, $\boldsymbol{v}$ étant le vecteur (x, y, z)

Quaternions

- Un quaternion est un **4**-vecteur

  $q = (w, x, y, z)$

- Vu comme un scalaire et un **3**-vecteur

  $q = (s, \mathbf{v}) \qquad s = w \qquad \mathbf{v} = (x, y, z)$

  - notation alternative : $q = s + \mathbf{v}$

- Quaternions unitaires = **4**-vecteurs unitaires :

  $w^2 + x^2 + y^2 + z^2 = 1, \quad \text{ou} \quad s^2 + \|\mathbf{v}\|^2 = 1$

  - **s** et **||v||** vus comme **sin** et **cos** d'un angle : $q = \cos\psi + \hat{\mathbf{v}}\sin\psi$

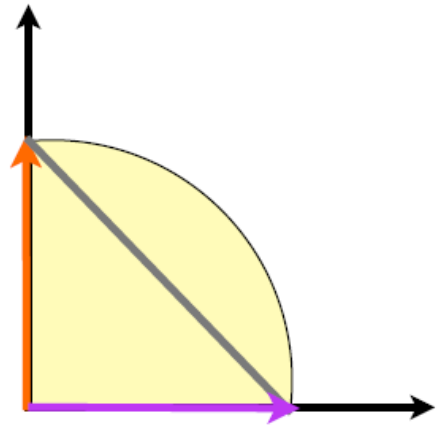
- Représentation de rotations type angle/axe
  - direction de **v** donne l'axe de rotation
  - **s** et **||v||** donnent l'angle de rotation

Pourquoi les quaternions ?

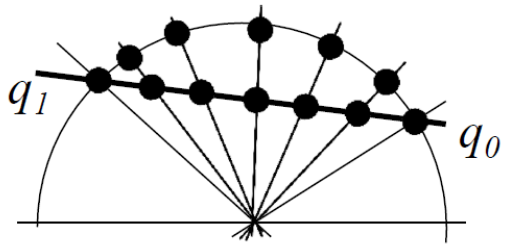
- Rapides, peu d'opérations, non redondants
- Numériquement stables aux changements incrémentaux
- Compositions de rotations faciles
- Se convertit en matrice
- Raison pincipale : interpolation spherique

Interpolations entre quaternions

- Pourquoi pas une interpolation linéaire ?
  - Besoin d'être normalisé
  - N'a pas une vitesse constante d'interpolation



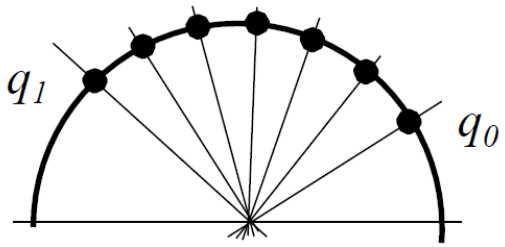
$$\frac{(1-\alpha)x + \alpha y}{||(1-\alpha)x + \alpha y||}$$

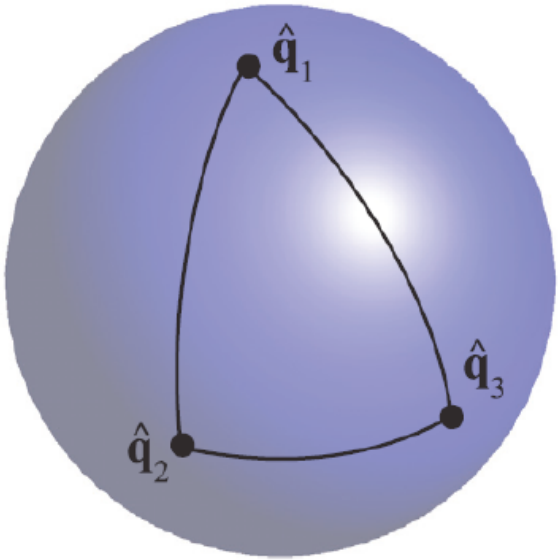


Spherical Linear Interpolation (slerp)

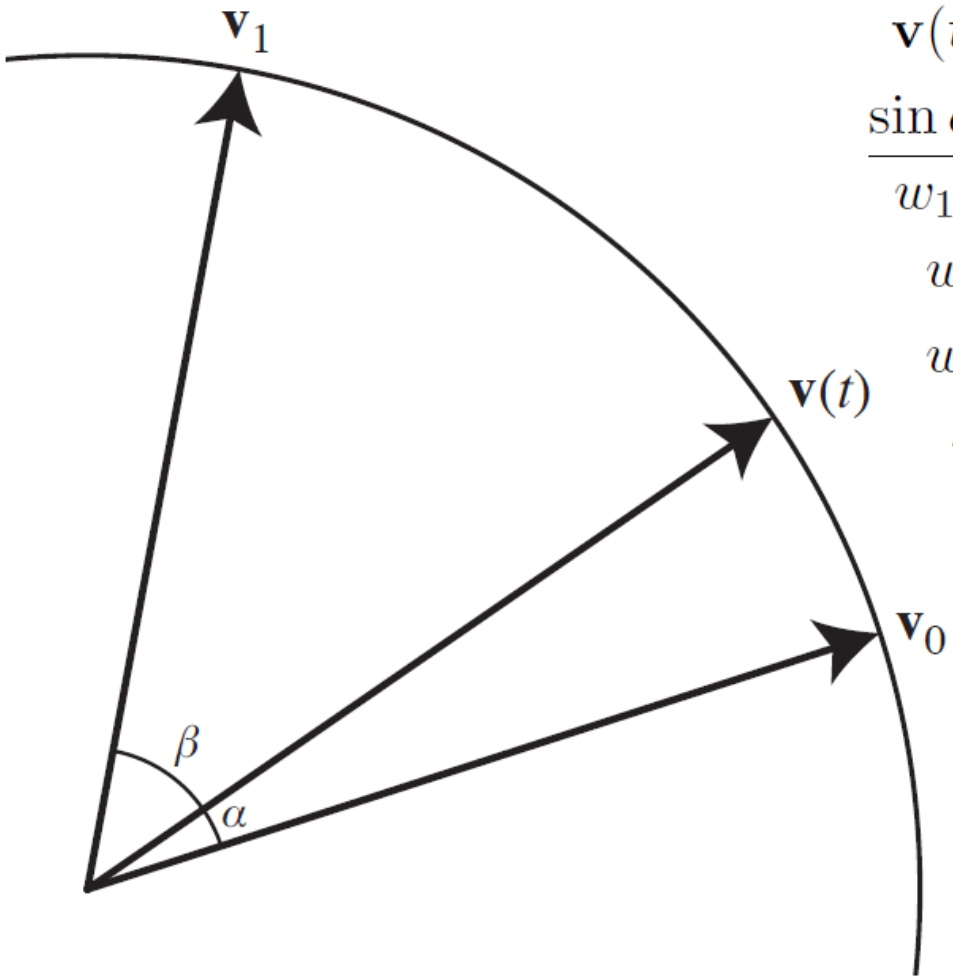
- Interpolation intuitive entre les orientations
  - Bien défini avec les quaternions
  - Très utile pour l'animation
  - Interpolation entre 2 quaternion = chemin le plus court entre 2 point sur une sphere

Geodesic, on Great Circle





Spherical linear interpolation ("slerp")



$$\alpha + \beta = \psi$$

$$\mathbf{v}(t) = w_0 \mathbf{v}_0 + w_1 \mathbf{v}_1$$

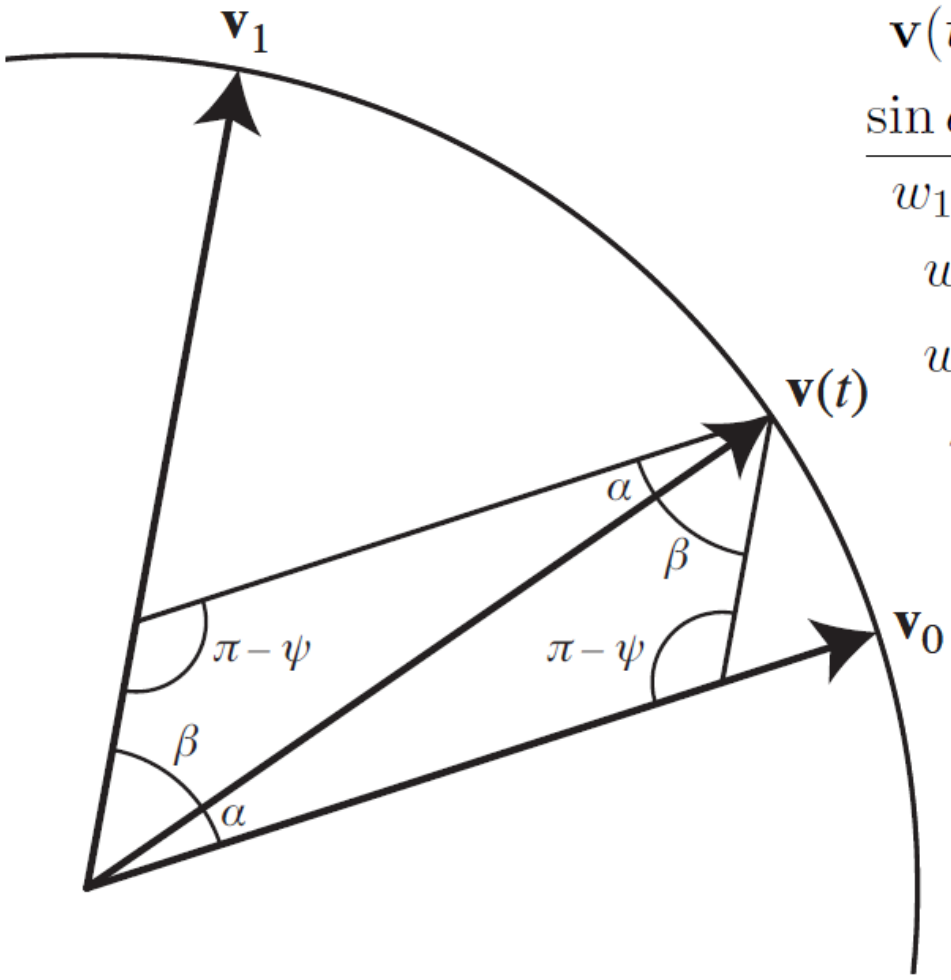
$$\frac{\sin\alpha}{w_1} = \frac{\sin\beta}{w_0} = \frac{\sin(\pi - \psi)}{1} = \sin\psi$$

$$w_0 = \sin\beta / \sin\psi$$

$$w_1 = \sin\alpha / \sin\psi$$

$$\psi = \cos^{-1}(\mathbf{v}_0 \cdot \mathbf{v}_1)$$

Spherical linear interpolation ("slerp")



$$\alpha + \beta = \psi$$

$$\mathbf{v}(t) = w_0 \mathbf{v}_0 + w_1 \mathbf{v}_1$$

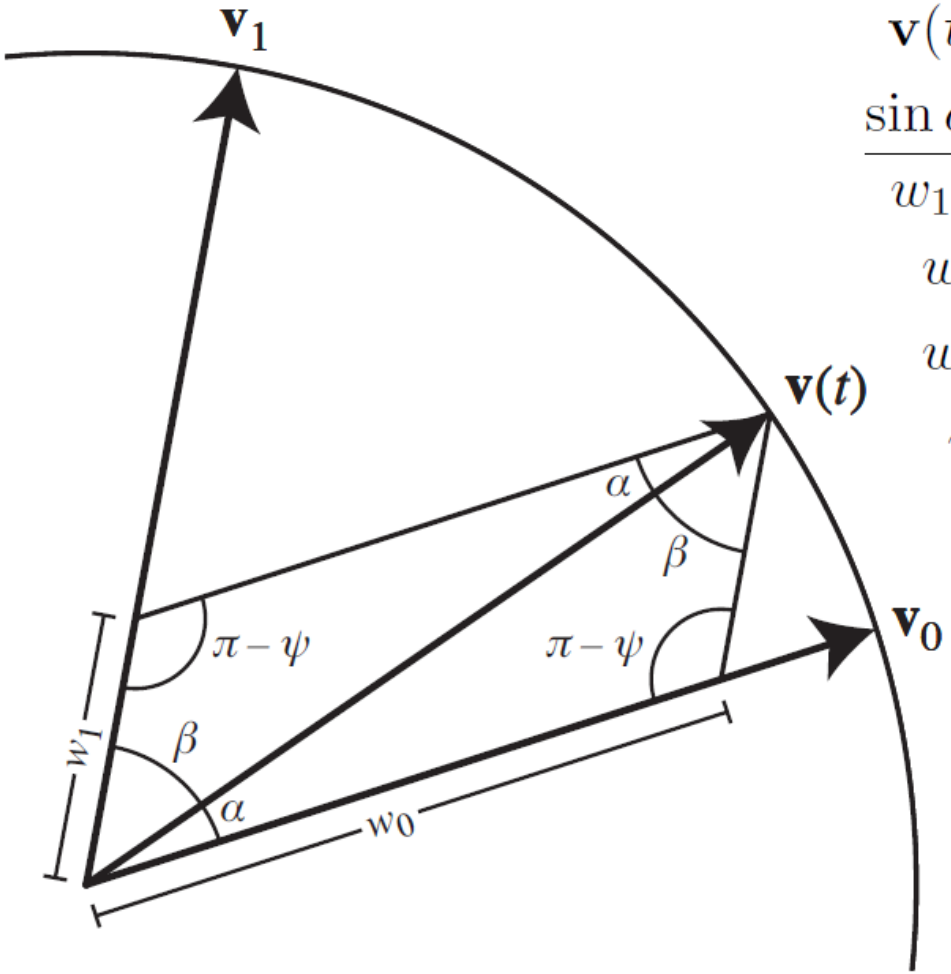
$$\frac{\sin \alpha}{w_1} = \frac{\sin \beta}{w_0} = \frac{\sin(\pi - \psi)}{1} = \sin \psi$$

$$w_0 = \sin \beta / \sin \psi$$

$$w_1 = \sin \alpha / \sin \psi$$

$$\psi = \cos^{-1}(\mathbf{v}_0 \cdot \mathbf{v}_1)$$

Spherical linear interpolation ("slerp")



$$\alpha + \beta = \psi$$

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$$w_0 = \sin\beta / \sin\psi$$

$$w_1 = \sin\alpha / \sin\psi$$

$$\psi = \cos^{-1}(\mathbf{v}_0 \cdot \mathbf{v}_1)$$

Interpolation de quaternions

- Spherical linear interpolation : fonctionne naturellement en toute dimension
- Traverse un arc sur la sphere unité des quaternions
  - Vitesse de rotation angulaire uniforme autour d'un axe fixe

$$\psi = \cos^{-1}(q_0 \cdot q_1)$$

$$q(t) = \frac{q_0 \sin(1-t)\psi + q_1 \sin t}{\sin}$$

Cinématique

Mouvement non-contraint

- Hocher la tête, faire un signe de la main…

$\Longrightarrow$Cinématique directe (FK)

Mouvement contraint

- Attraper un objet, marcher sur le sol…

$\Longrightarrow$Cinématique inverse (IK)

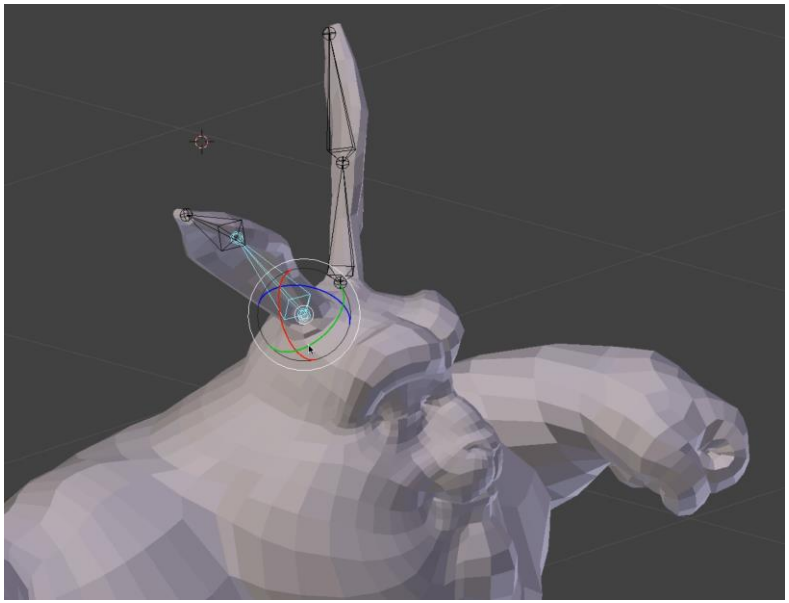
Cinématique directe

Entrées : configuration de la chaine = valeurs des paramètres des articulations à un temps donnée :

$$\mathbf{q} = (\theta 1, \theta 2, \theta 3, \ldots, d1, d2, \ldots)$$

Sortie : position **p** d'une extrémité de la chaîne (coordonnées cartésiennes + orientation, 3 ou 6D)

On **calcule** : $\mathbf{p} = f(\mathbf{q})$



Cinématique inverse

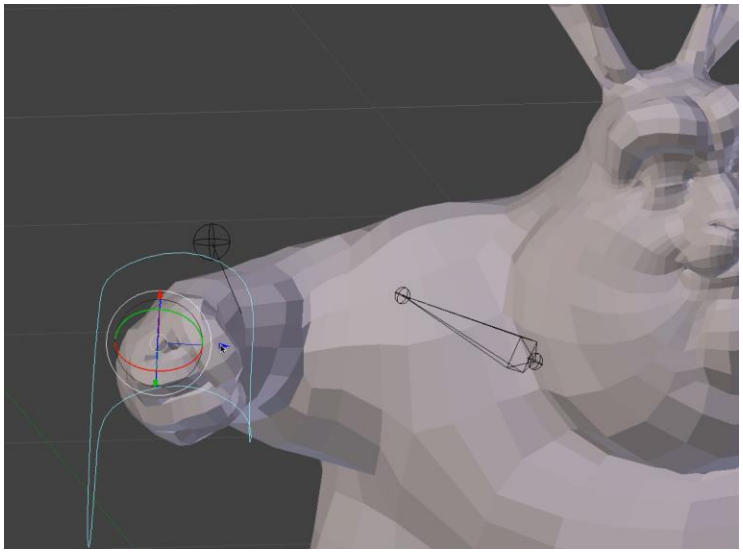
Entrée : position à atteindre **p**

Sortie : valeurs des paramètres des articulations

$\mathbf{q} = (\theta 1, \theta 2, \theta 3, \ldots, d1, d2, \ldots)$

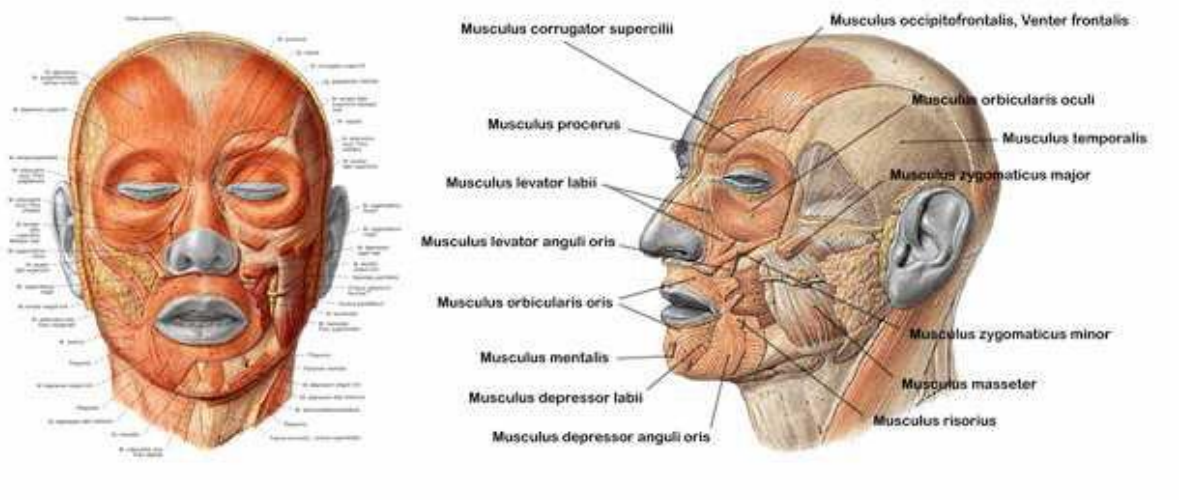
On veut trouver **q** tel que

$f(\mathbf{q}) = \mathbf{p}$ c'est à dire $\mathbf{q} = f^{-1}(\mathbf{p})$



Déformation de surface

- Squelette d'animation vs. modèle visuel
- En réalité, forme visible composée de tissus organiques

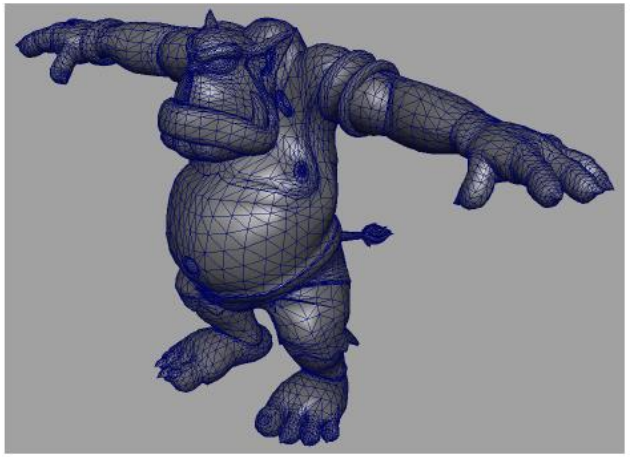


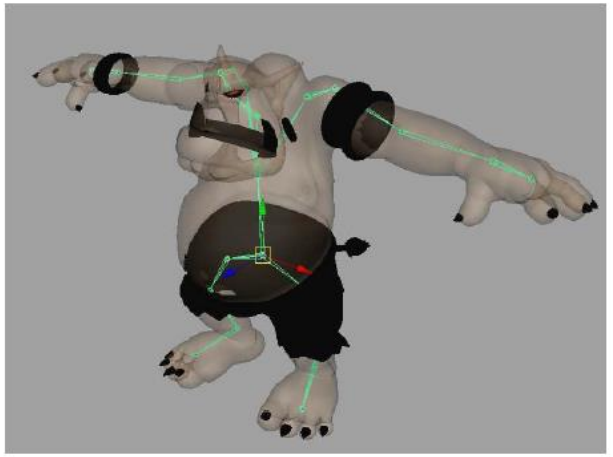
Modèle visuel

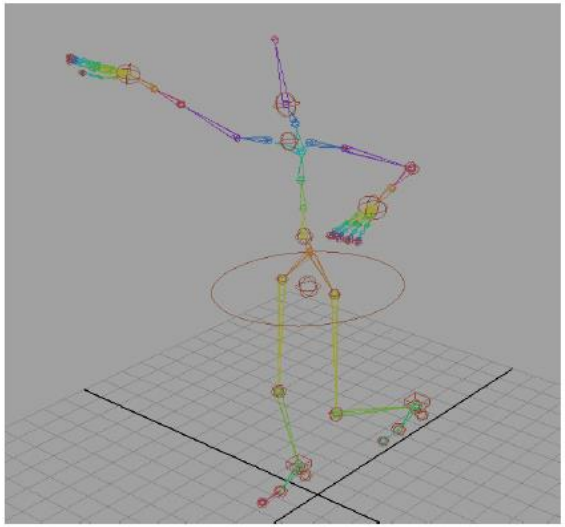
- Le niveau de réalisme dépend de l'application

Pipeline 3D

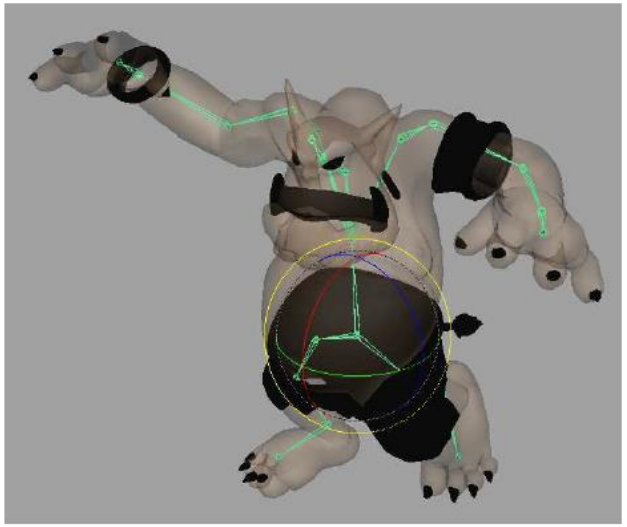
Squelettage ou **rigging**
+ calcul des poids de **skinning**



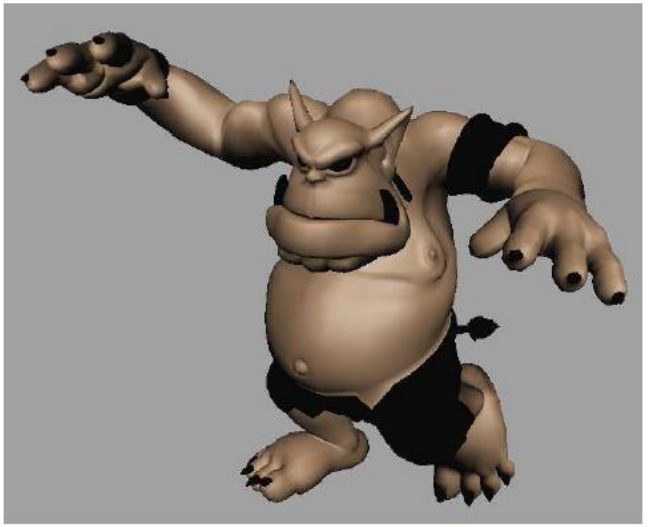




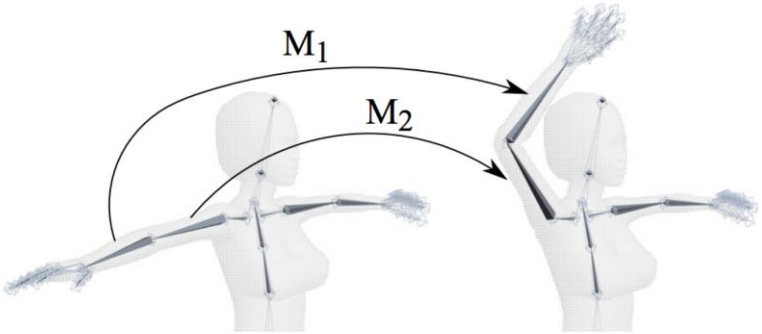
Animation



Calcul des positions
des sommets du maillage



Rigging



- **Entrées :** sommets p_i de la surface 3D (*skin*) et squelette dans une pose de base (*bind/rest pose*)

- **Sortie :** positions $\boldsymbol{p}_i{}'$ après mouvement du squelette
  - On connaît $\boldsymbol{p}_i$ dans le repère monde (ou objet)
  - On connaît la matrice B_j de passage de l'os j au repos au repère monde

$\Longrightarrow$nouvelles coordonnées : $\boldsymbol{p}_i{}' = T_j {B_j}^{-1} \boldsymbol{p}_i = M_j \boldsymbol{p}_i$

- T_j la matrice de transformation de l'os j

Skinning linéaire

Linear Blend Skinning [Alexa et al. 02]

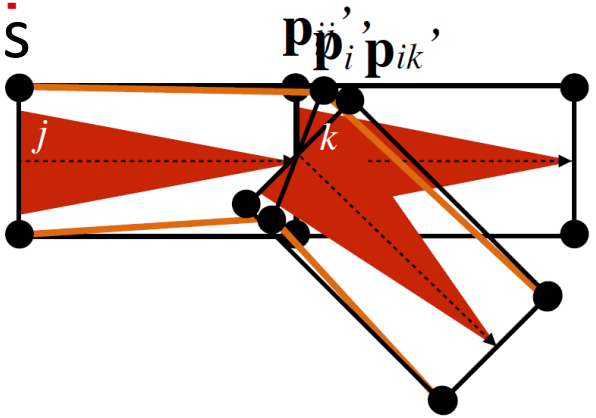
- Sommets influencés par **plusieurs os**

$\Longrightarrow$**interpolation linéaire** des positions

- Si $\boldsymbol{p}_i$ lié aux os j et k :

$$\boldsymbol{p}_i' = w\,\boldsymbol{p}_{ij}' + (1\text{-}w)\,\boldsymbol{p}_{ik}'$$

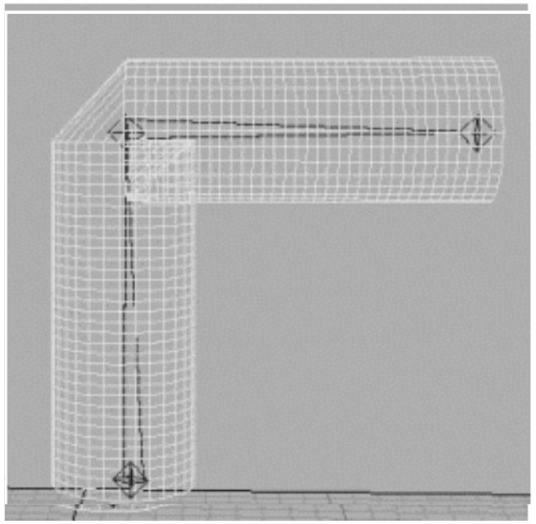
$w \in [0,1]$ *skin weight*



Cas général

$$\boldsymbol{p}_i' = \sum_j w_{ij} T_j B_j^{-1} \boldsymbol{p}_i$$
$$= \sum_j w_{ij} M_j \boldsymbol{p}_i$$

avec $\sum_j w_{ij} = 1$



David Lanier, 2002

Poids de skinning

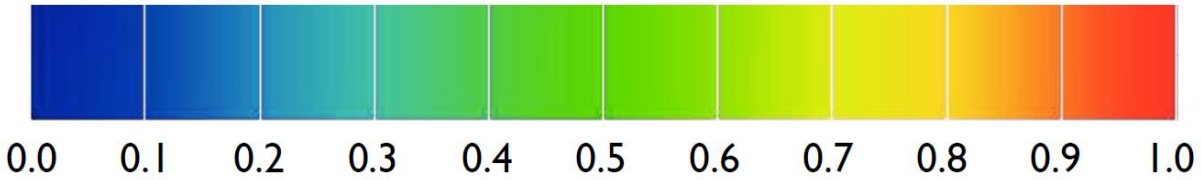
Spécifiés (« peints ») par un artiste os par os

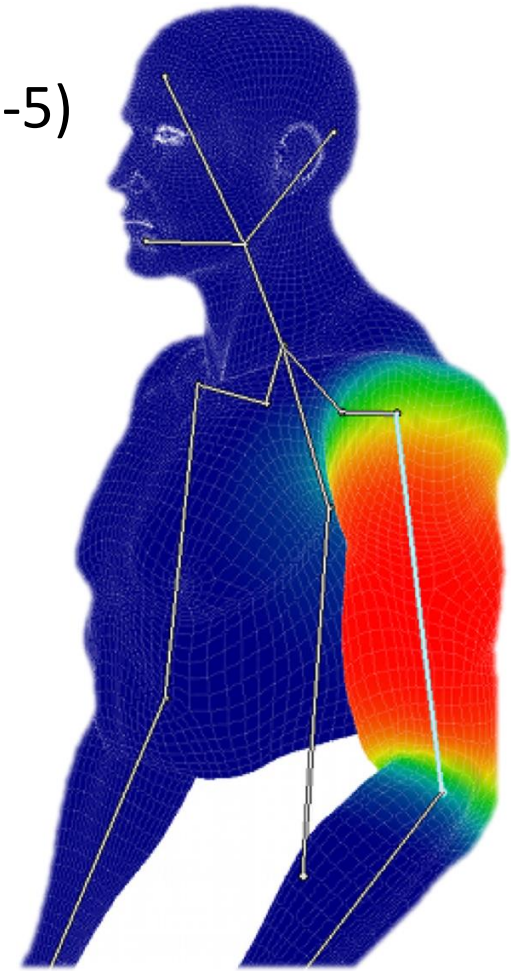
- w_{ij} = 1⟹mouvement rigide avec l'os
- Limiter le nombre de poids par sommet (4-5)

⟹ coût de la sommation

⟹ stockage mémoire

et/ou calculés automatiquement
(distance euclidienne, harmonique, géodésique)





Skinning linéaire

***1. Rigging* – pré-calcul**

$\Longrightarrow$matrices de pose : B_j

$\Longrightarrow$poids de *skinning* : w_{ij}

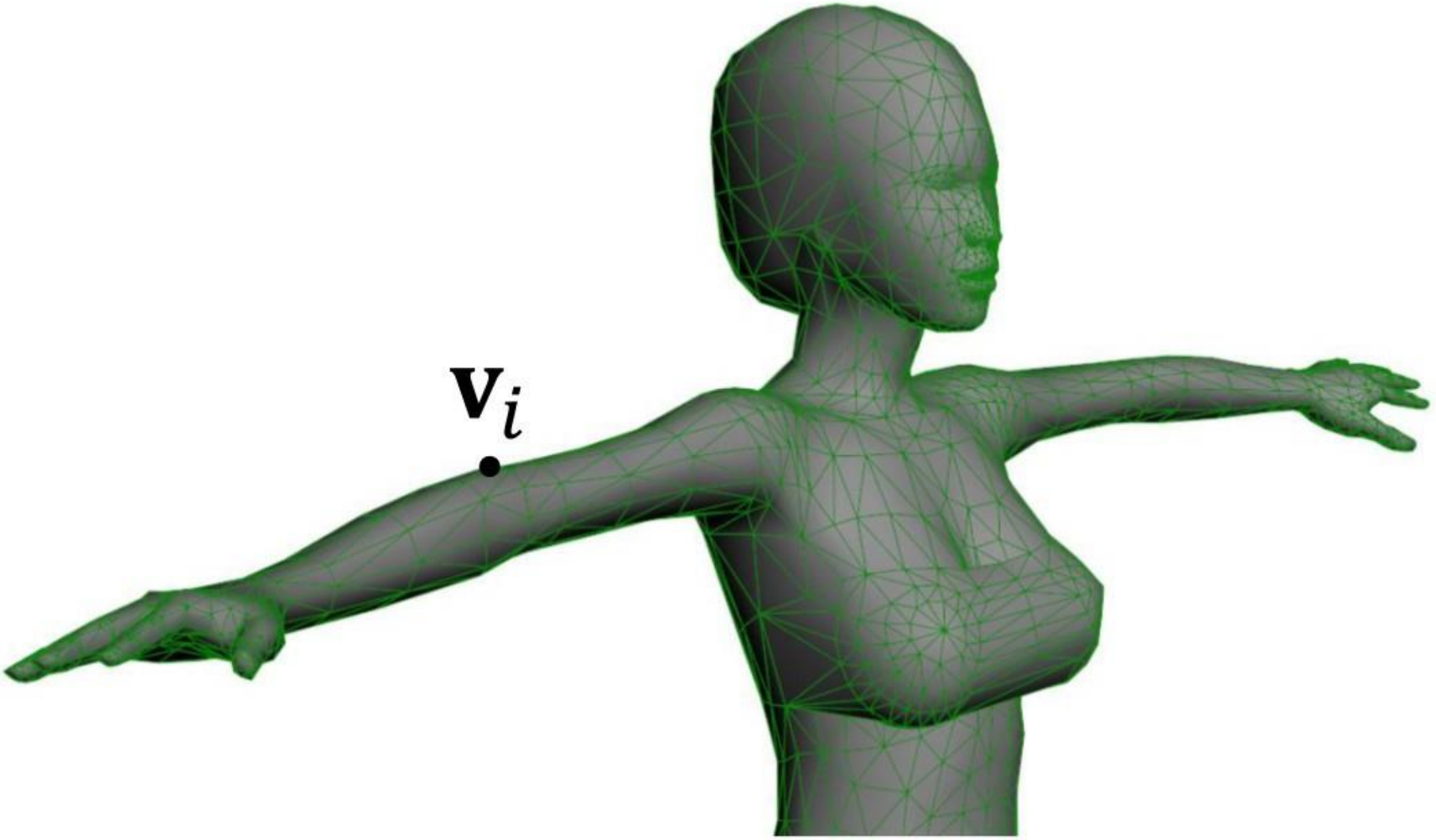
2. Cinématique direct ou inverse – à chaque temps *t*

$\Longrightarrow$matrices de transformation $M_j(t) = T_j(t){B_j}^{-1}$

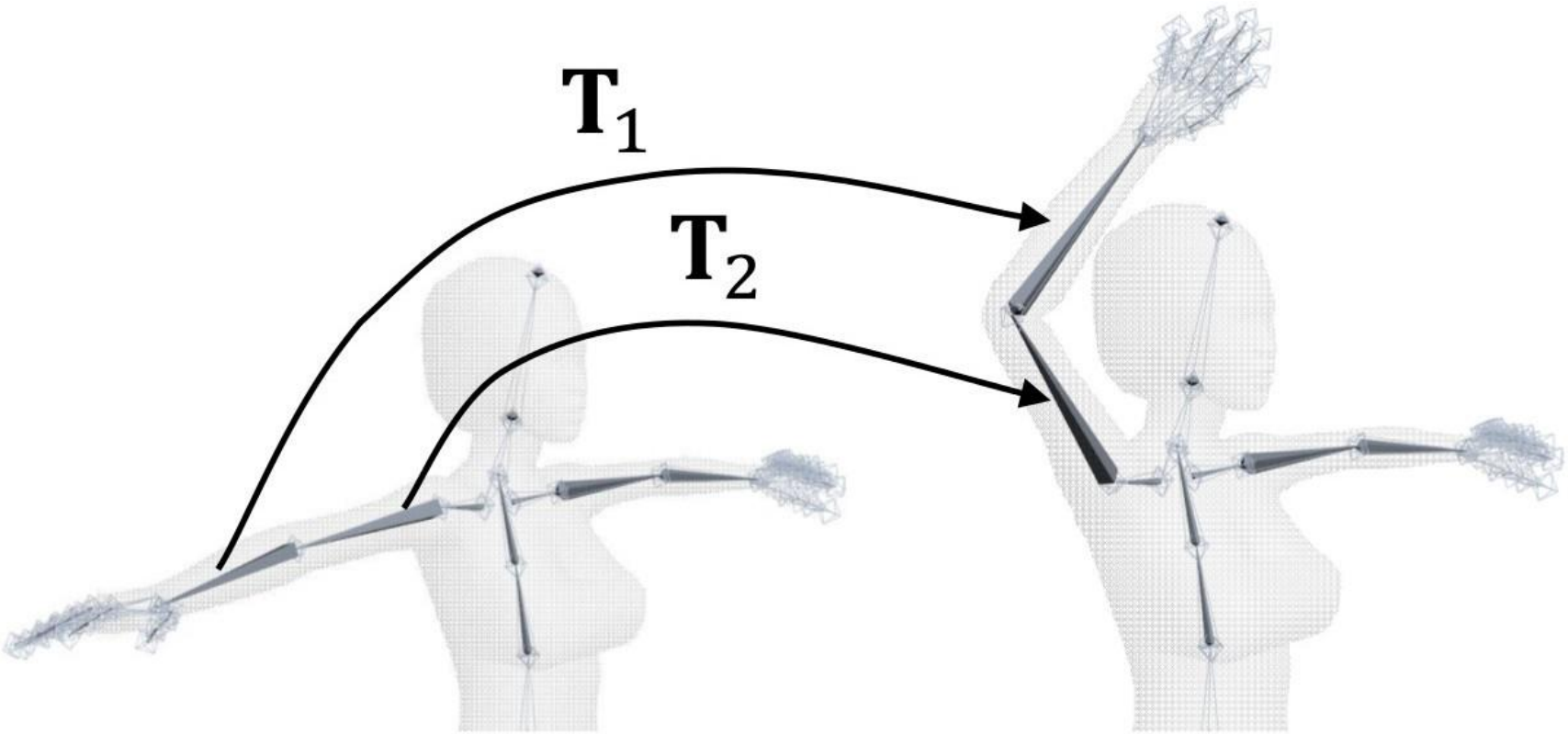
3. Skinning linéaire – *vertex shader*

$\Longrightarrow \boldsymbol{p}_i{}' = \sum_j w_{ij} M_j(t) \boldsymbol{p}_i$

TP :Linear blend skinning

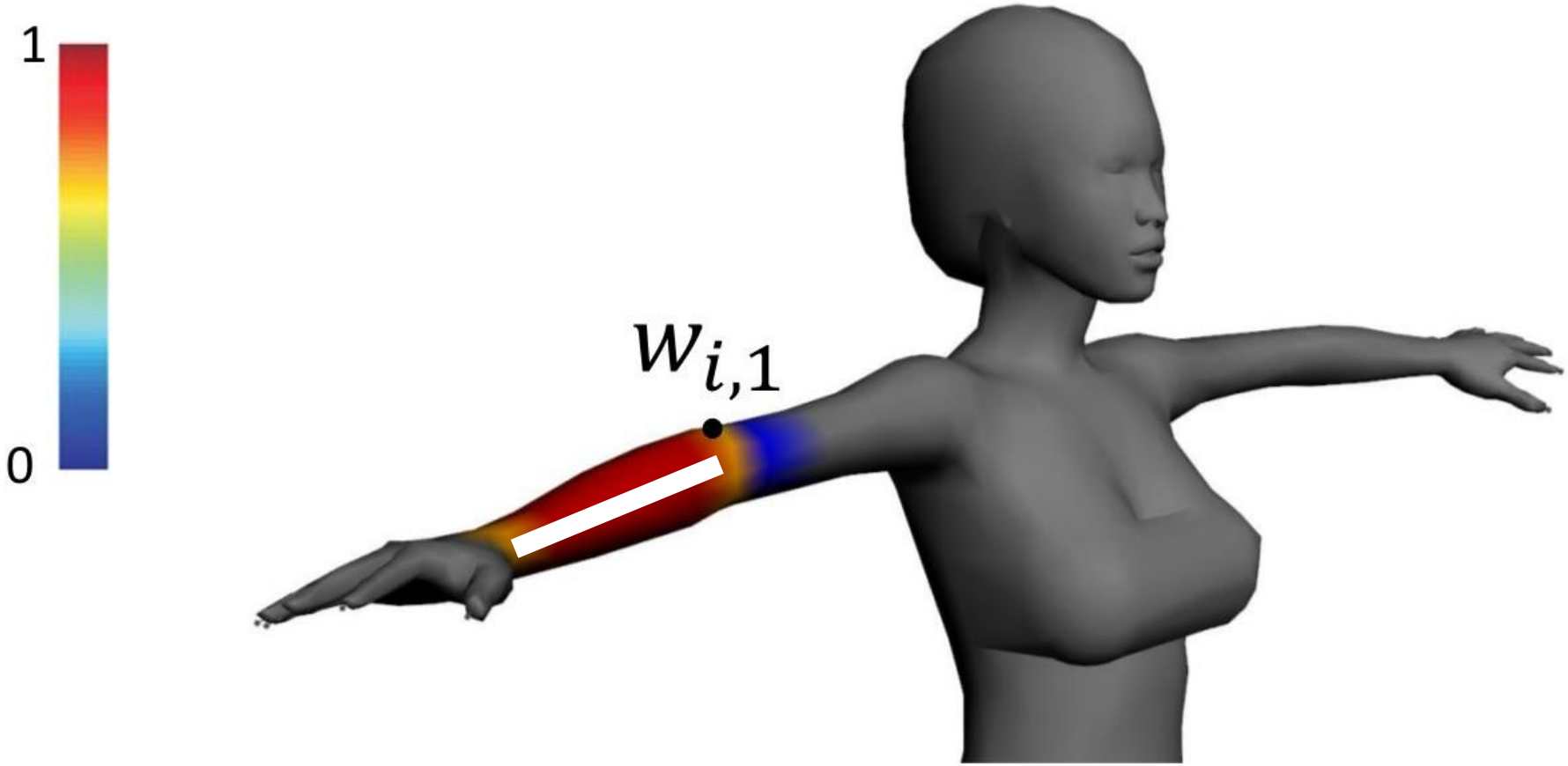


Linear blend skinning

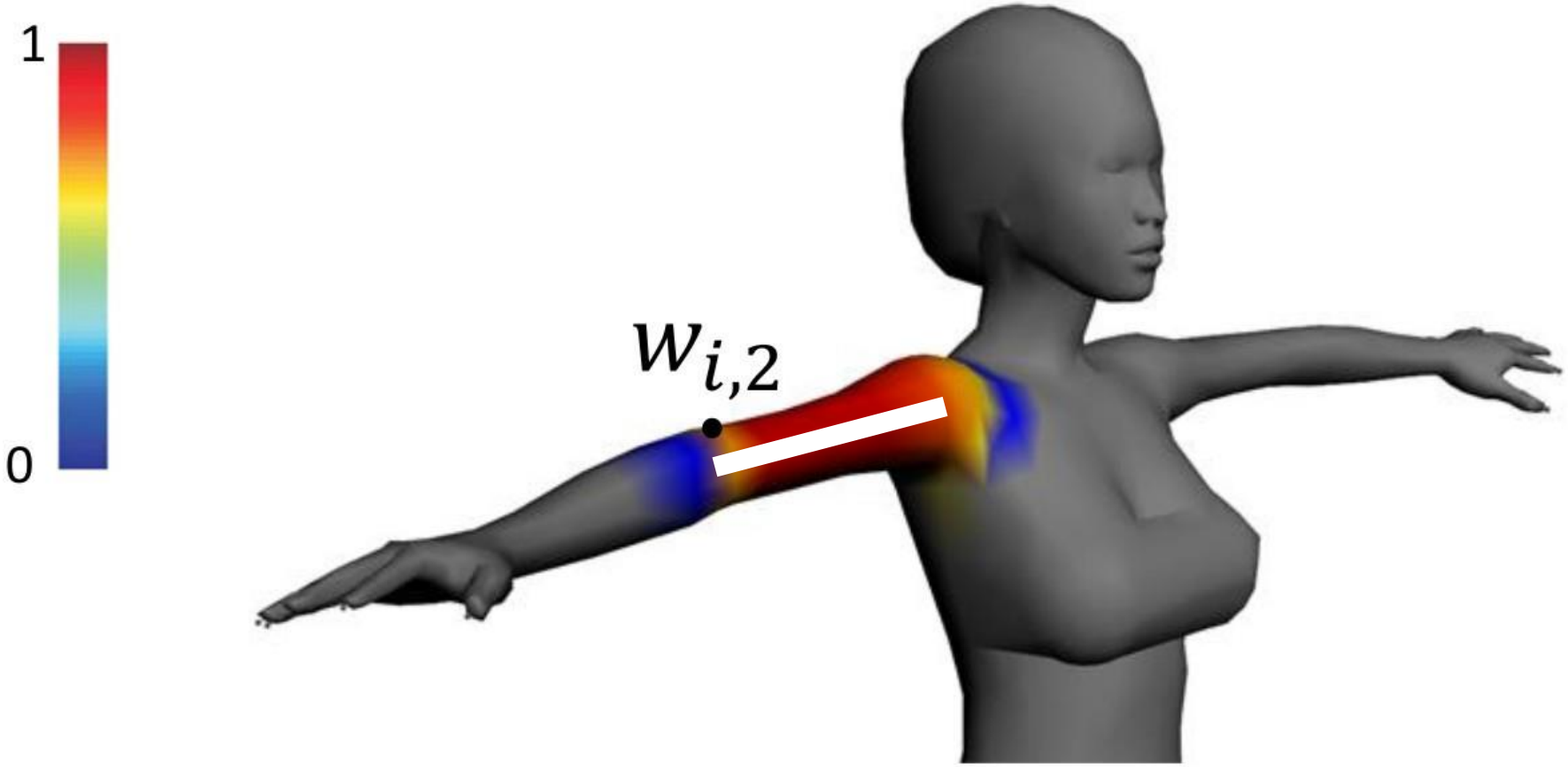


Nous devons définir l’influence des os sur les somets du maillage

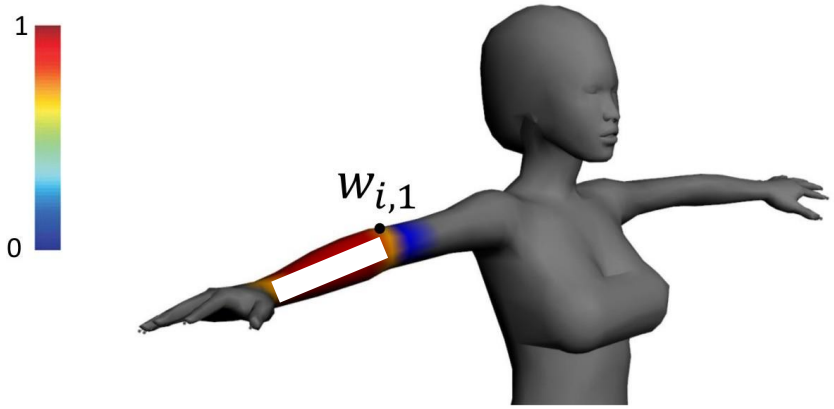
Linear blend skinning

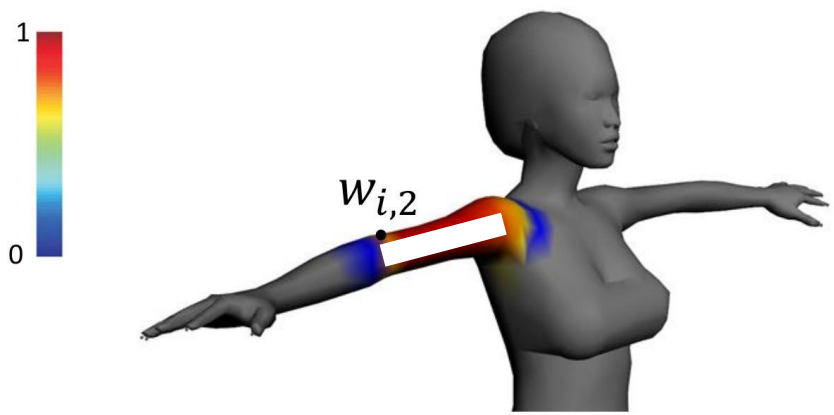


Linear blend skinning



Linear blend skinning





Sommet i

Poids de l'os j sur le sommet i

$$f : v_i \rightarrow \sum_j w_{ij}(R_j . v_i + T_j)$$

Fonction de déformation

Os influençant le sommet i

Rotation de l'os j

Translation de l'os j

Propriété des poids de skinning

$$f : v_i \rightarrow \sum_j w_{ij}(R_j . v_i + T_j)$$

Poids basés sur la distance euclidienne :

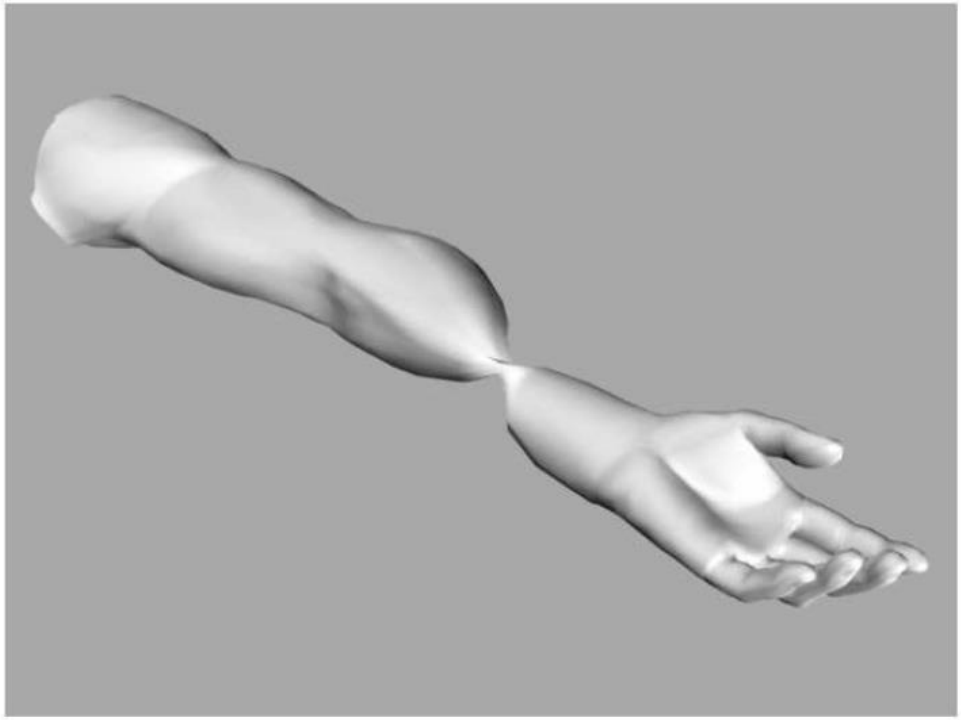
$$w_{ij} = \left(\frac{1}{d_{ij}}\right)^n \text{ avec n>=1}$$

- Positifs $w_{ij} \geqslant 0$
- Affines $\Sigma_j w_{ij} = 1 \quad \rightarrow \quad w_{ij} = \frac{w_{ij}}{\sum w_{ij}}$

Skinning linéaire

- **Limitation : rotations**

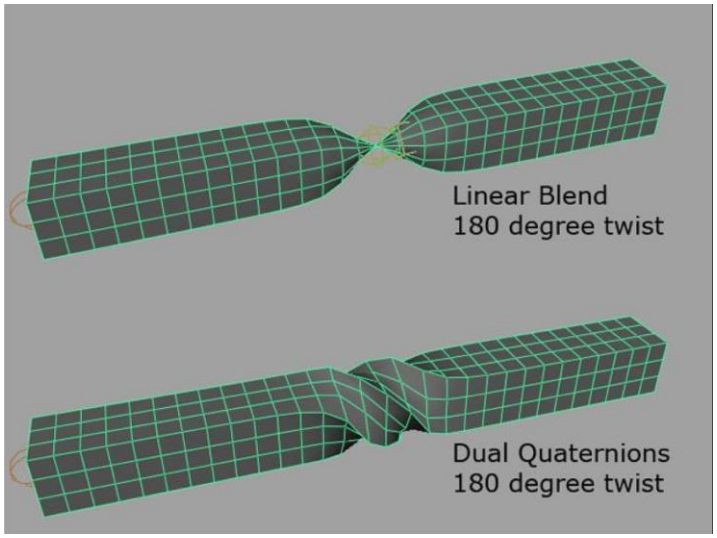
(la moyenne de 2 rotations n’est pas une rotation !)

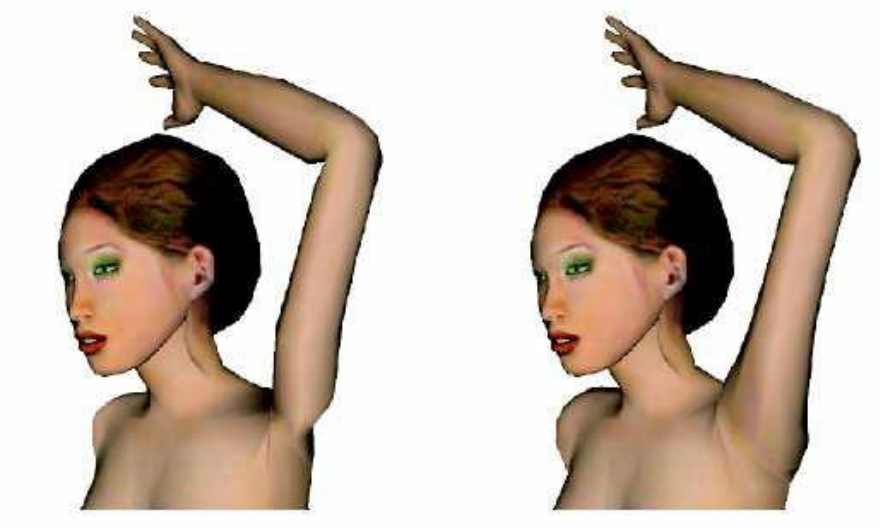


Skinning + quaternions duaux

[Kavan et al. 08]

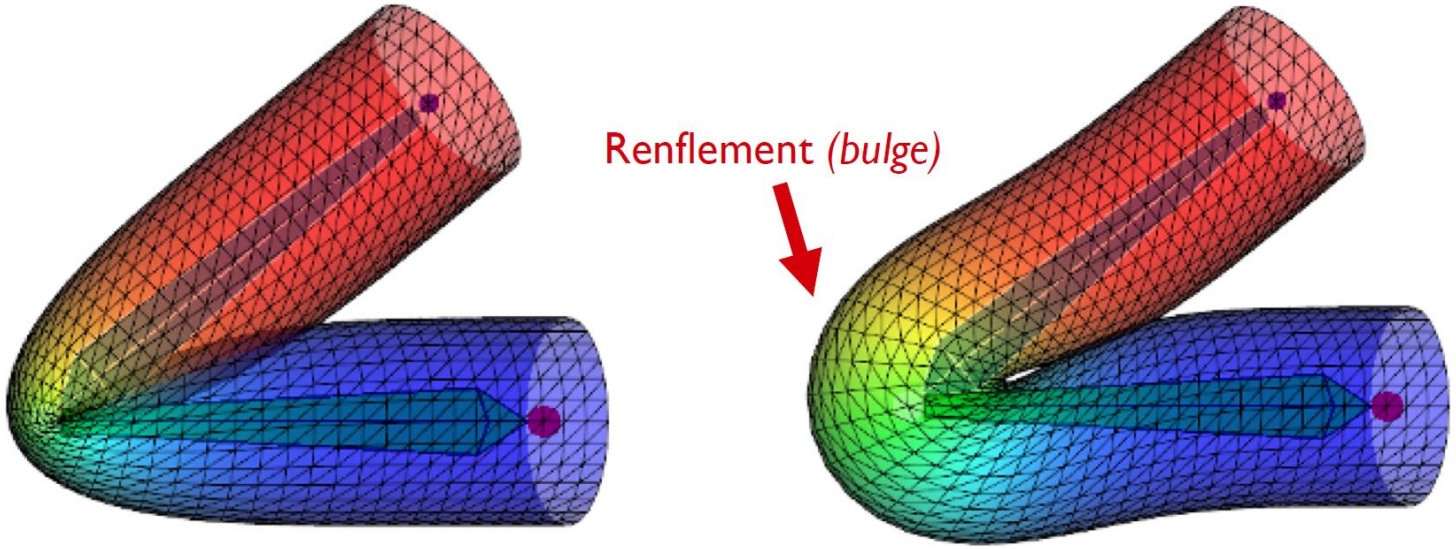
Interpolation des matrices de transformation à l'aide de **quaternions duaux** (encodant rotation et translation)



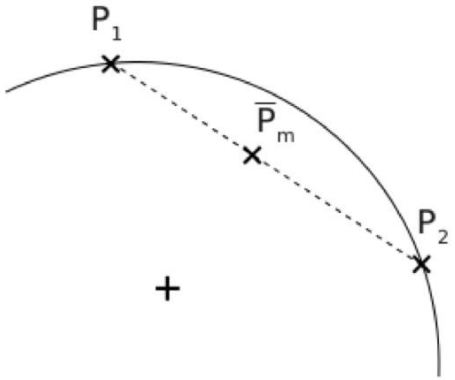


Skinning + quaternions duaux

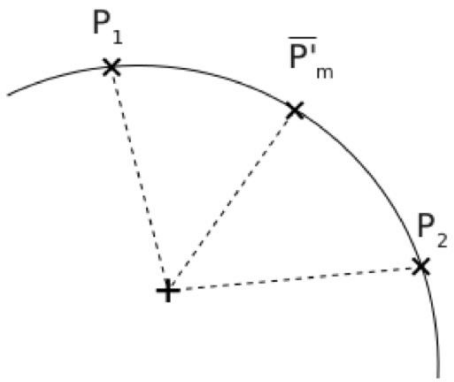
[Kavan et al. 08]



Skinning linéaire



Dual quaternions



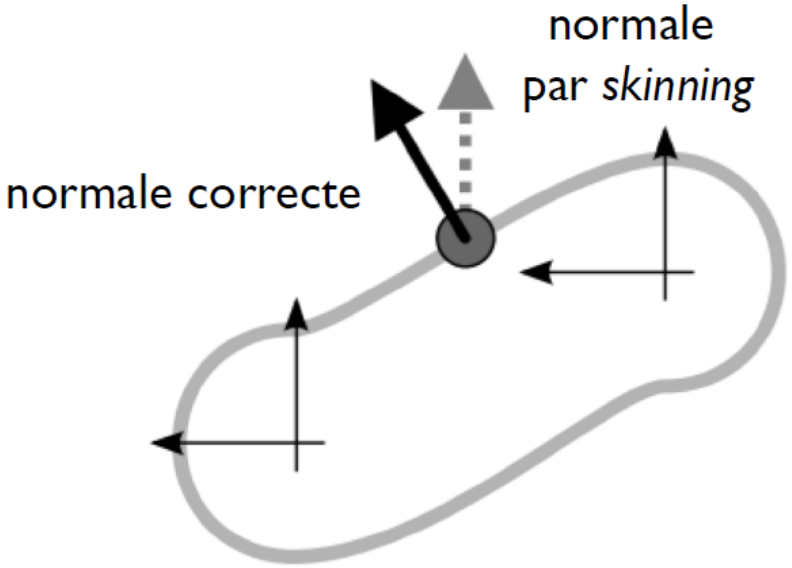
Recalcule des normales

Calculer la transformation linéaire moyenne pour le sommet i : $C_i = \sum_j w_{ij} M_j$

…et transformer sa normale par $(C_i^{-1})^T$

$\Longrightarrow$**approximation grossière**

Pose de base

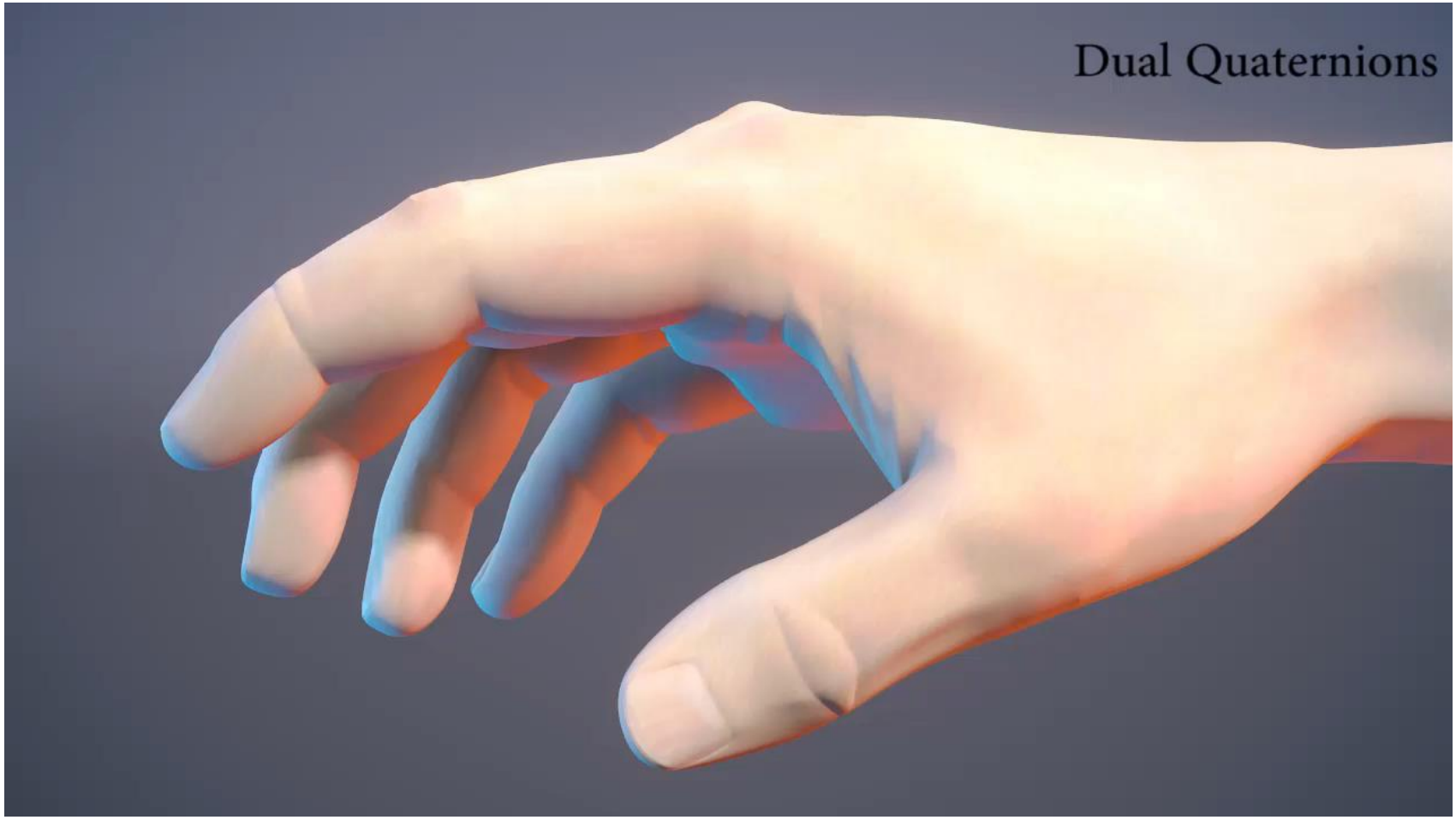


Pose déformée

Skinning + surface implicites

[Vaillant et al. 13 & 14]

Modélisation des **contacts**



Blending transformations

$$f : v_i \rightarrow \sum_j w_{ij}(R_j . v_i + T_j)$$

Blend « the transformed vertices »

Blending transformations

$$f: v_i \rightarrow \left(\sum_j w_{ij} R_j\right).v_i + \left(\sum_j w_{ij} T_j\right)$$

?

Blend « the transformations »

$$1/2\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix} + \qquad 1/2\begin{pmatrix}-1 & 0\\ 0 & -1\end{pmatrix} = \qquad \begin{pmatrix}0 & 0\\ 0 & 0\end{pmatrix}$$

Rotation by 0

Rotation by π

Not a rotation

Blending transformations

$$f: v_i \rightarrow \left(\sum_j w_{ij} R_j\right).v_i + \left(\sum_j w_{ij} T_j\right)$$

?

Blend « the transformations »

$$1/2\begin{pmatrix}1 & 0\\ 0 & 1\end{pmatrix} +$$

Rotation
by 0

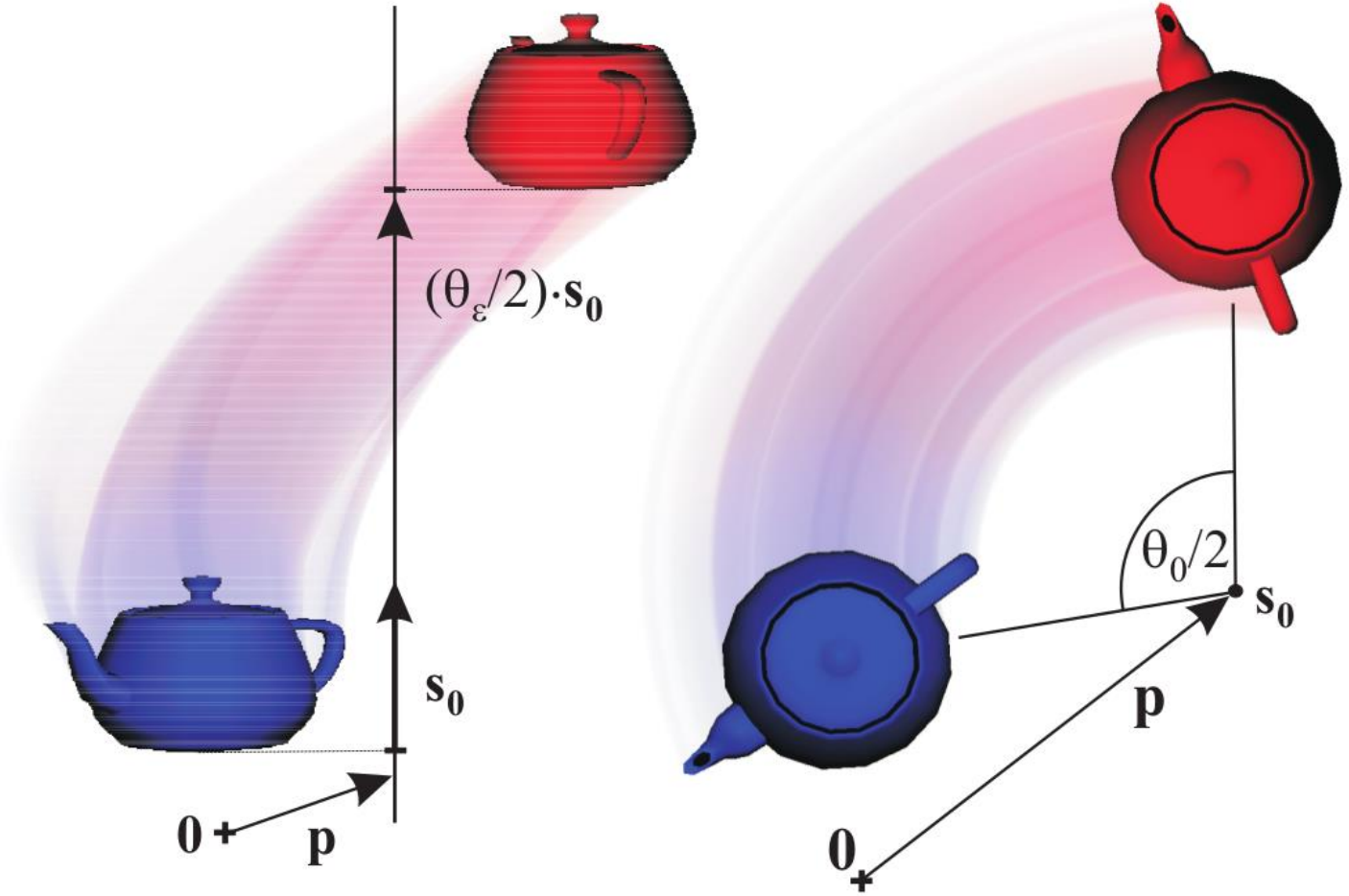
$$1/2\begin{pmatrix}-1 & 0\\ 0 & -1\end{pmatrix}\text{« = »}$$

Rotation
by π

$$\sqrt{(2)}/2\begin{pmatrix}1 & -1\\ -1 & 1\end{pmatrix}$$

Rotation
by π/2

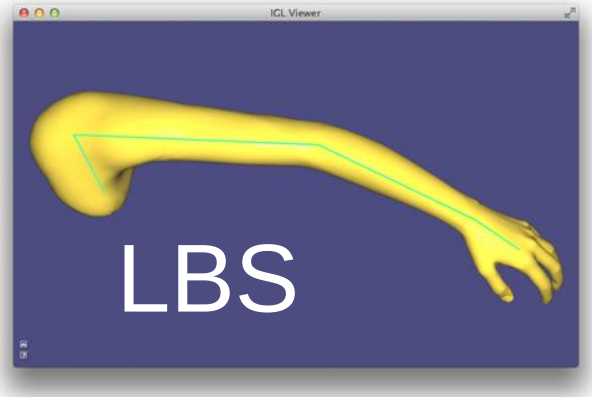
Dual quaternion Skinning

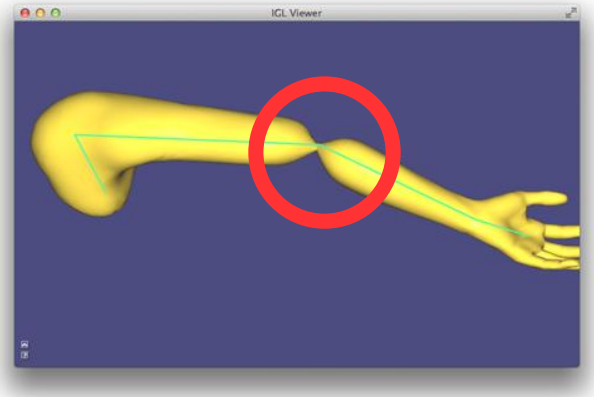


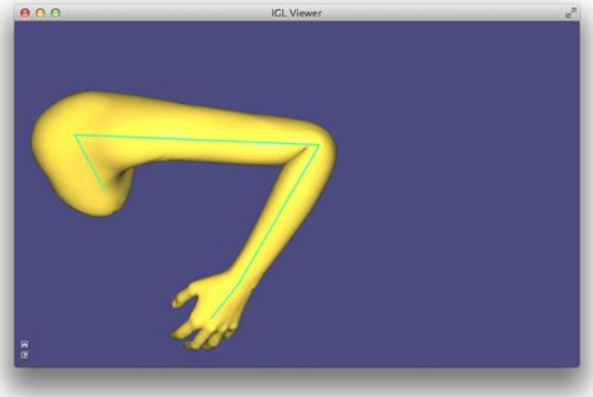
[Kavan et al.] : Skinning with Dual Quaternions

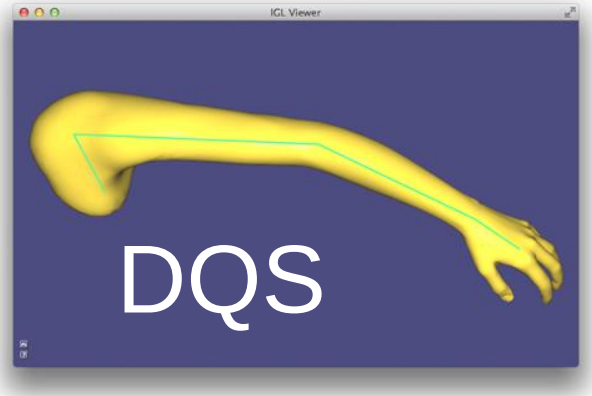
Dual quaternion Skinning

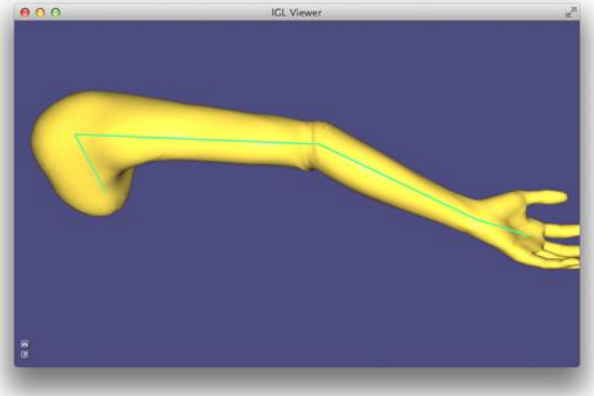
« candy-wrapper »

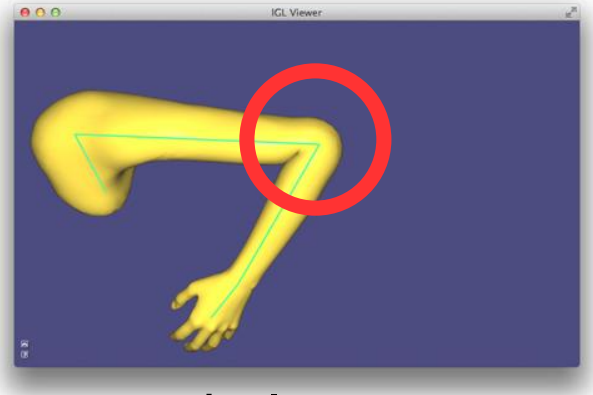






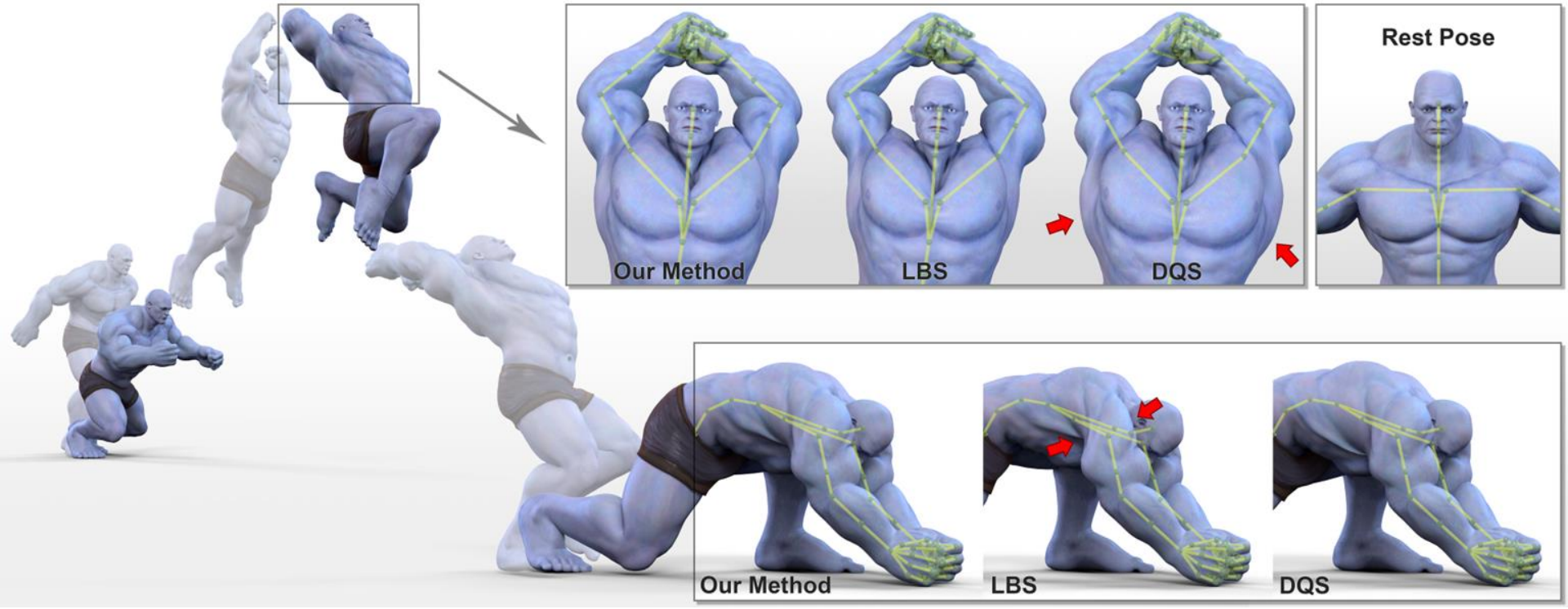






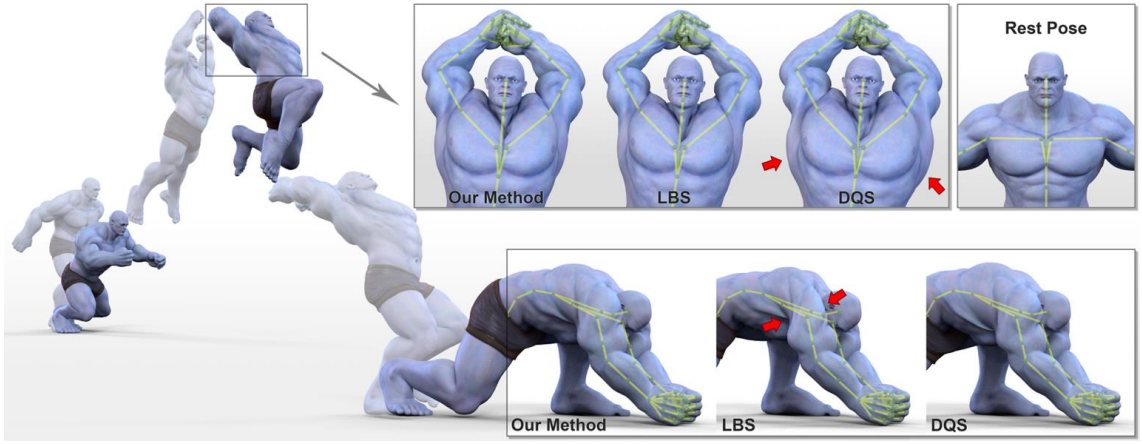
« bulge »

Disney's CoRs



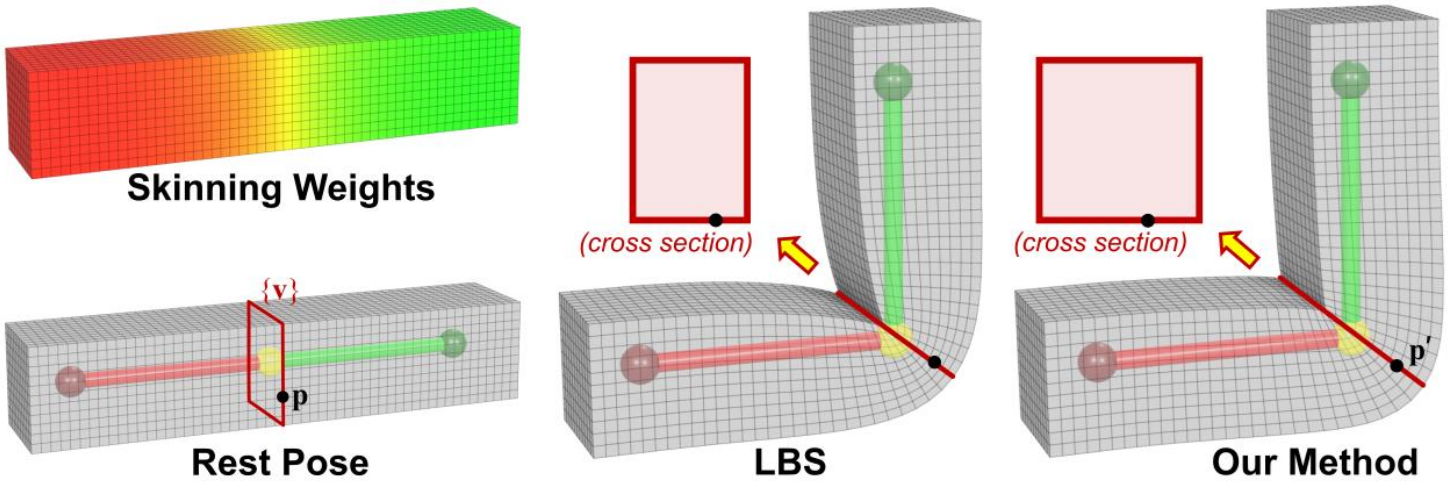
Key ideas

- LBS and DQS have « orthogonal » problems
- DQS is good at blending the rotations
- The bulge effect is due to a non-optimized translation (or a non-optimized center of rotation)



What is a good CoR ?

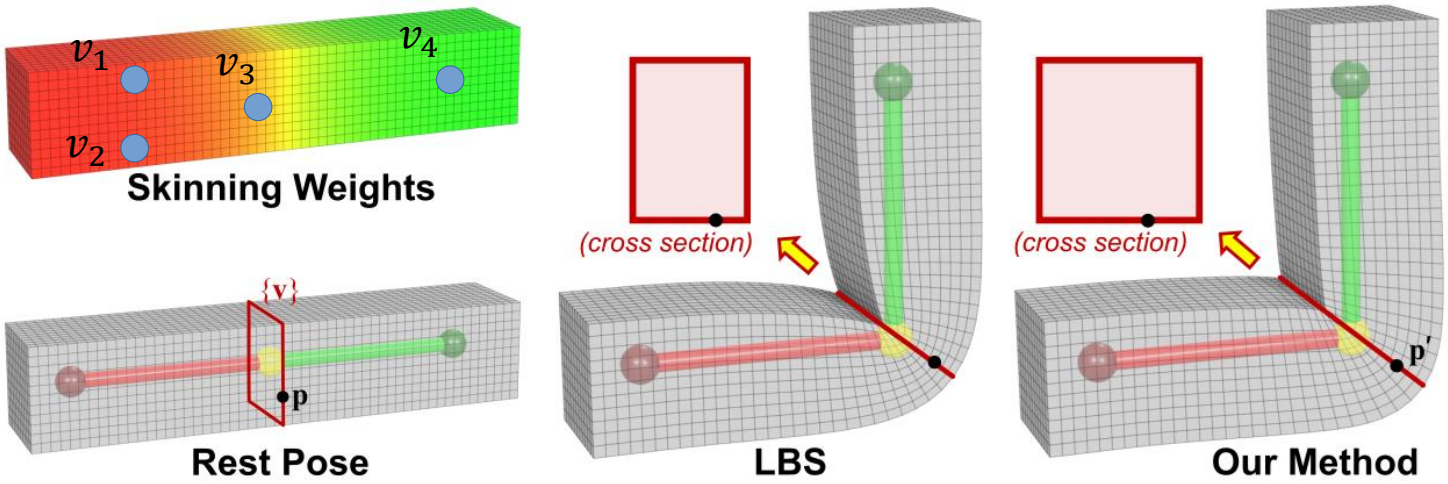
- Vertices with similar weights will have a similar rotation
- They are organized as cross sections orthogonal to the bones, and ideally should be transformed rigidly.



What is a good CoR ?

- Vertices with similar weights will have a similar rotation
- They are organized as cross sections orthogonal to the bones, and ideally should be transformed rigidly.
- Requires a similarity function between weights

$s(w_1, w_2) = 1$ $s(w_1, w_3) = 0.01$ $s(w_1, w_4) = 0$



What is a good CoR ?

- Vertices with similar weights will have a similar rotation
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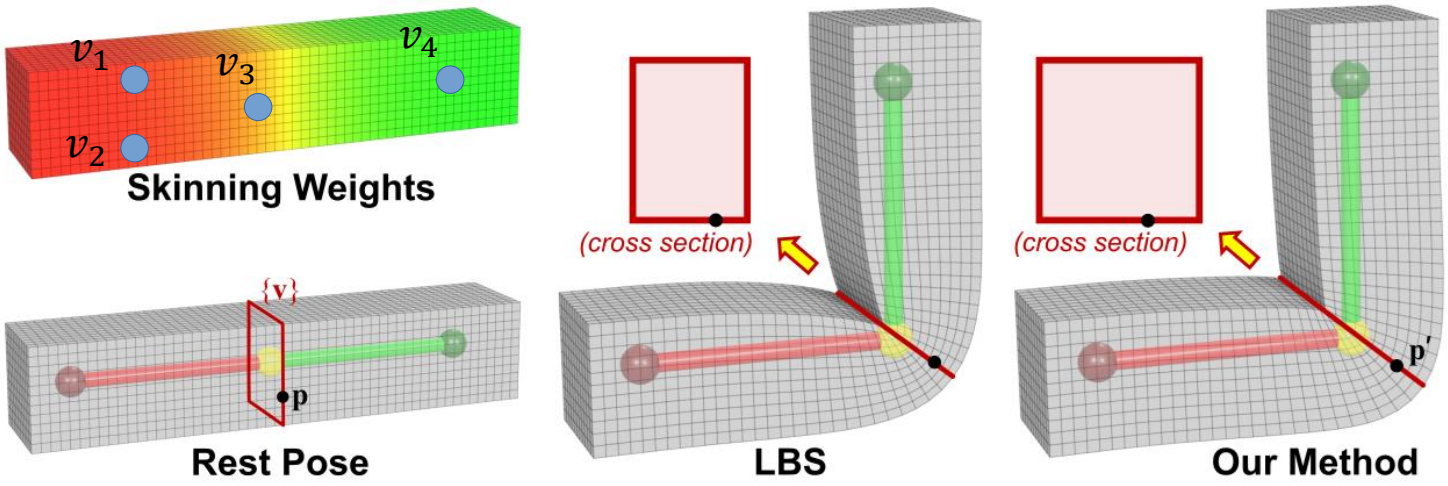
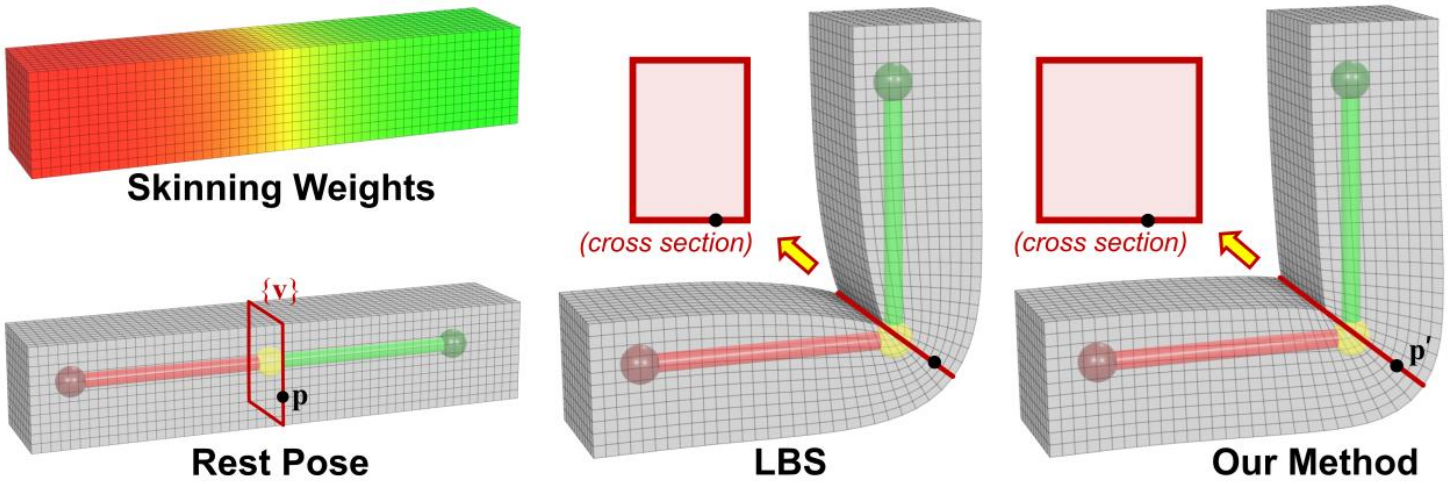
$$s(\mathbf{w_p}, \mathbf{w_v}) = \sum_{\forall j \neq k} \mathbf{w}_{\mathbf{p}j}\mathbf{w}_{\mathbf{p}k}\mathbf{w}_{\mathbf{v}j}\mathbf{w}_{\mathbf{v}k}\ \mathrm{e}^{-\frac{(\mathbf{w}_{\mathbf{p}j}\mathbf{w}_{\mathbf{v}k} - \mathbf{w}_{\mathbf{p}k}\mathbf{w}_{\mathbf{v}j})^2}{\sigma^2}}$$



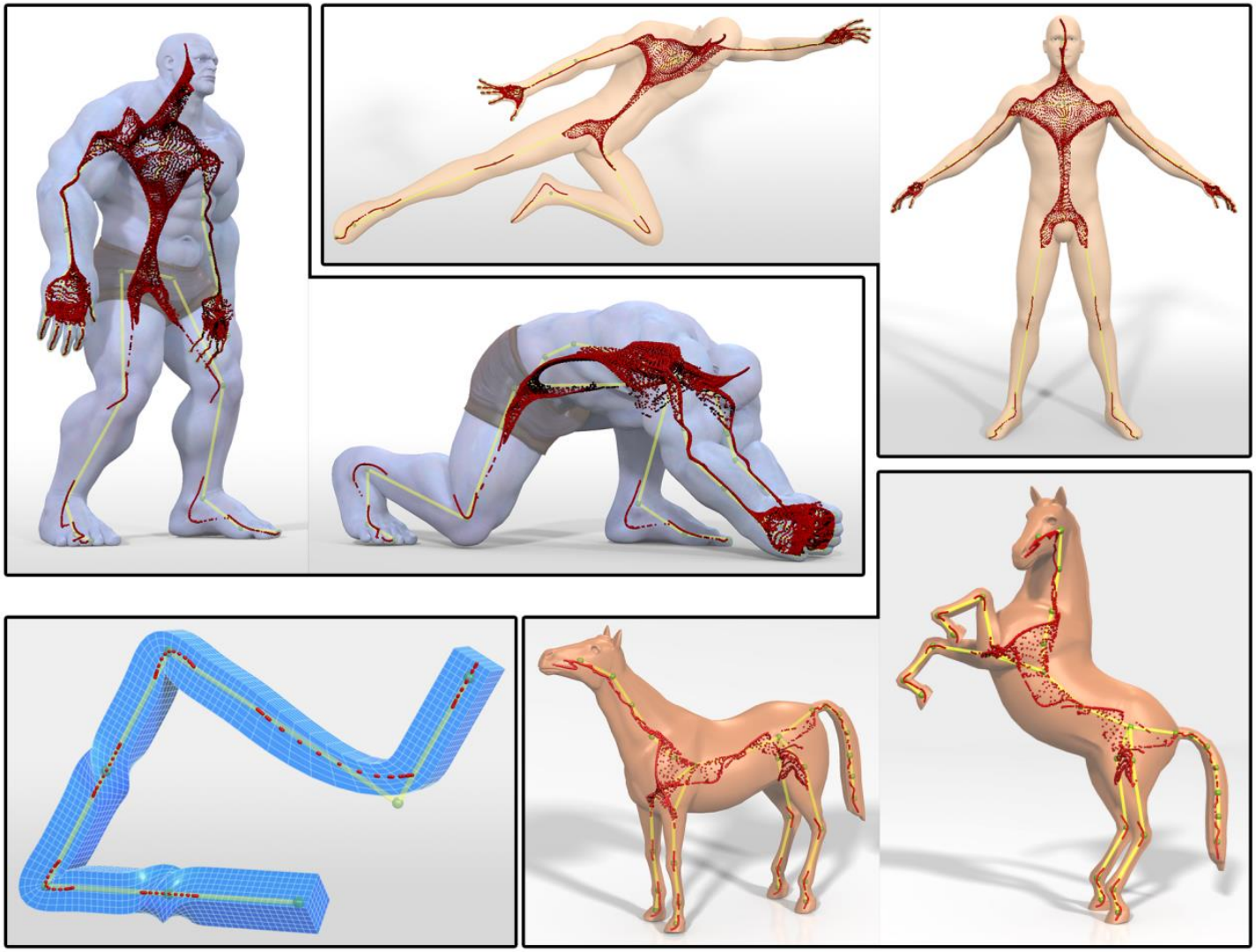
Idea

- Consider the LBS transformation of the mesh
- Use the DQS rotation for each vertex
- Optimize per-vertex translation to fit the LBS deformation while enforcing rigid sections.



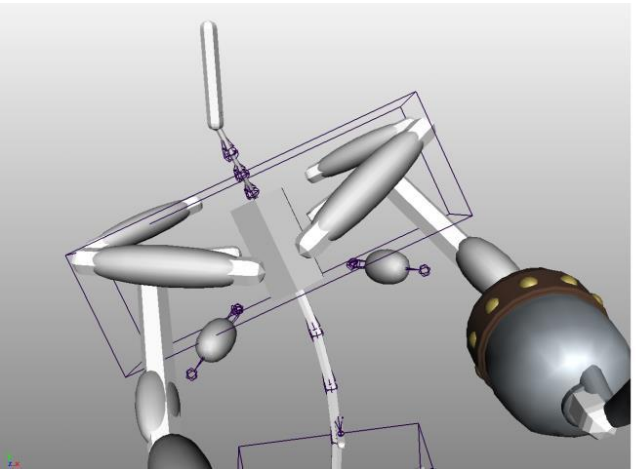
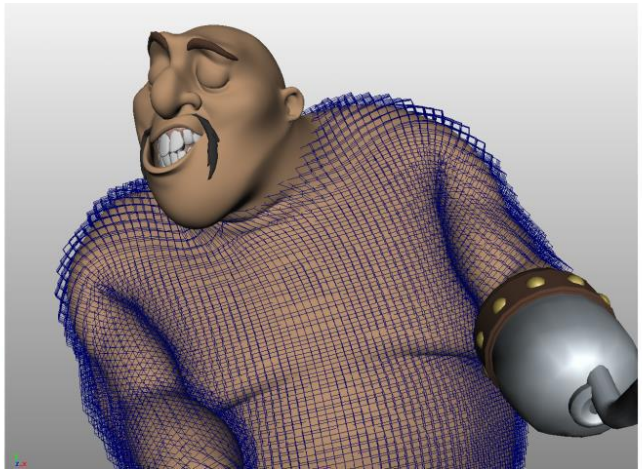
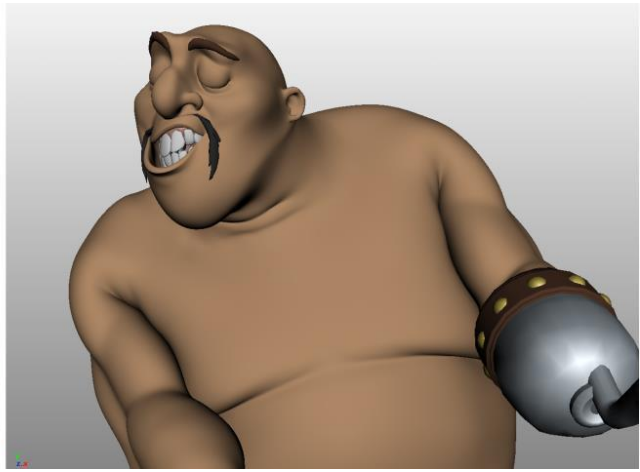
CoRs

$$\mathbf{p}^* = \frac{\int_{\mathbf{v}\in\Omega} s(\mathbf{w_p}, \mathbf{w_v})\mathbf{v}\,\mathrm{d}\mathbf{v}}{\int_{\mathbf{v}\in\Omega} s(\mathbf{w_p}, \mathbf{w_v})\,\mathrm{d}\mathbf{v}}$$



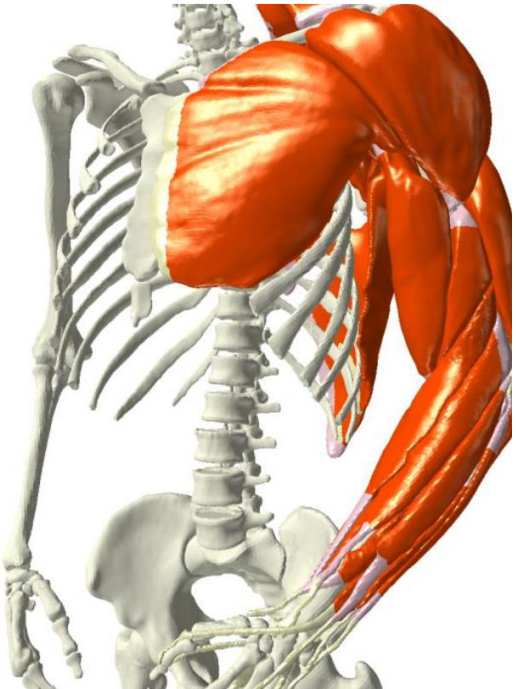
Skinning basé-physique

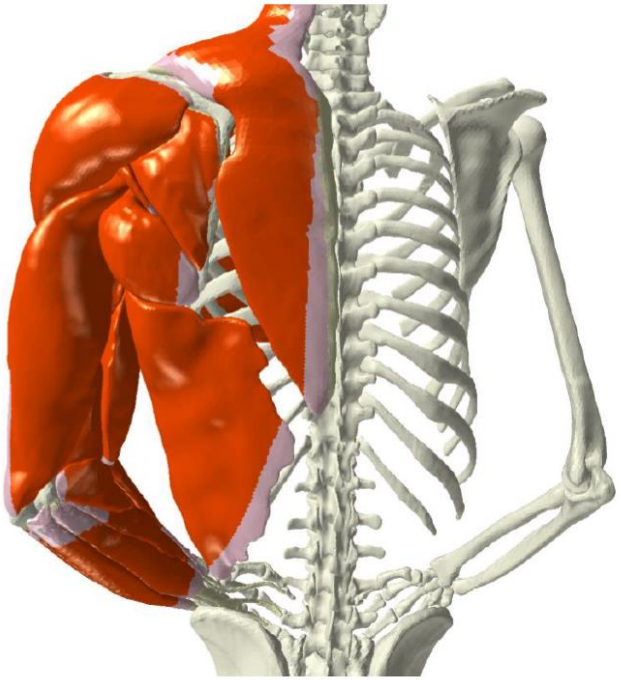
- Inclure le squelette dans un modèle volumique (e.g. maillage tétraédrique). Simulation de matière élastique (chaire, muscle) guidé par le squelette.

Muscles

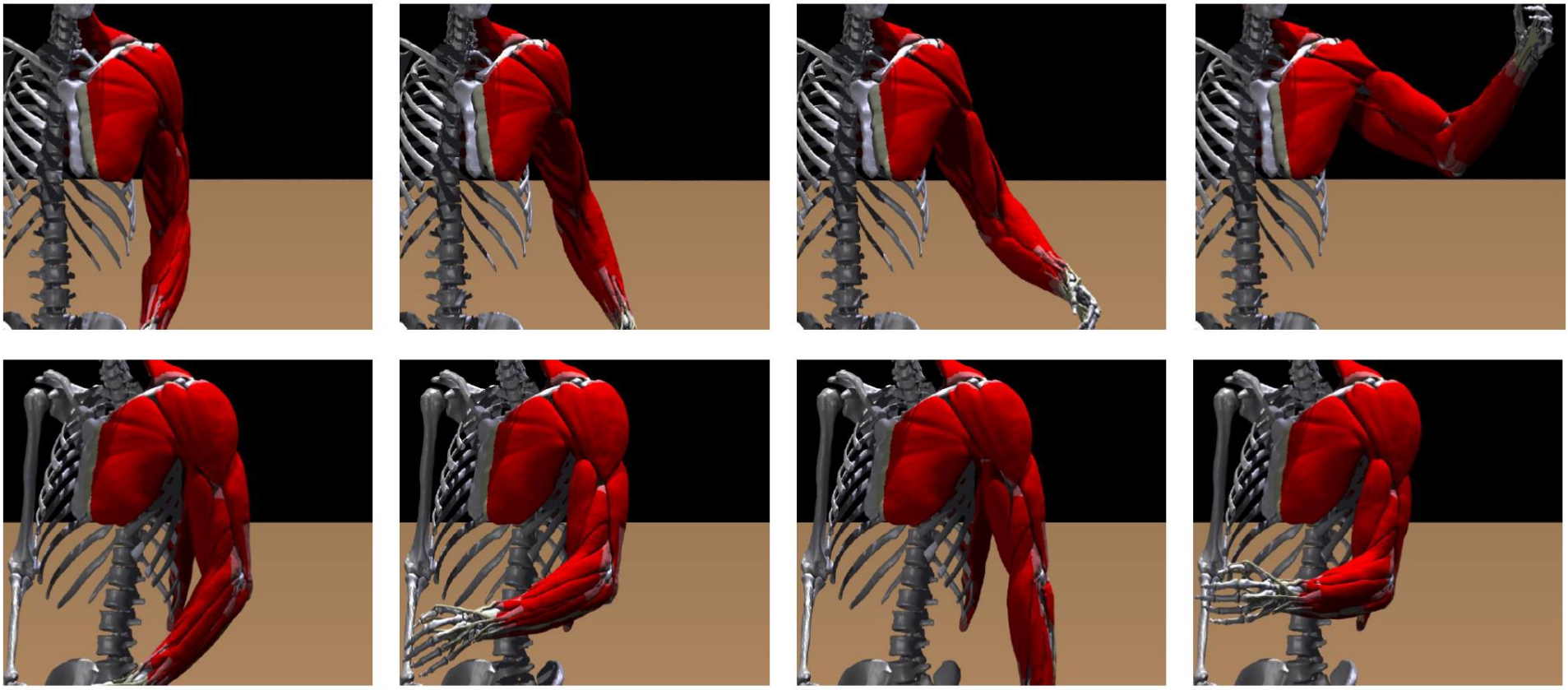
- Amélioration du réalisme en ajoutant des muscles se contractant quand ils sont activés et exercent des forces sur les tissus mous (chair)
- Données réelles pour la forme des muscles



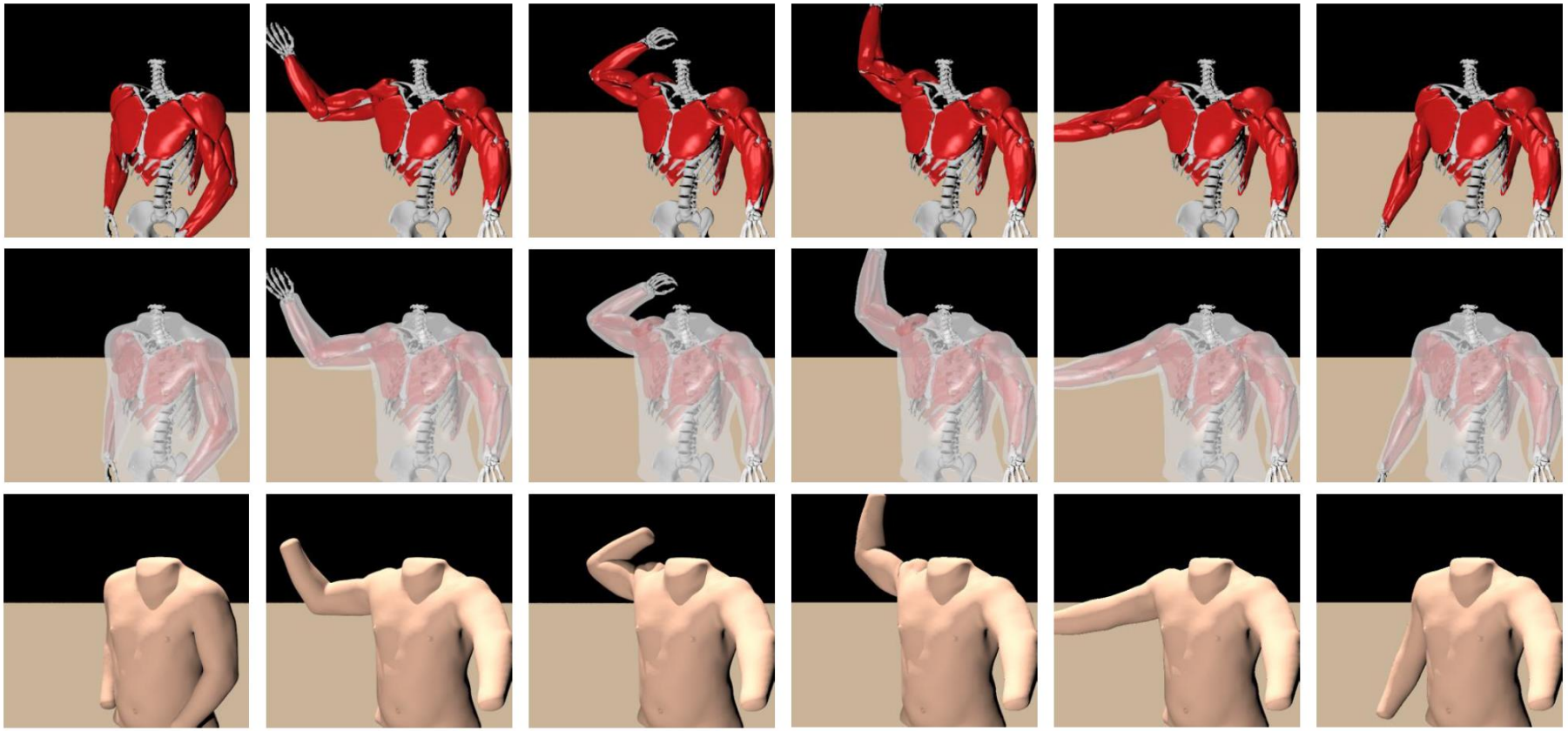


Muscles

Résoudre un problème inverse pour déduire quels muscles doivent s'activés d'après le mouvement des os



Muscles

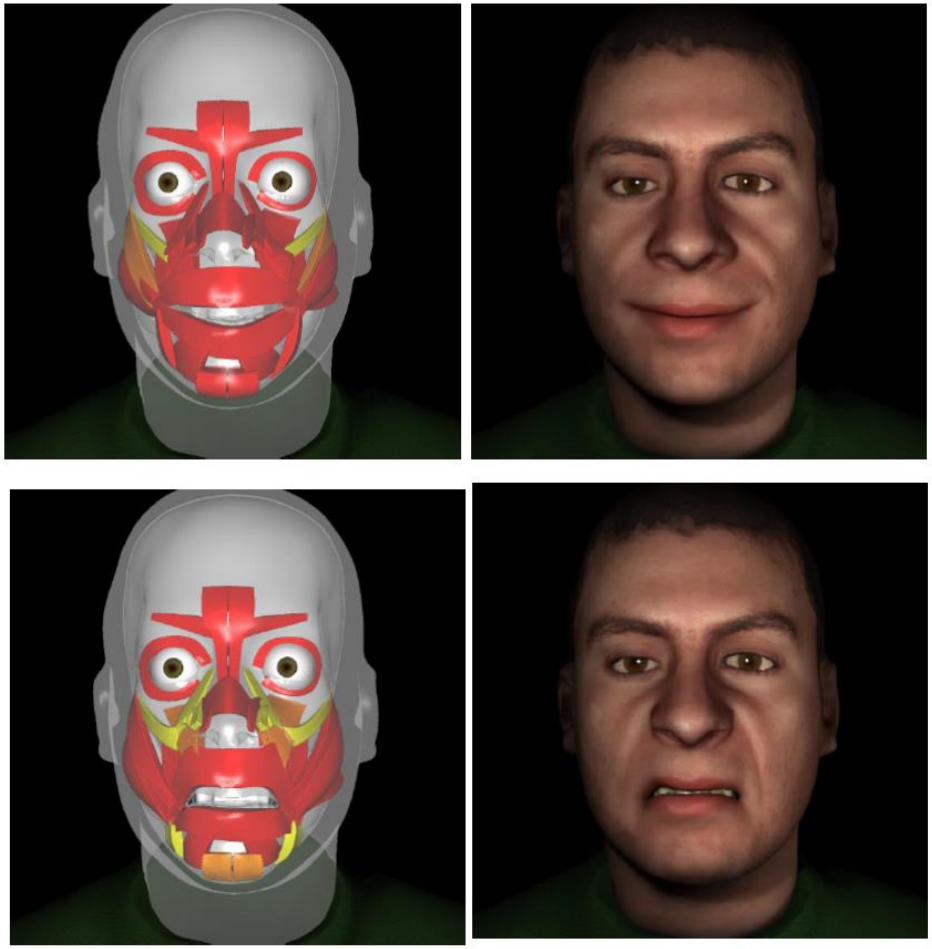


Modèle anatomique du visage

Même principe pour obtenir des expressions réalistes du visage

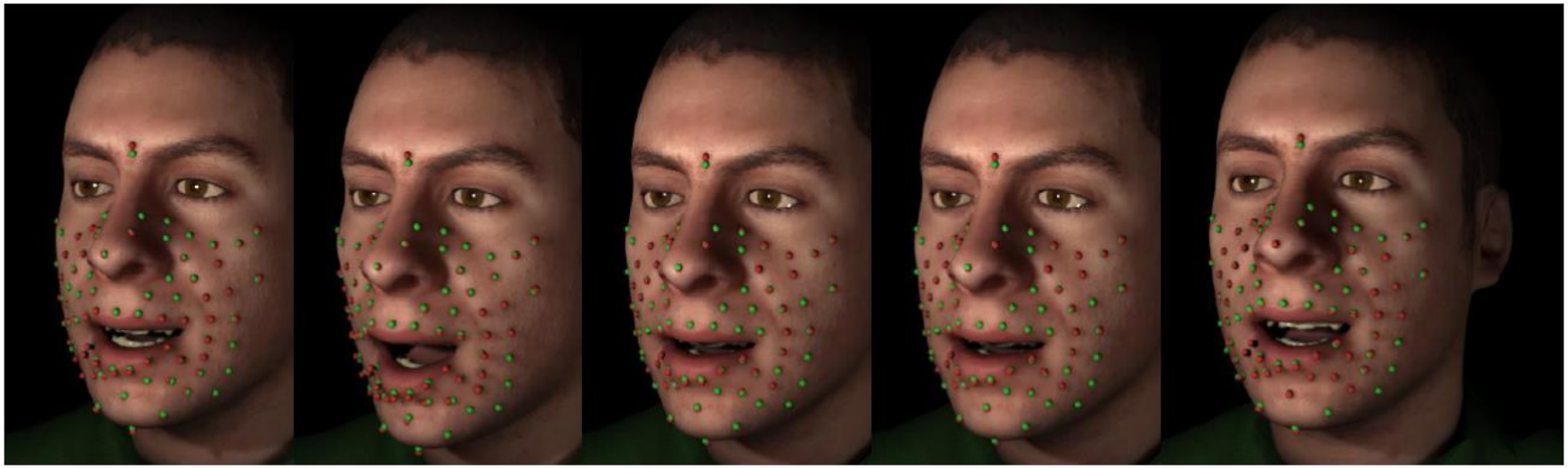
Activation :

- Jaune : complètement
- Rouge : inactif



Activation des muscles

- Utilisation de la capture de mouvement avec des marqueurs à matcher avec des positions du maillage
- Modification des expressions en interpolant les angle et les activations entre les keyframes



Capture de mouvements

Discovery, “Avatar: Motion Capture Mirrors Emotions”, https://youtu.be/1wK1Ixr-UmM

Blend shapes

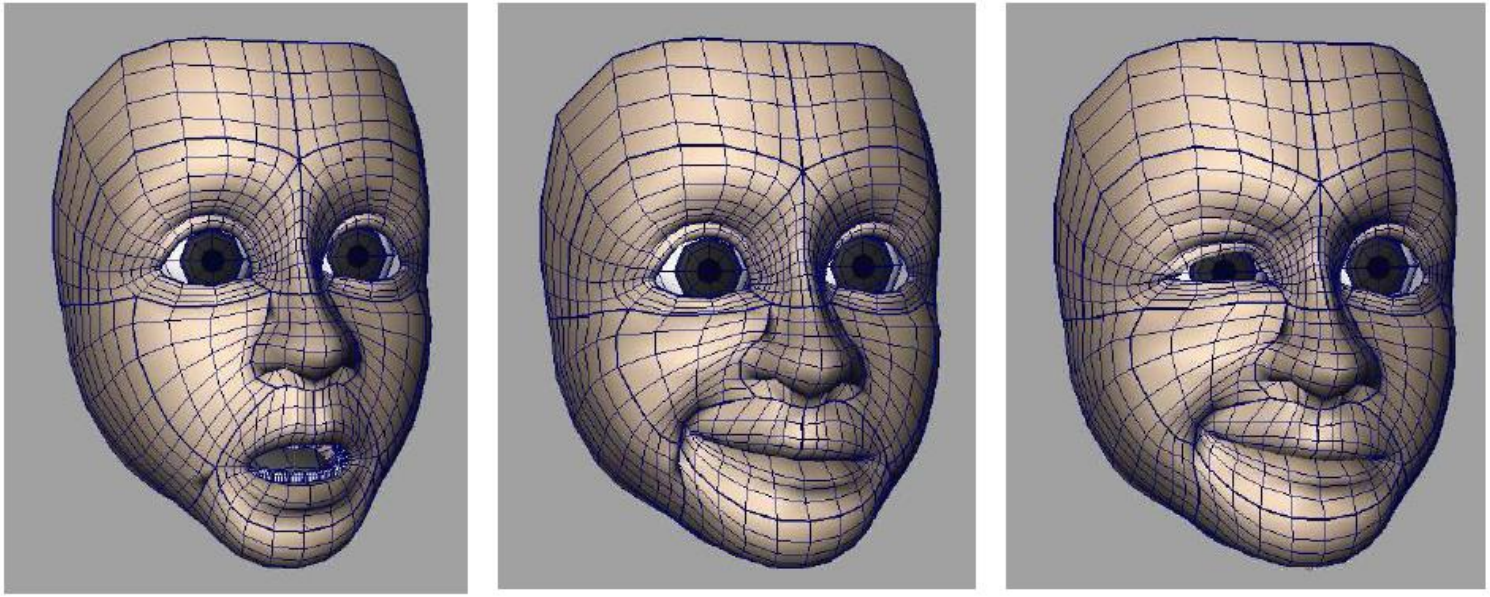
Interpolation de **formes clés**

- Interpolation linéaire de la position des sommets

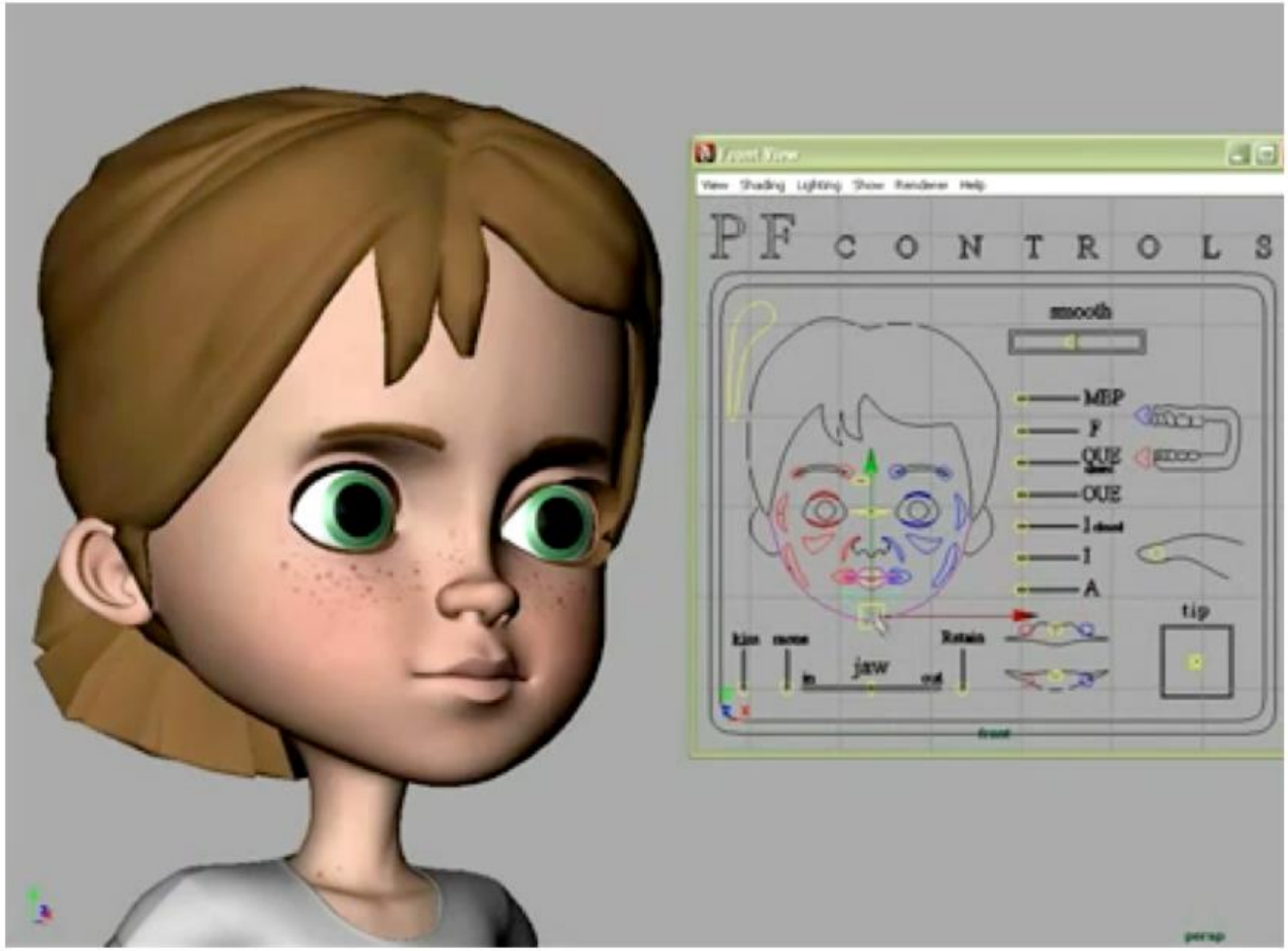
$$p' = p_0 + \Sigma_i w_i (p_i - p_0)$$

- Contrôle de l'animation par les poids w_i

Surtout pour l'**animation faciale**



Blend Shapes (198 expressions)



Remy Terreaux

Cinématique

Mouvement non-contraint

- Hocher la tête, faire un signe de la main…

$\Longrightarrow$Cinématique directe (FK)

Mouvement contraint

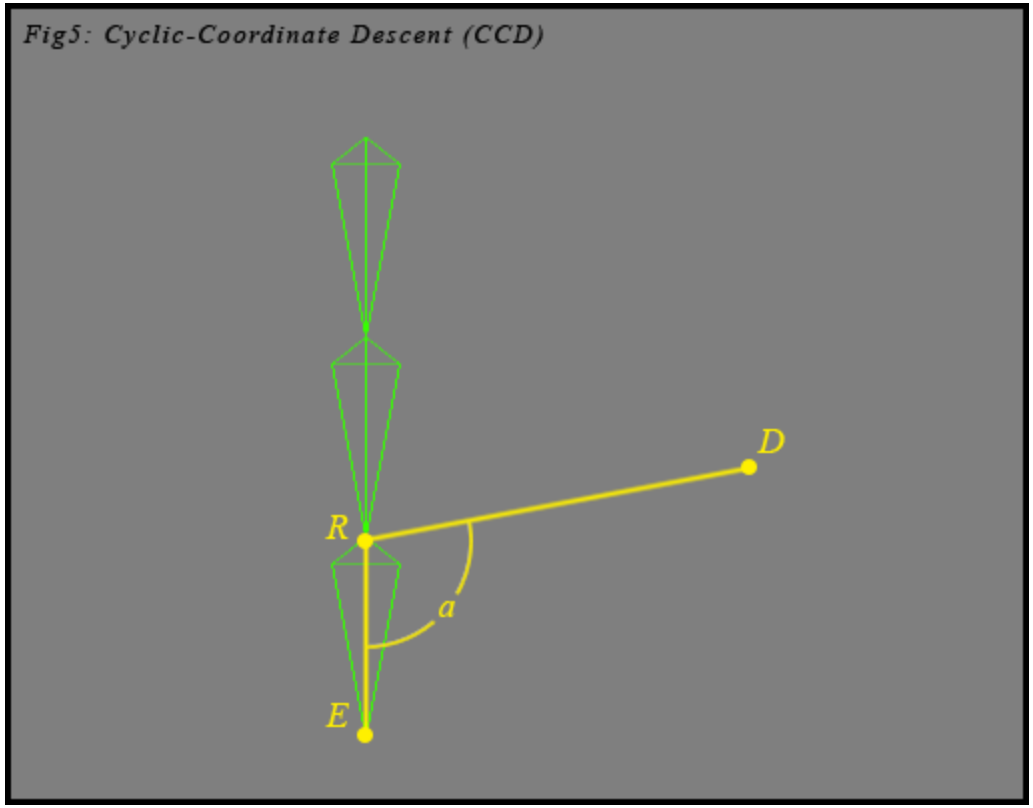
- Attraper un objet, marcher sur le sol…

$\Longrightarrow$Cinématique inverse (IK)

One type of IK Solutions

Cyclic-Coordinate Descent

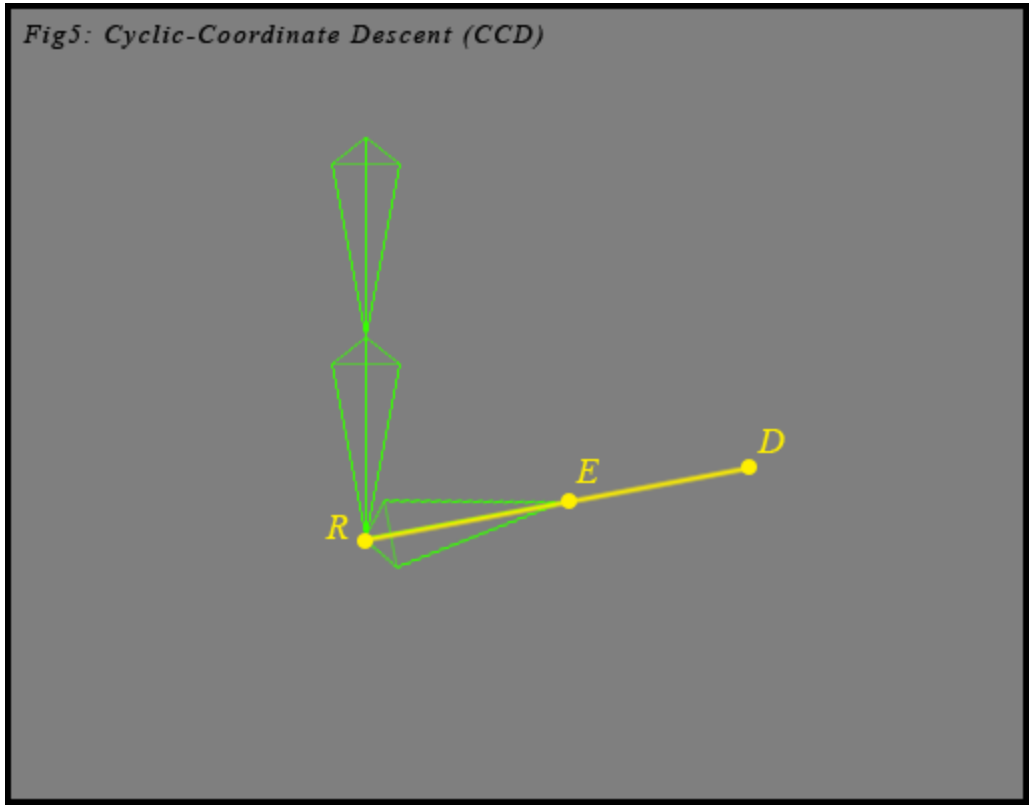
- Starting with the root of our effector, R, to our current endpoint, E.
- Next, we draw a vector from R to our desired endpoint, D
- The inverse cosine of the dot product gives us the angle between the vectors: cos(a) = RD ● RE



One type of IK Solutions

Cyclic-Coordinate Descent

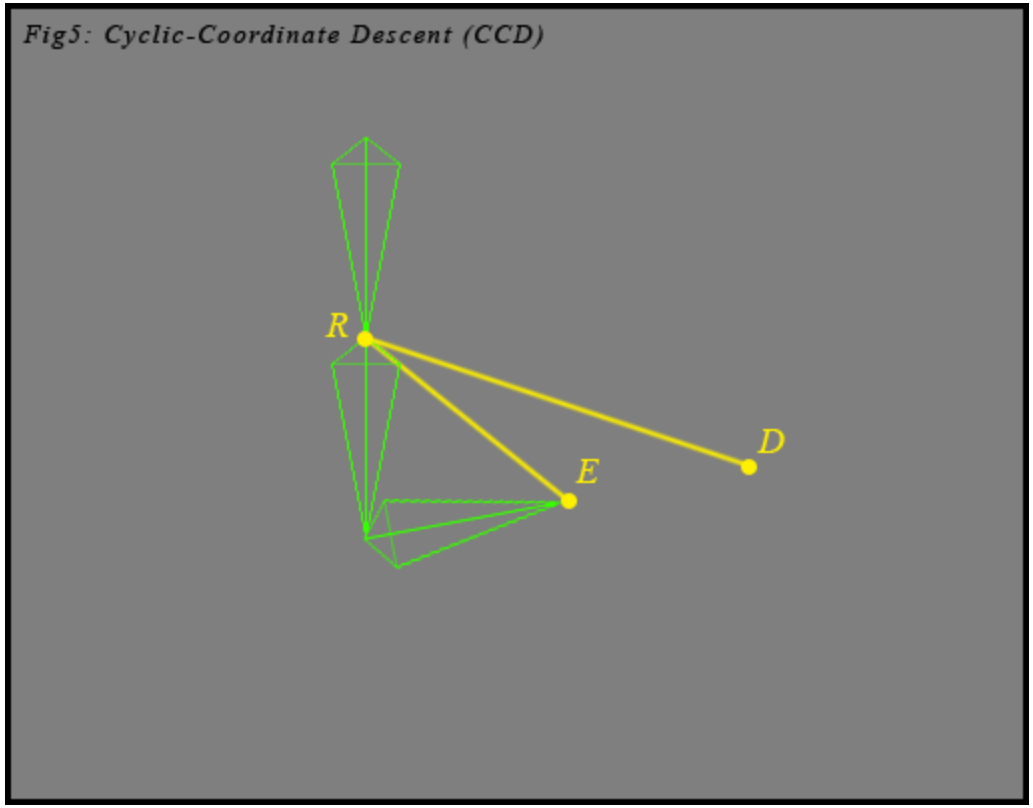
Rotate our link so that RE falls on RD



One type of IK Solutions

Cyclic-Coordinate Descent

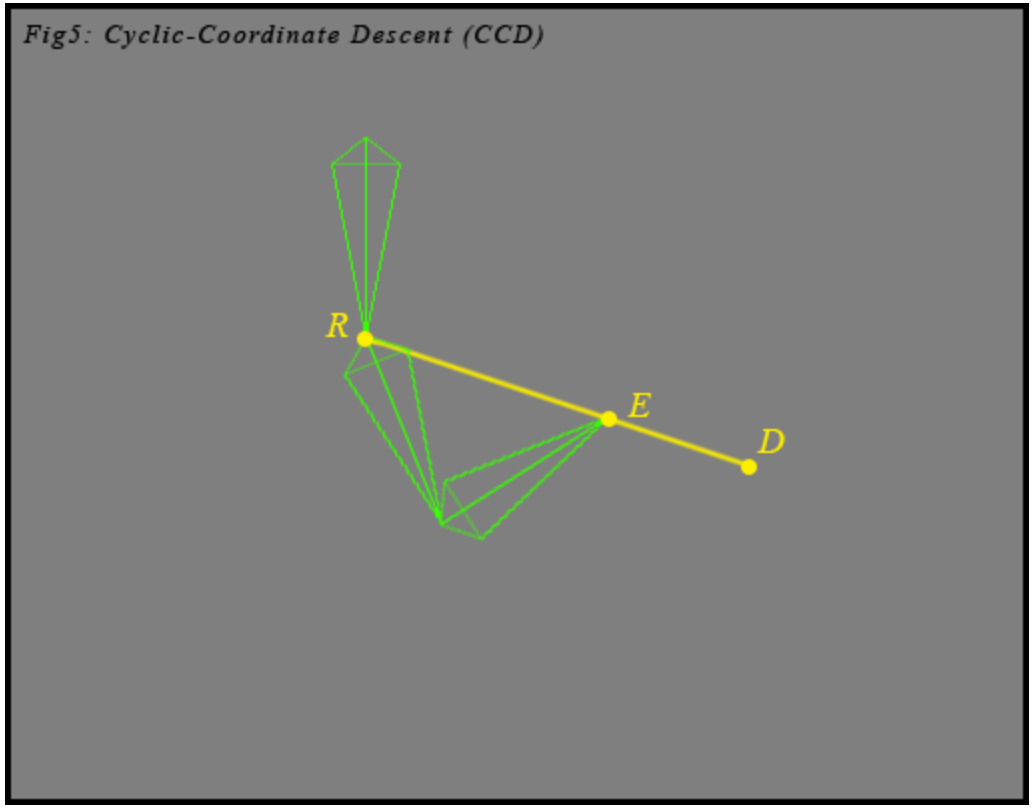
Move one link up the chain, and repeat the process



One type of IK Solutions

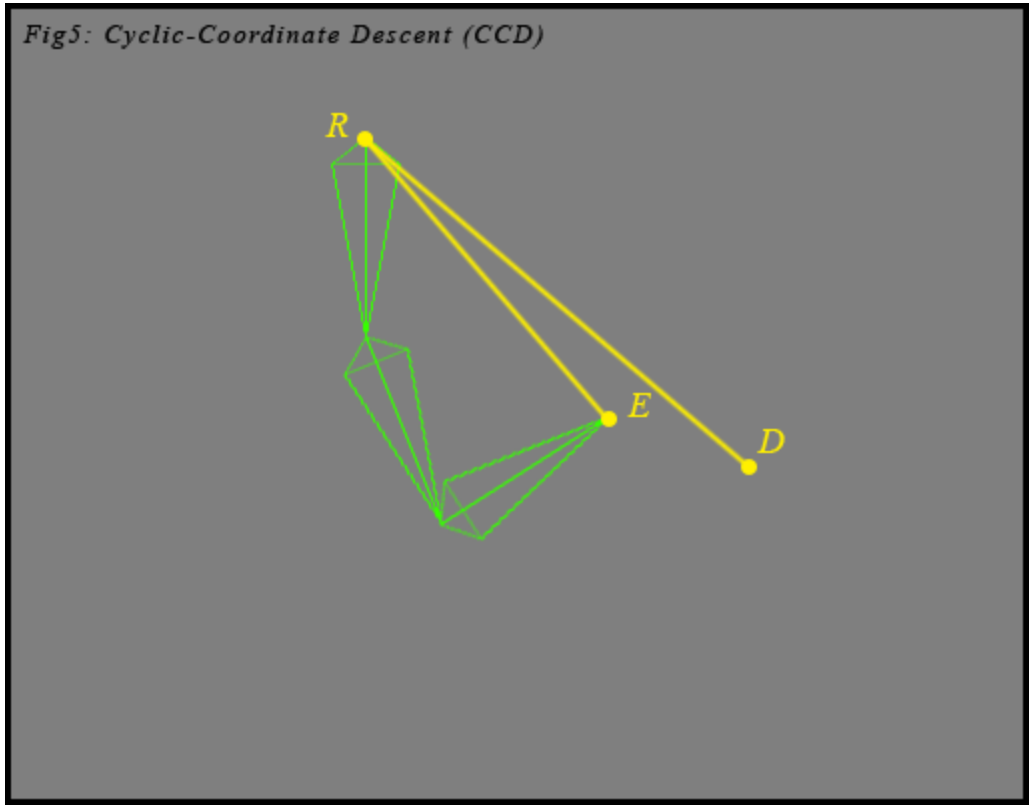
Cyclic-Coordinate Descent

The process is basically repeated until the root joint is reached. Then the process begins all over again starting with the end effector, and will continue until we are close enough to D for an acceptable solution.



One type of IK Solutions

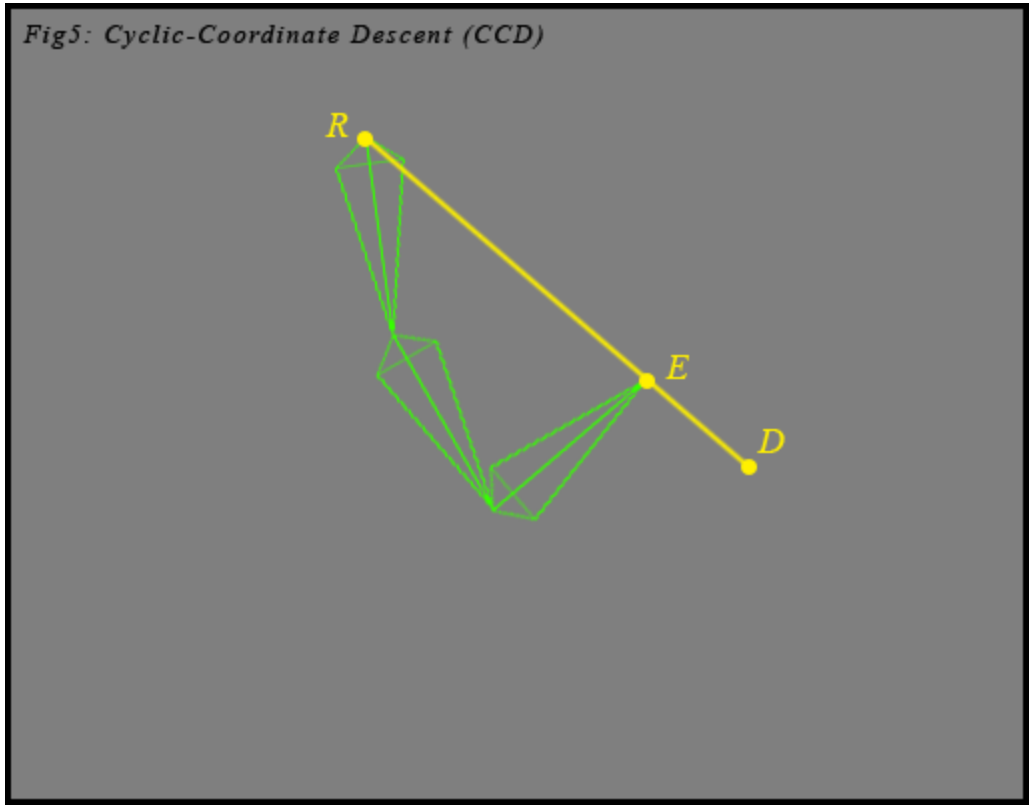
Cyclic-Coordinate Descent



One type of IK Solutions

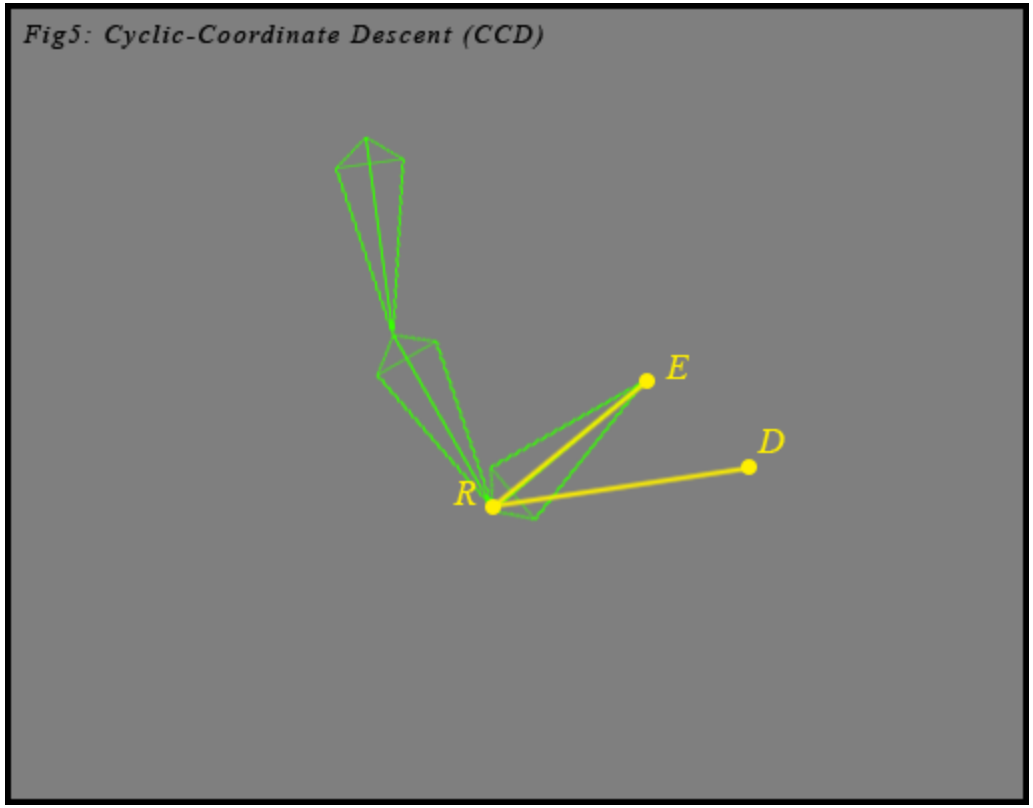
Cyclic-Coordinate Descent

We've reached the root. Repeat the process



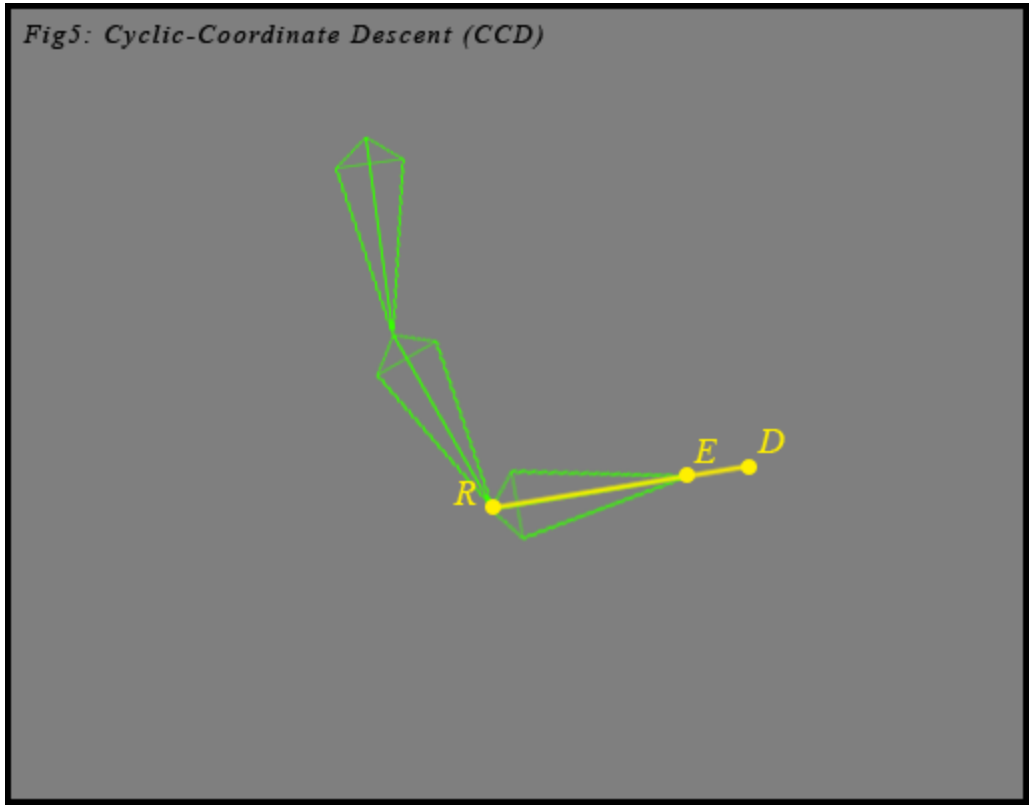
One type of IK Solutions

Cyclic-Coordinate Descent



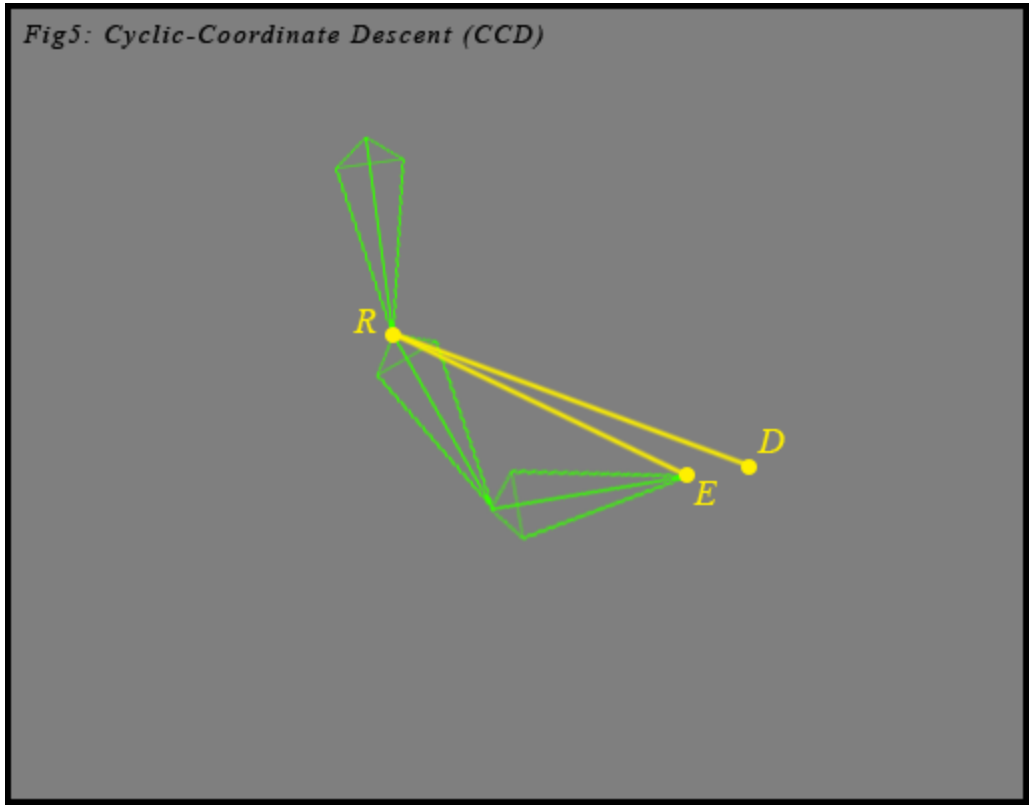
One type of IK Solutions

Cyclic-Coordinate Descent



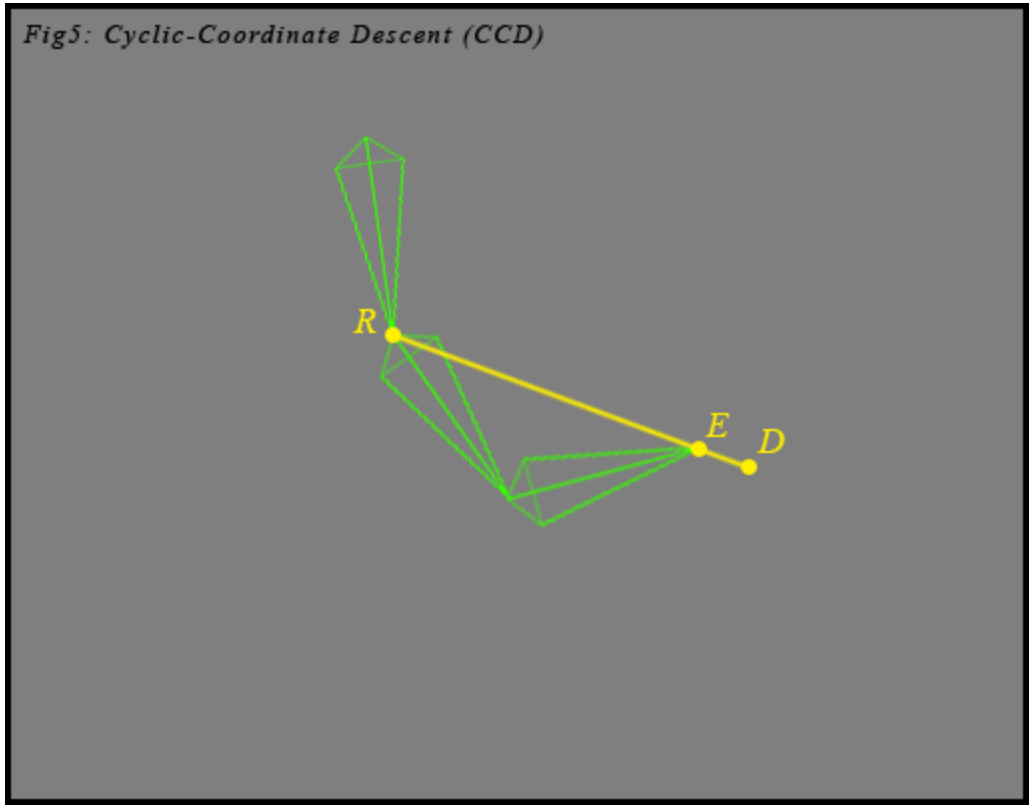
One type of IK Solutions

Cyclic-Coordinate Descent



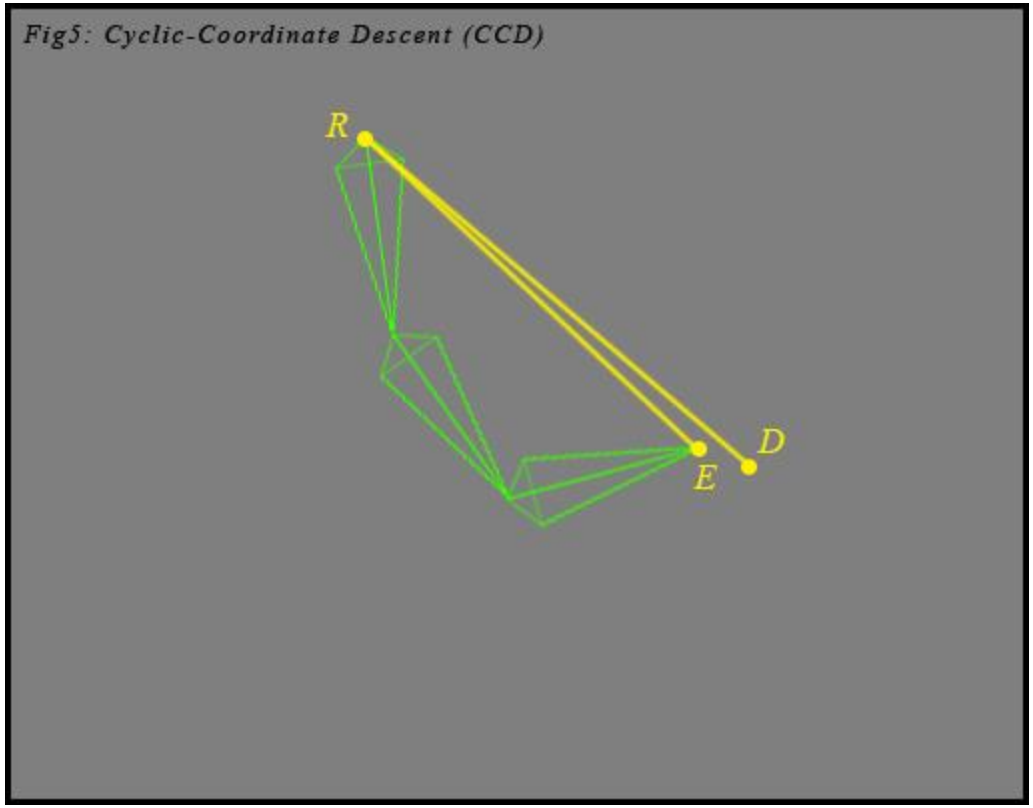
One type of IK Solutions

Cyclic-Coordinate Descent



One type of IK Solutions

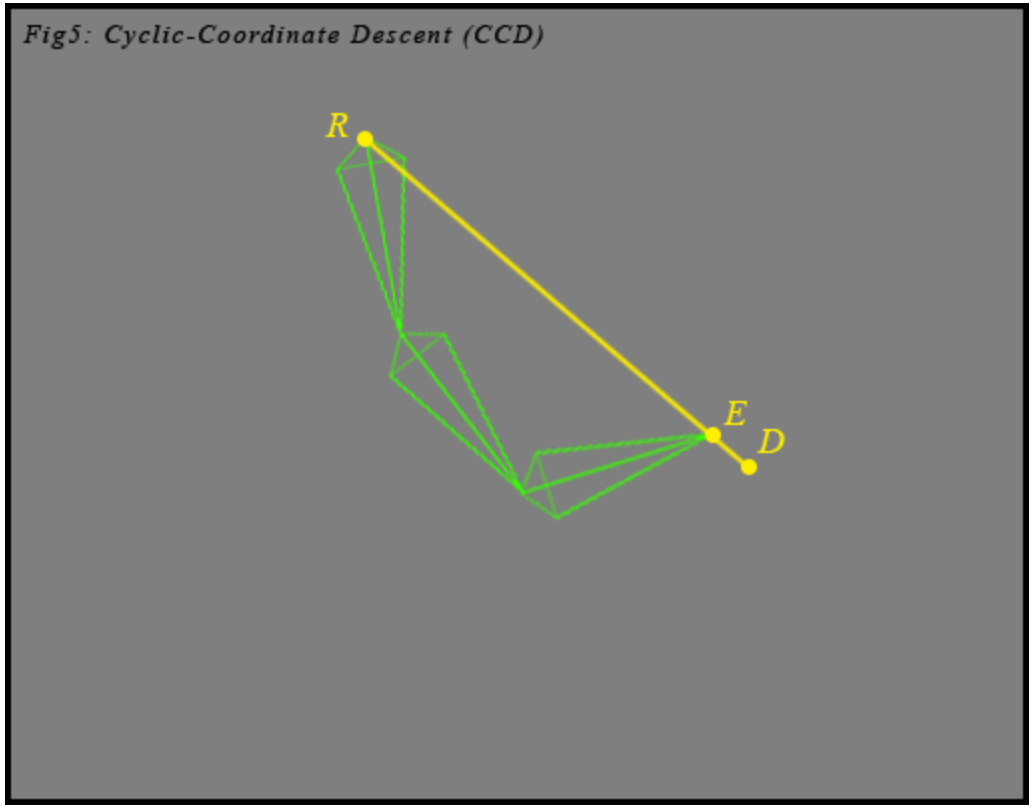
Cyclic-Coordinate Descent



One type of IK Solutions

Cyclic-Coordinate Descent

We've reached the root again. Repeat the process until solution reached.



Using IK in Game Development

- Examples of IK in action:

–Character Animation Demo (Softimage XSI 5.0, Blender, Maya, everywhere)

–Real-Time calculations: E3 2003 Demo Footage of Half-Life 2