« Advanced 3D Graphics »

Focus: Graphical techniques with strong links to AI

Part 1. From 3D modeling & simulation to Creative AI

1. Expressive 3D modeling : smart geometry controlled by gestures
2. Extension to virtual worlds

Part 2. Character animation

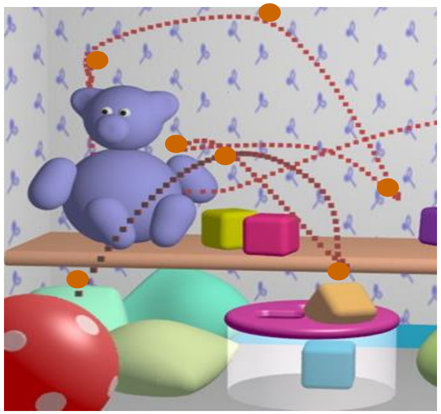
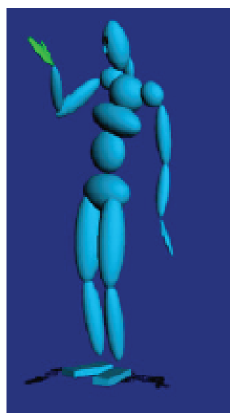
3. Motion planning and crowd simulation (Julien Pettré)
4. **Motion synthesis and control for individual characters**
   – Skeletal motion : from kinematics to dynamics
   – Passive layers : Skin, clothes and hair

   \+ Recent advances: Learning motion control (*student talks*)

Computer Animation, reminders
Descriptive *vs* ***Physically-based*** *animation*

Kinematics

- Direct: Interpolate key-frames (using spline curves…)

- Inverse: Controlling end-effectors of articulated bodies

Mechanical model **Simulation**

- Parameters
- Initial conditions
- Laws of motion

Integrate PDE over time

No help towards realism | Indirect control only

Computer Animation, reminders
Layered Models

Motivation : Complex scenes

- Natural phenomena
- Characters with clothes & hair

Using « layered models »

Different animation layers, one per feature

- Eases conception & control
- Best choice & scale for each feature
- Layers interact for consistency, possibly with retroaction

Layered model for characters?

- Brain (AI) layer
  - Taking decisions
    (eg. finite state automata)
  - Planning motion

← Autonomous characters

- Animated layers
  - Skeleton
  - Skin (+ muscles, flesh…)
  - Faces
  - Clothes
  - Hair

← All virtual characters!

In this lecture

- Brain (AI) layer
  - Taking decisions (eg. finite state automata)
  - Planning motion

← **Autonomous characters**

- **Animated layers**
  - **Skeleton**
  - **Skin** (+ muscles, flesh…)
  - Faces
  - **Clothes**
  - **Hair**

← **All virtual characters!**

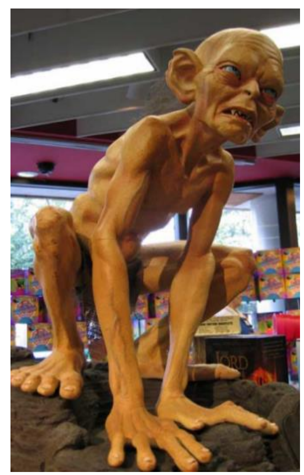
- Skeletal motion
- Skin & face
- Clothing & hair

Animating the skeleton

Three alternative methods

1. Design by artists: Direct & Inverse kinematics (3D movies…)
2. Motion capture & re-use (special effects, sport games…)
3. Simulation & Control of physical motion (bio-mechanics, games…)






…

?

- Skeletal motion
- Skin & face
- Clothing & hair

Animating the skeleton

1. Descriptive motion design

Direct kinematics

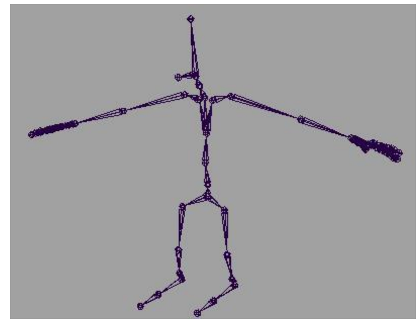
- Interpolate key-poses

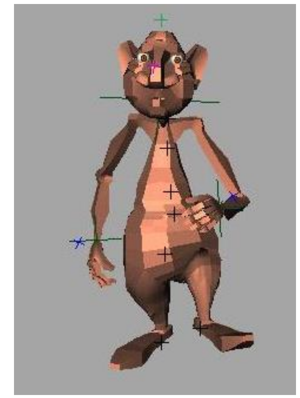
Inverse kinematics

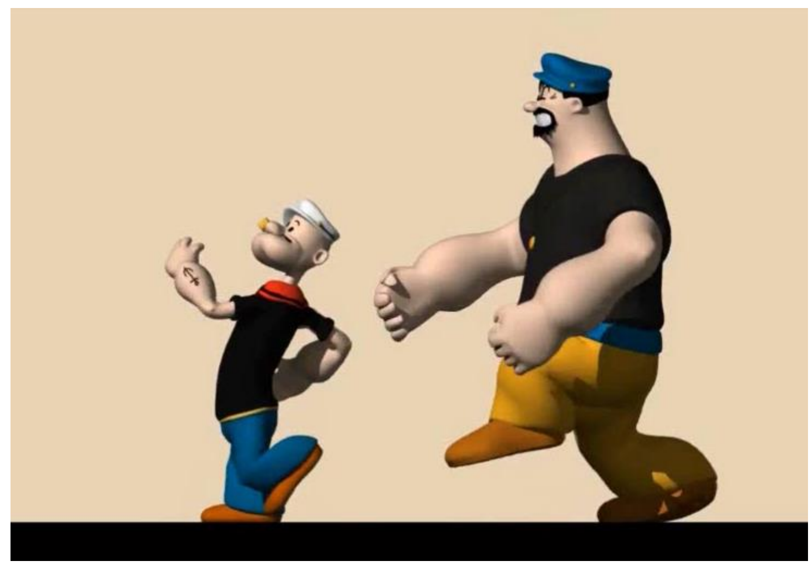
- Control the end effectors (feets, hands…)

+ Freedom for the artist

- Specialized skills required







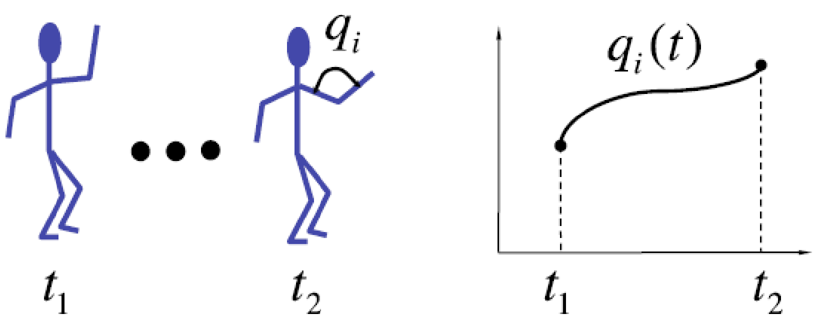
Direct kinematics
Animating a character?

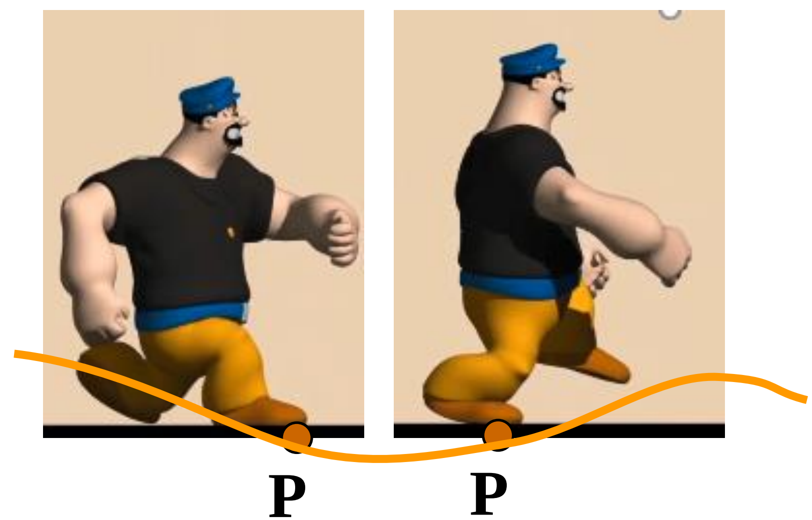
Skeleton = hierarchy of frames

- Generalized coordinates (T, $q_1 \ldots q_n$)
  - Root in world frame (T= translation + orientation)
  - Relative rotation angles (qi) with respect to the parent frame
- Interpolate angles over time

- Skeletal motion
- Skin & face
- Clothing & hair

Direct kinematics
Animating a character?





- Difficult to control extremities
  eg. foot on the ground while walking
- In practice: Top-down set-up strategy
  - Try to compensate undesired motions!

- Skeletal motion
- Skin & face
- Clothing & hair

Descriptive animation

Alternative : Inverse kinematics

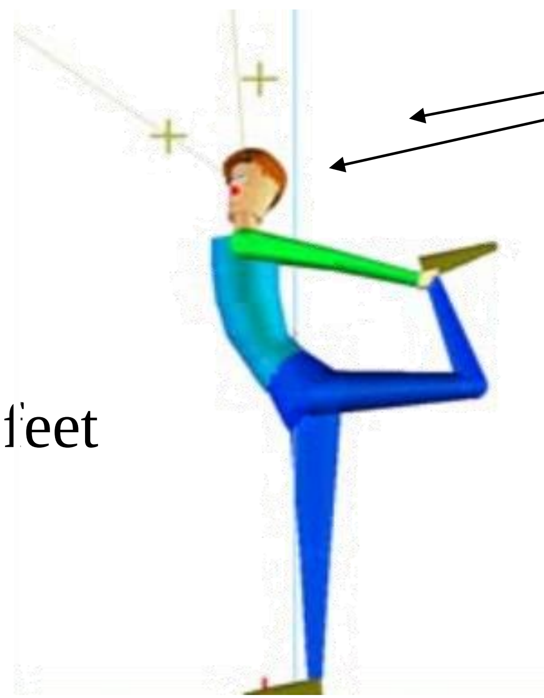
- Specify end-effectors positions (eg through key-frames)
- Solve for generalized coordinates

Under-constrained problem

→ Add a secondary task

Example *[Baerlocher 2004]*

- Maintaining balance
  - → Center of mass above the feet



Constraints:
Head & gaze direction goals

Foot & hand position goal

Practice: Combing direct & inverse kinematics

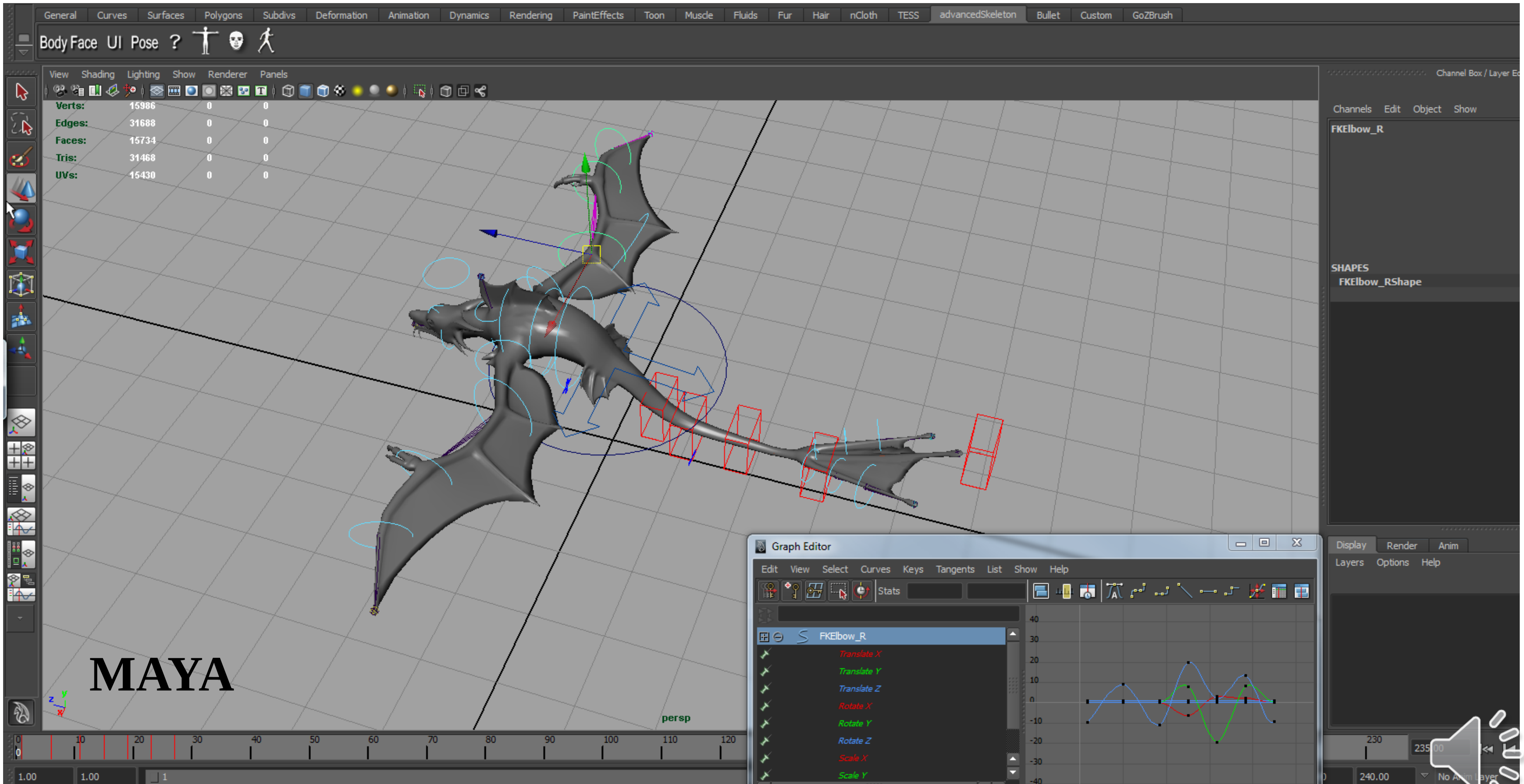
Example from Unity

- Walking motion key-framed on flat ground
- Inverse kinematics to change feet target positions (ray-casting)

- Skeletal motion
- Skin & face
- Clothing & hair

Authoring character animation?

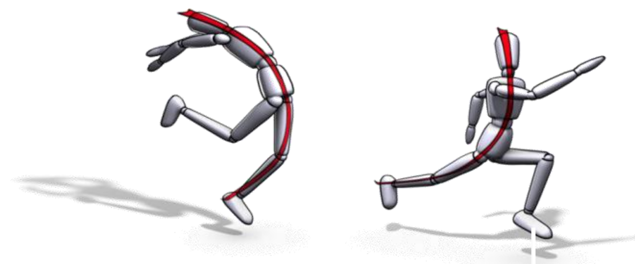
Complex interfaces with high learning curve

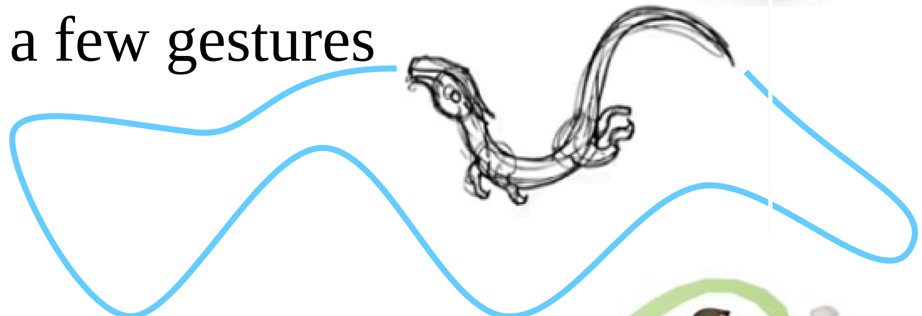


- Skeletal motion
- Skin & face
- Clothing & hair

Authoring character animation Expressive methods?

- **Line of action (LOA)** *[Guay 2013]*
  - Posing a character with a stroke
- **Space-time sketching** *[Guay 2015]*
  - Creating & refining motion in a few gestures
- **SketchiMO** *[Choi 2016]*
  - Editing existing motions

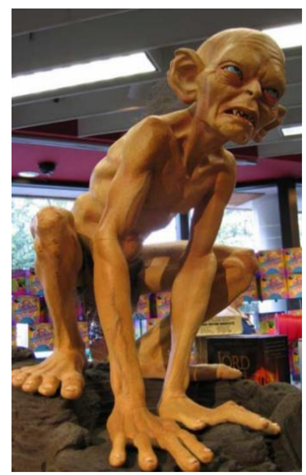




Animating the skeleton

Three alternative methods

1. Design by artists: Direct & Inverse kinematics (3D movies…)
2. **Motion capture & re-use** (special effects, sport games…)
3. Simulation & Control of physical motion (bio-mechanics, games…)



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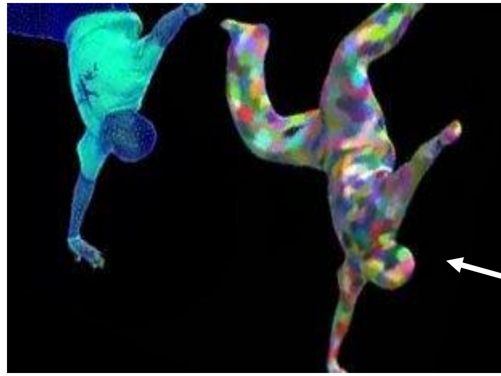
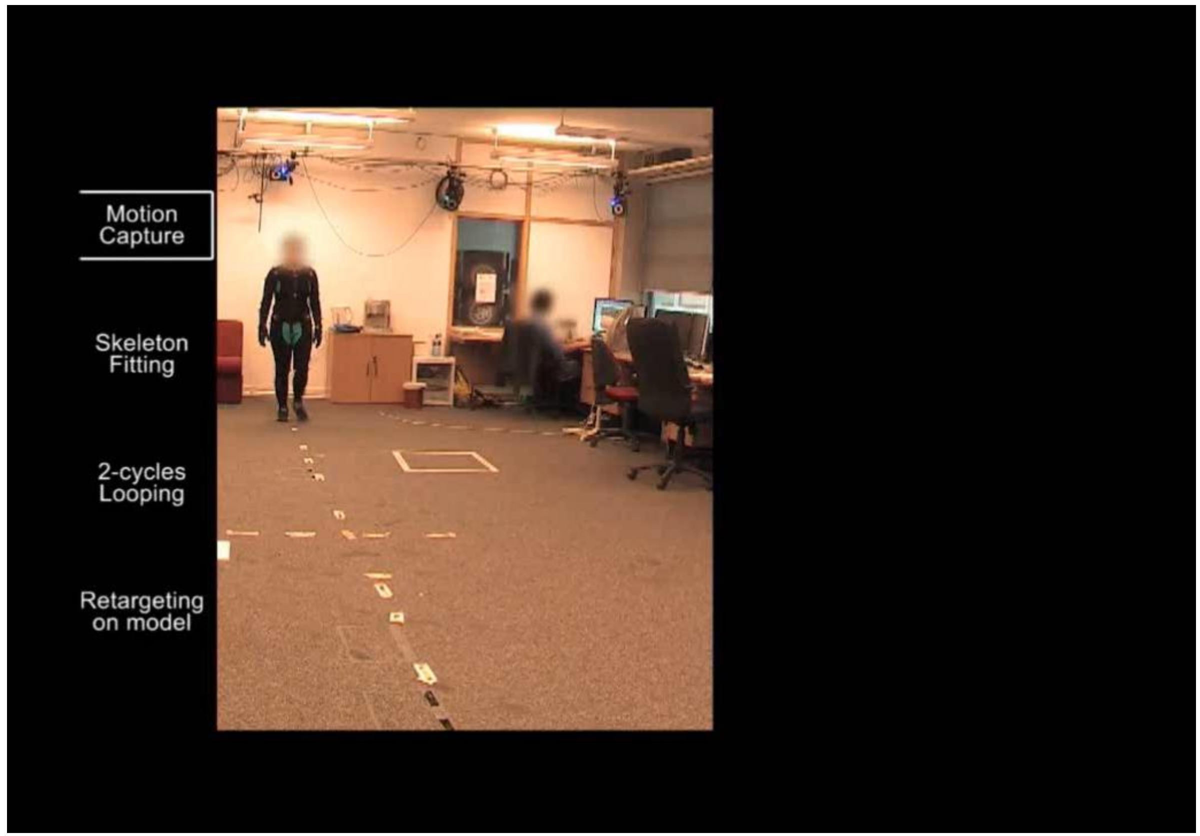
- Kinematic skeleton animation
- Motion capture
- Simulation + Control

Motion capture

- Optic
- Magnetic
- First issue
  - Occlusion



Visual hull



@Hoyet

Motion capture

Challenges

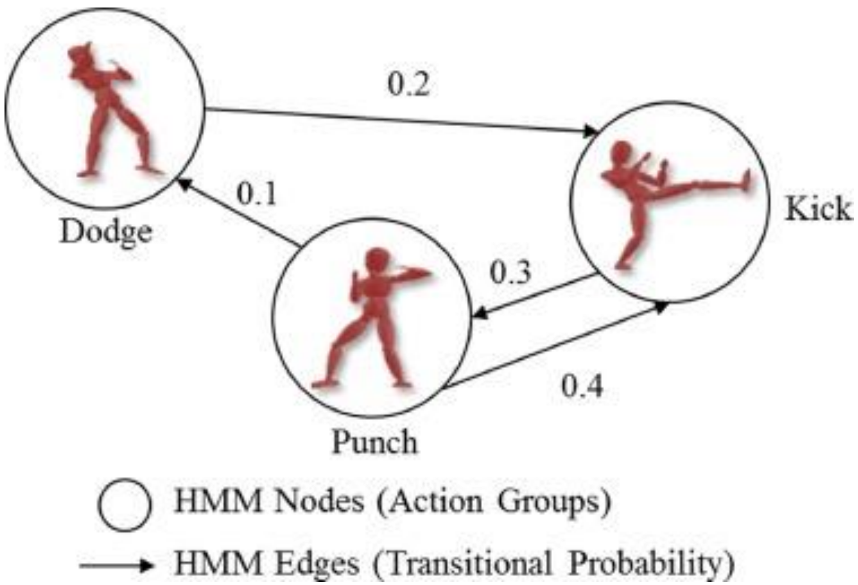
- Adapting to different morphologies
  - monsters, aliens…
- Combining different motions
  - walk while raising arms
  - transitions (walk, fall, get up, run….)
- Editing (ex: walk on uneven ground)
  - filter (Fourier, wavelets…), edit and apply details back

@ Weta digital

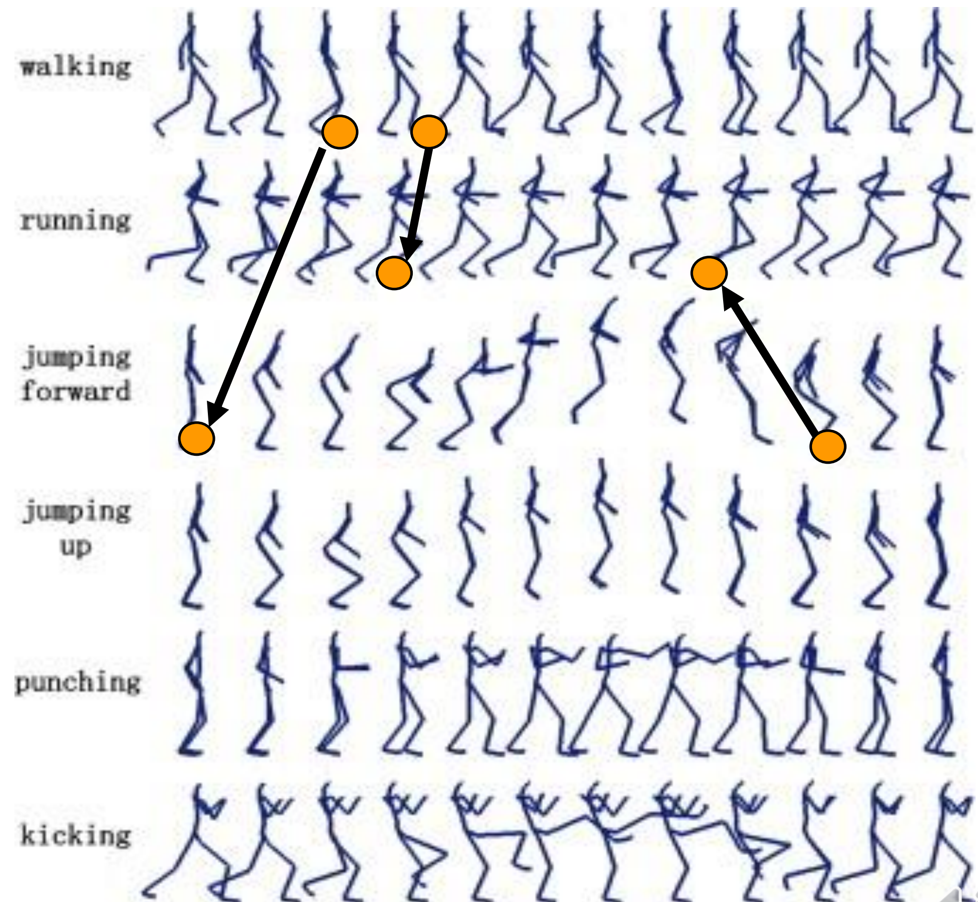
Motion capture

Combining motions: Motion graphs

- Computing valid transitions between motions data
- Higher level control: a Fighter



[Beaudoin 2008]



- Skeletal motion
- Skin & face
- Clothing & hair

Animating the skeleton

2. Capture

- Specific motion for a movie
- Motion samples in a database

→ Adapted & combined for reuse

3. Simulation

Physical model

- Solids
- Joints

+ Automatic motion generation

- Control is difficult
  - Action of muscles ?
  - Control of equilibrium ?

- Kinematic skeleton animation
- Motion capture
- Simulation + Control

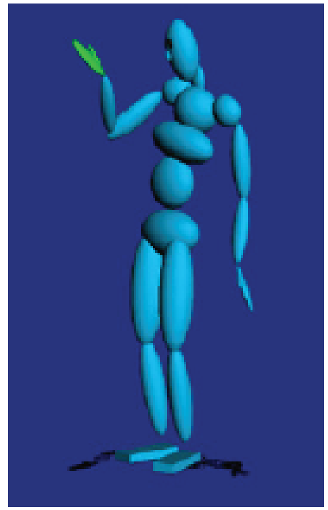
Generation of new motion?
Physically-based simulation + Control

Rigid bodies : Lagrangian mechanics

$$\begin{cases} m\,(dV/dt) = \sum F \\ I\,(d\omega/dt) + \omega \wedge I\,\omega = \sum M \end{cases}$$

Articulated bodies : Unknown internal force at joints

- Computed using "Lagrange multipliers" (ideal zero-length damped spring at joints)



Characters: Actuator attached to each joint

Controller

(eg. Trying to reach target angle)

→ Actuator forces →

Simulation engine

← Sensors feedback

« Feedback loop »

Generation of new motion?
Simulation + Control

Benefits

- Getting general, physically-plausible motion
- Motion will adapt to the surrounding

Challenge

- Muscular forces unknown
- Even keeping equilibrium is difficult

→ Until recently, mainly used for passive motions…

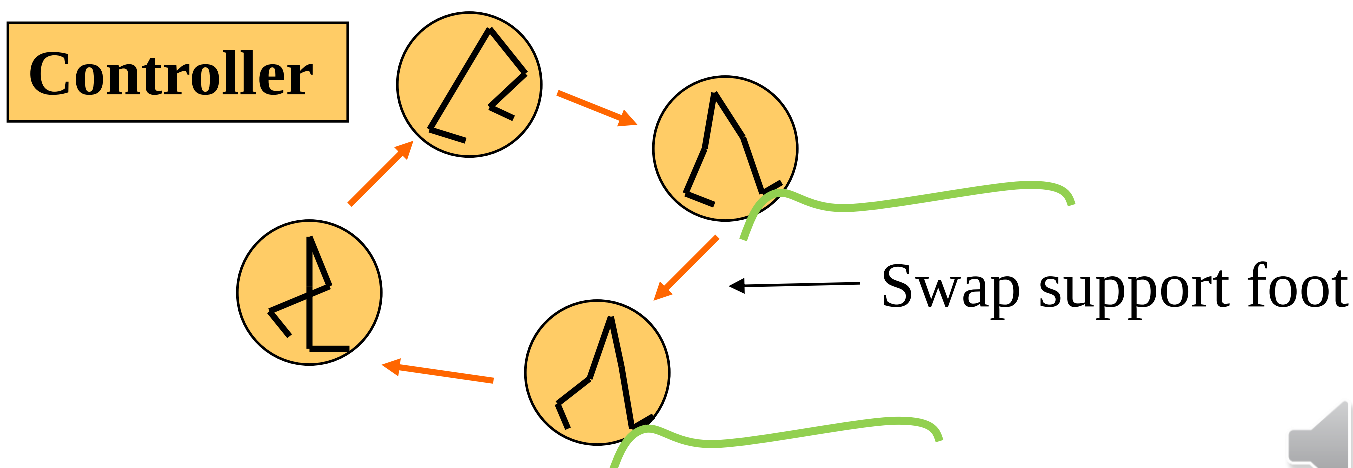
- Kinematic skeleton animation
- Motion capture
- Simulation + Control

Simulation + Control
Actuator forces over time

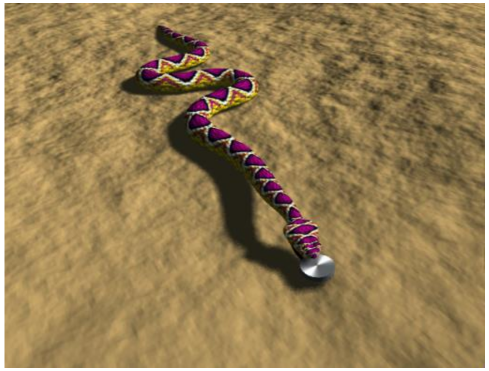
How to create motion controllers ? *[Van de Panne 1988..1998]*

- Controllers act by "pulling" towards a succession of poses
  - Blind control : finite-states automata similar to wind-up toys
  - Feedback control : takes contacts into account (sensors)

Pixar's walking teapot



Simulation + Control
Actuator forces over time



Methods to create motion controllers

1. Manual design
2. Automatic methods
   - Optimization : random search, selection, improvement
   - Genetic algorithms : population, crossings
   - Reinforcement learning

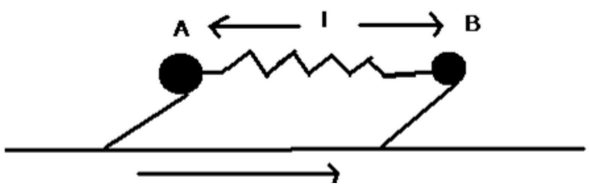
→ Find how creatures best uses their muscles to move

- Kinematic skeleton animation
- Motion capture
- Simulation + Control

Physics + Control
Actuator forces over time

Manual tuning of motion controllers

[Miller 88]



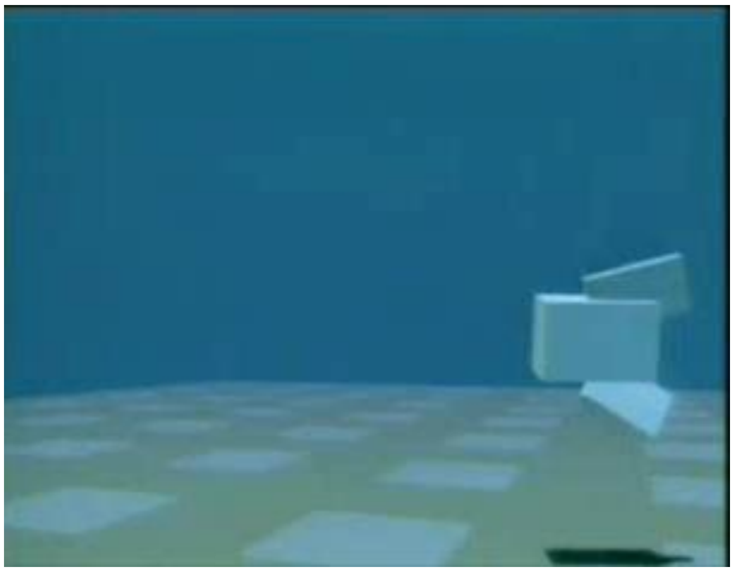
Animating human athletics

[Hodgins 95]

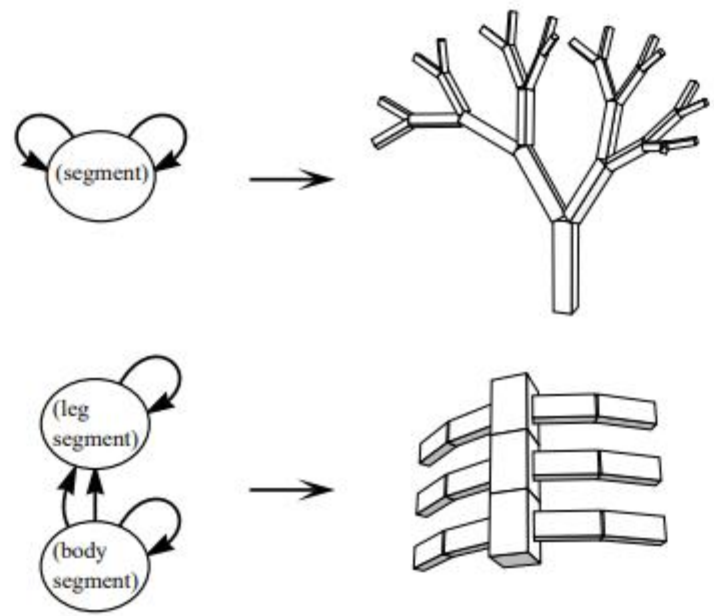
- Kinematic skeleton animation
- Motion capture
- Simulation + Control

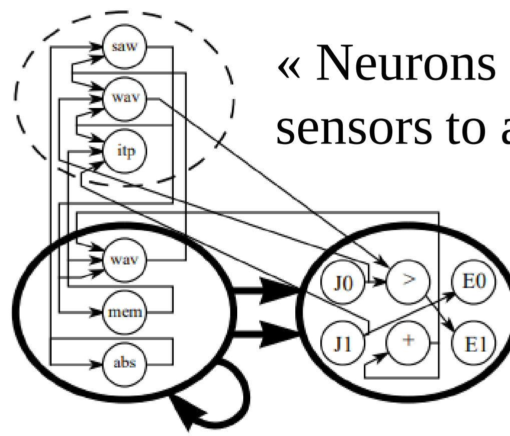
Evolving virtual creatures *[Sims 1994]*

- Selection based on “fitness level”



Genotype Phenotype





« Neurons » connecting sensors to actuators

Biologically-inspired evolution using

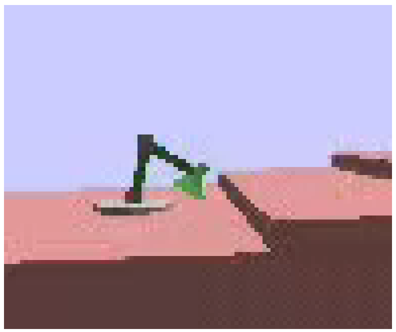
- Mutations
- Crossovers from parents

- Kinematic skeleton animation
- Motion capture
- Simulation + Control

Physics + Control
Actuator forces over time

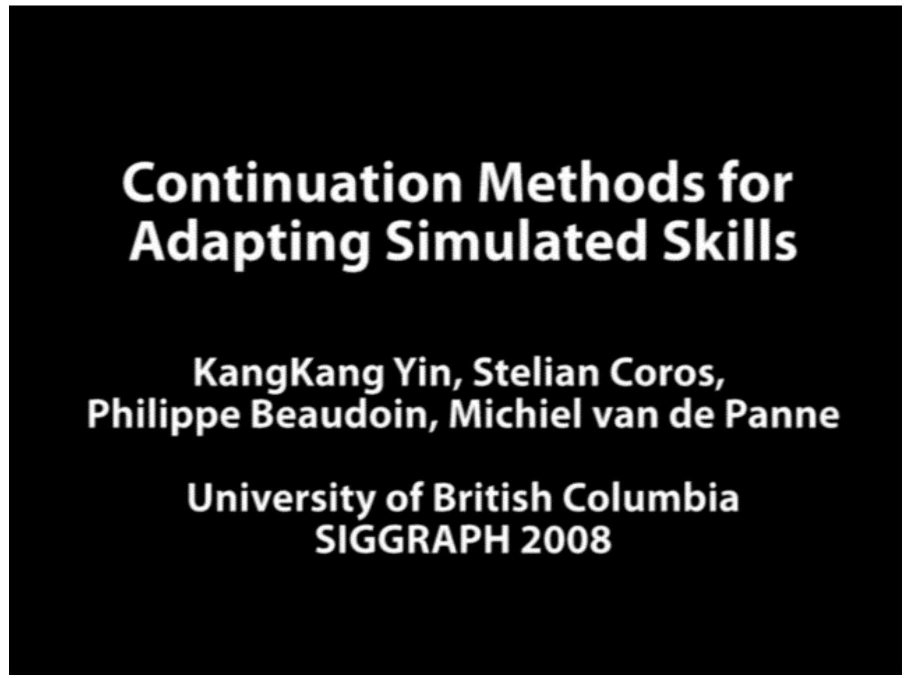
Automatic generation of controllers

– optimization in a large search space!



[Van de Panne 93]

[Yin 2008]



« Sensor-Actuator networks »

- Random search for weights
- Reward any forward move

Adapting the SIBICON controller using a progressive sequence of tasks
SIBICON *[Yin2007]* includes an inverse pendulum for balance control

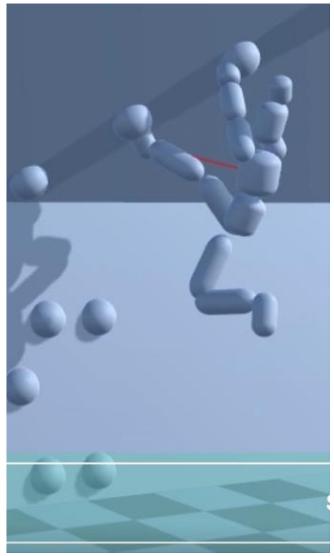
- Expressive authoring
- Generation + Control
- Brain layer?

Simulation + Control

Can we generate complex motion sequences?

Classic pipeline : Humanoid climbing motion *[Naderi 2017]*

1. Motion planning, shortest path
2. Sampling-based optimization

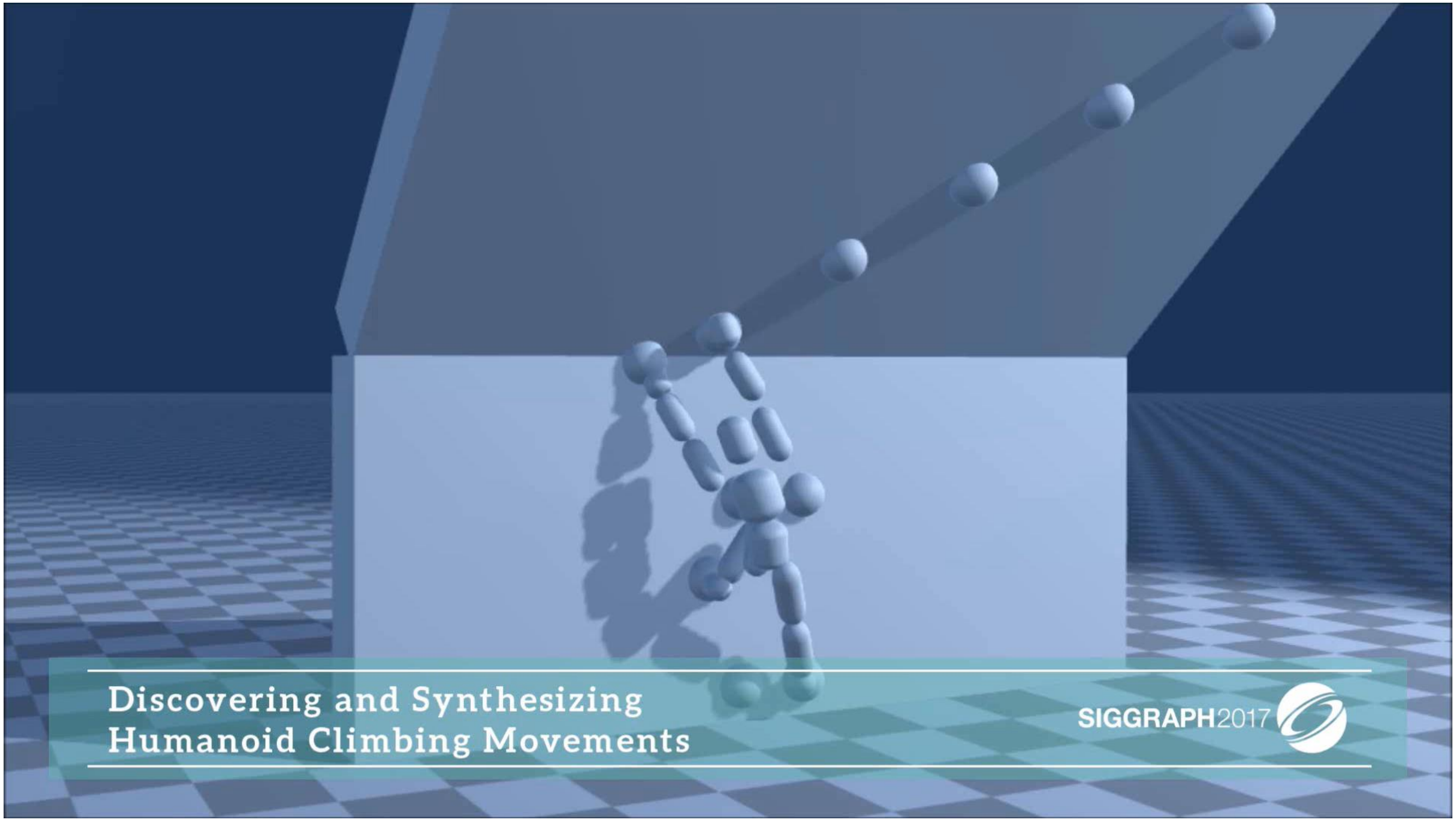


Simulation enabling to discover useful strategies:

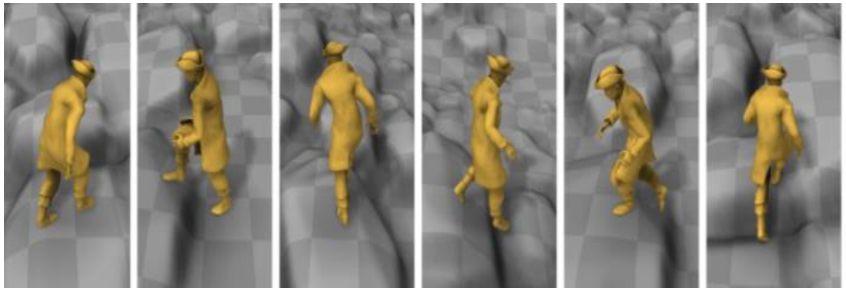
- Simultaneous limb motions
- Swing to maintain balance
- Friction on wall to push the body

- Expressive authoring
- Generation + Control
- Brain layer?

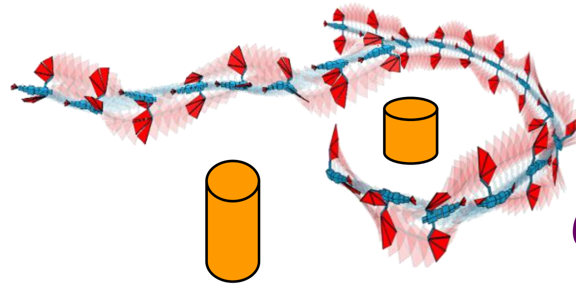
Character animation
Simulation vs Learning



https://youtu.be/ruSEAzzOmSQ

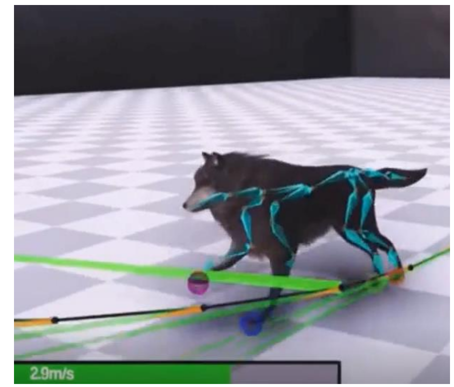


[Holden 2017]



[Won 2017]

Recent advances

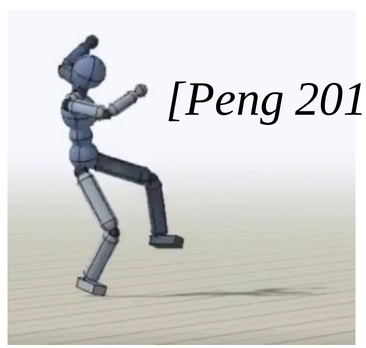


[Zhang 2018]

Learning character motion control ?

- Use of deep vs reinforcement learning
- Motion capture data as learning database
- Learning to interact with other moving objects

[Yu 2018]



[Peng 2018]

[Liu 2018]

Passive layers for virtual characters

- Brain (AI) layer
  - Taking decisions
    (eg. finite state automata)
  - Planning motion

← **Autonomous characters**

- **Animated layers**
  - **Skeleton**
  - **Skin** (+ muscles, flesh…)
  - **Faces**
  - **Clothes**
  - **Hair**

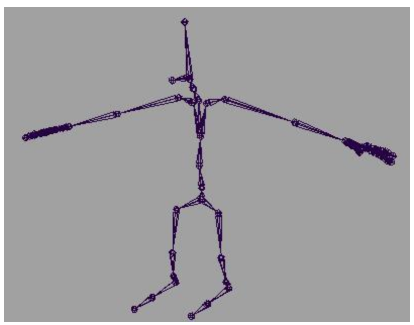
← **All virtual characters!**

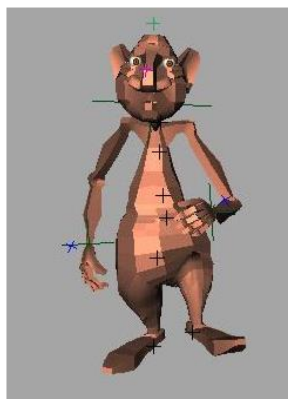
- Skeletal motion
- Skin & face
- Clothing & hair

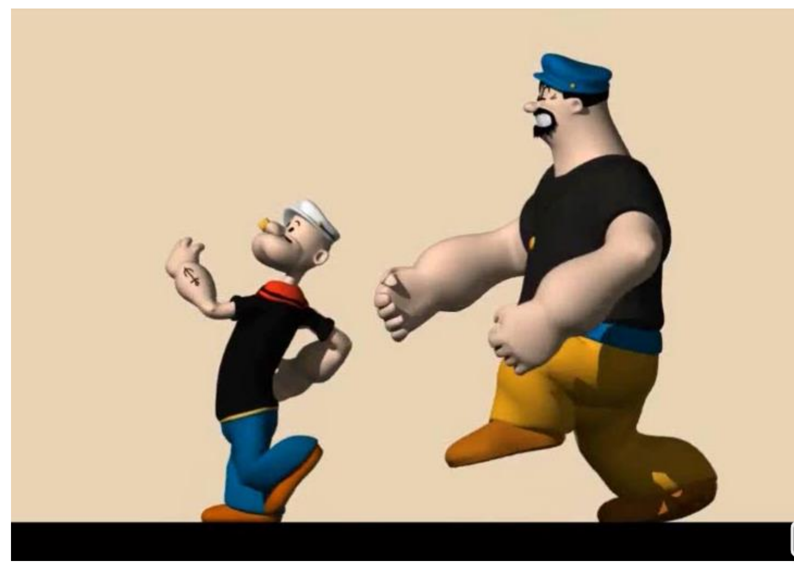
From skeletal motion…
Animating skin ?

- Goal

Deform the skin mesh, given the animated skeleton







- Skeletal motion
- Skin & face
- Clothing & hair

Animating skin ?
"Brute force" physically based approach

1. Model muscles attach to bones
2. Simulate muscle deformation using FEM
3. Add an elastic skin layer on top of the muscles

[Avatar, 2009] @ Weta Studio

@anatosctope

\+ Detailed, dynamic results
\- Computational time
\- Parameter tuning is difficult

- Skeletal motion
- Skin & face
- Clothing & hair

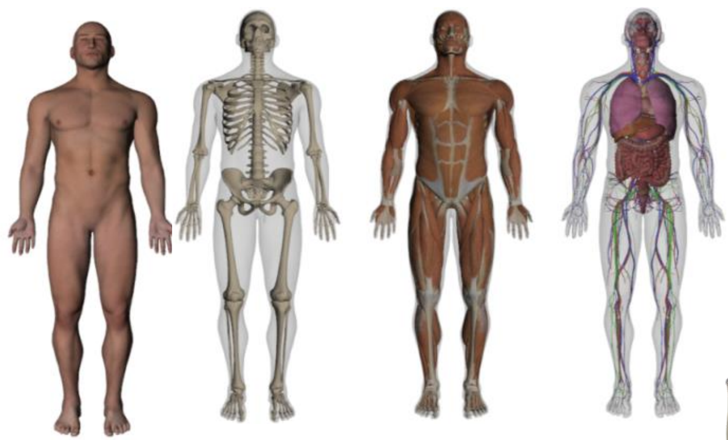
Expressive creation of anatomy?
"Anatomy transfer"

1. Bones straight & symmetric / sagittal plane
2. Muscles proportional to fat, skeleton is not!
3. Fat localized between skin and muscles
4. Maintain muscle insertion points on bones

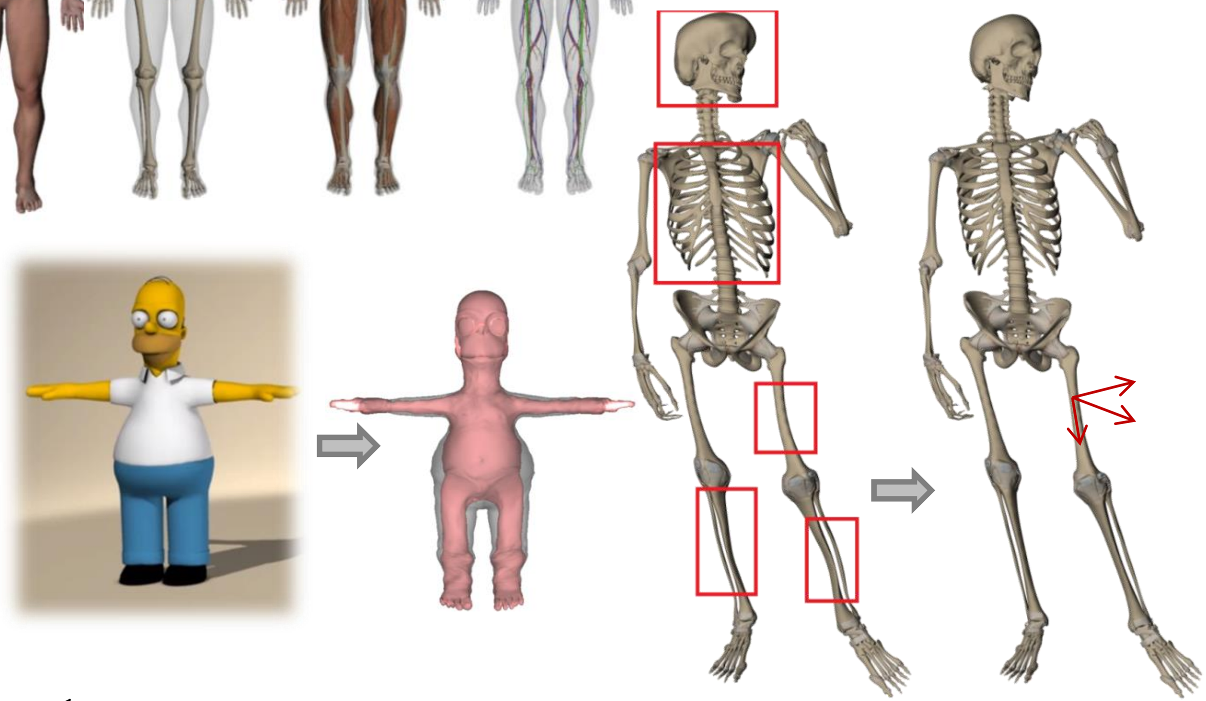
- Skeletal motion
- Skin & face
- Clothing & hair

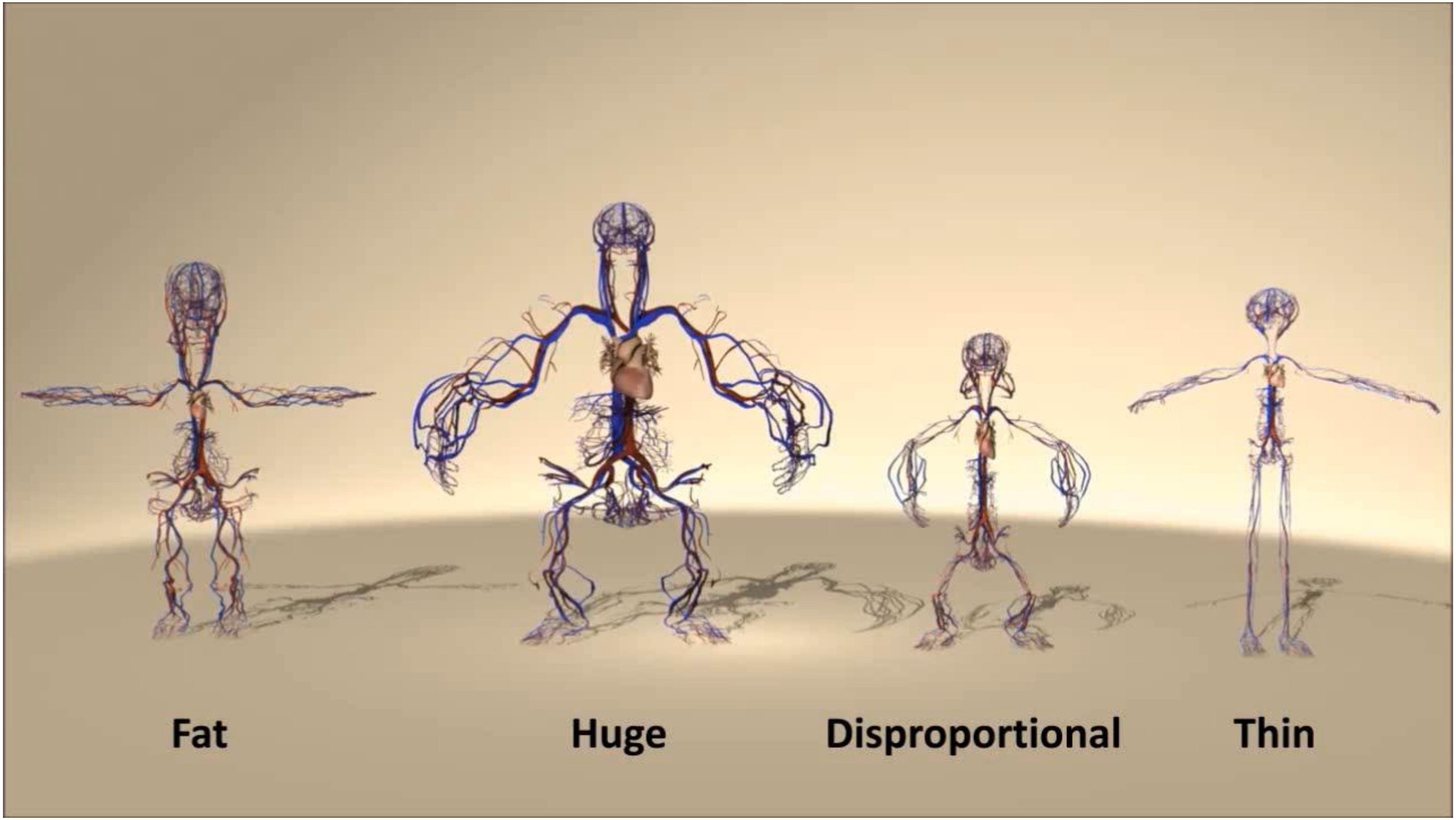
Anatomy transfer
Smart copy-paste based on knowledge

Input
- Anatomical model
- Target character



Algorithm
1. Erode fat
2. Register skins
3. Transfer bones
   - Laplace interpolation
   - Affine transformations
4. Transfer muscles and organs





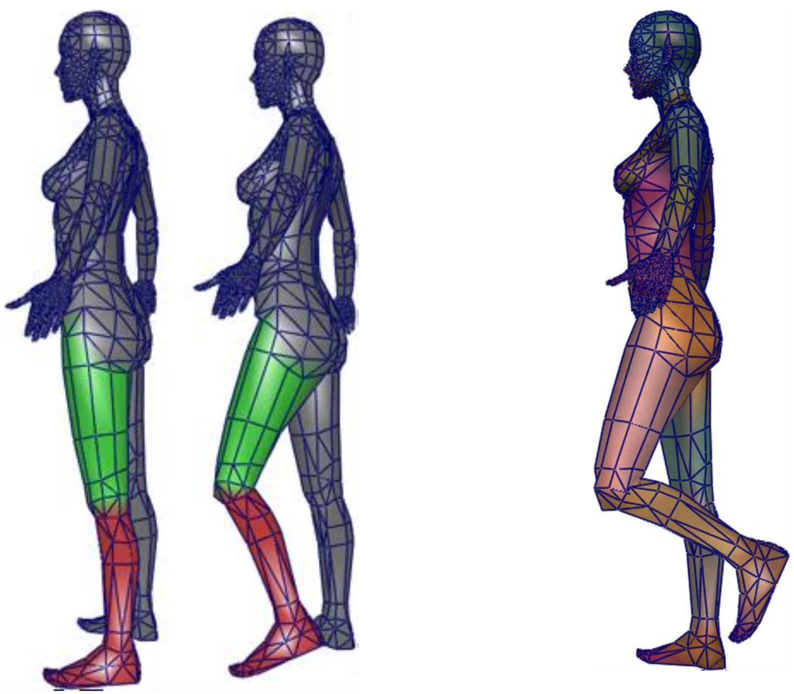
[Dicko 2013]

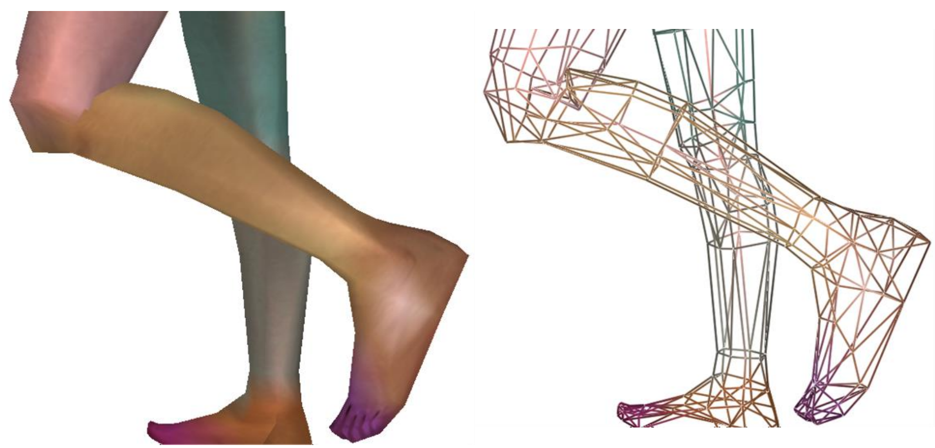
- Skeletal motion
- Skin & face
- Clothing & hair

Better fit to the production pipeline?
Geometric skinning

Rigid skinning

- Mesh parts rigidly attached to skeleton frames





Geometric skinning
Linear blend skinning (LBS)

- For each mesh point
  - skinning weight k_i with respect to each S_i
  - combine positions in the different frames

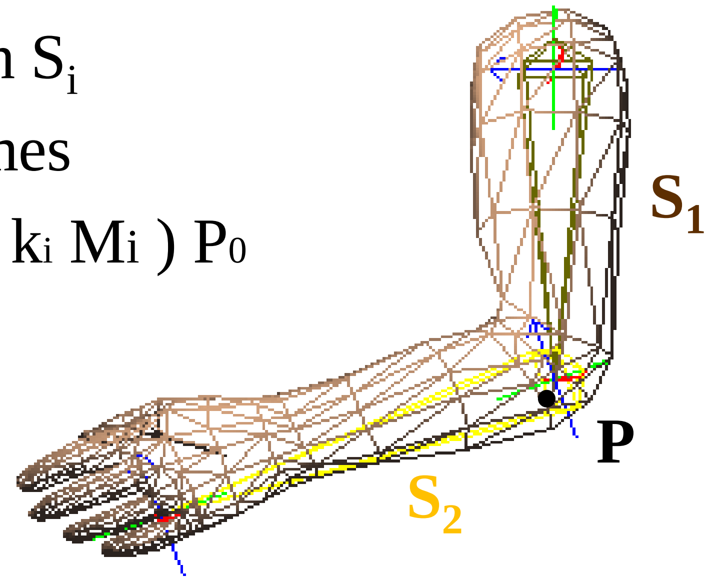
$$P = \sum k_i P_i = \sum k_i (M_i P_0) = (\sum k_i M_i) P_0$$

M_i is the transformation matrix for S_i

+ Almost no memory cost

+ Real-time computation

+ Skin motion created independently at each frame



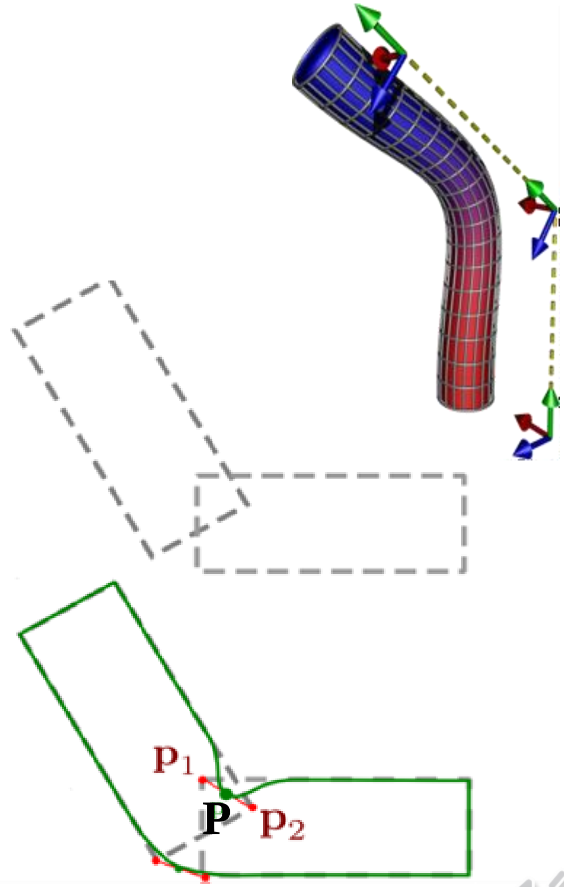
- Skeletal motion
- Skin & face
- Clothing & hair

Geometric skinning
Linear blend skinning (LBS)

- Drawbacks
  - Artifacts for large angles
  - Choose the weights? (painted by an artist!)

“Candy wrapper effect”

“Collapsing elbow”



Geometric skinning
From LBS to dual quaternions

- Linear Blend skinning (LBS) : P= (∑ k_i M_i) P_0

A linear combination of matrices is not a correct transform!

- Dual quaternions

Quaternions with dual numbers

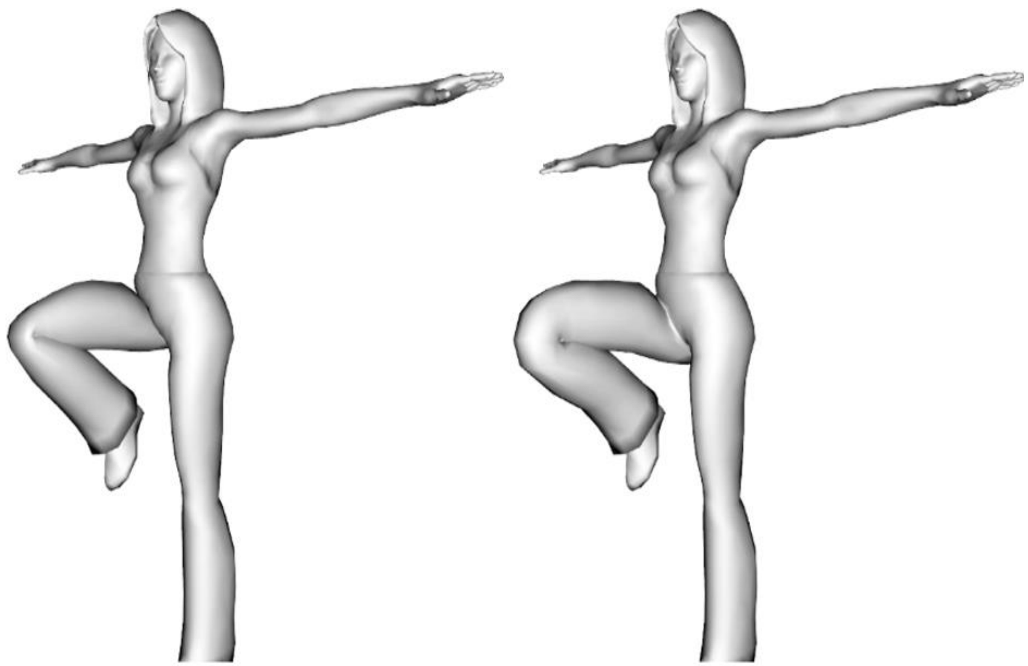
$$\hat{q} = q_0 + \epsilon q_\epsilon$$

Represent rotation & translation

Enables to blend rigid motions

$$\hat{q} = \sum_i \omega_i \hat{q}_i$$

$$\hat{q}_n = \hat{q} / ||\hat{q}||$$

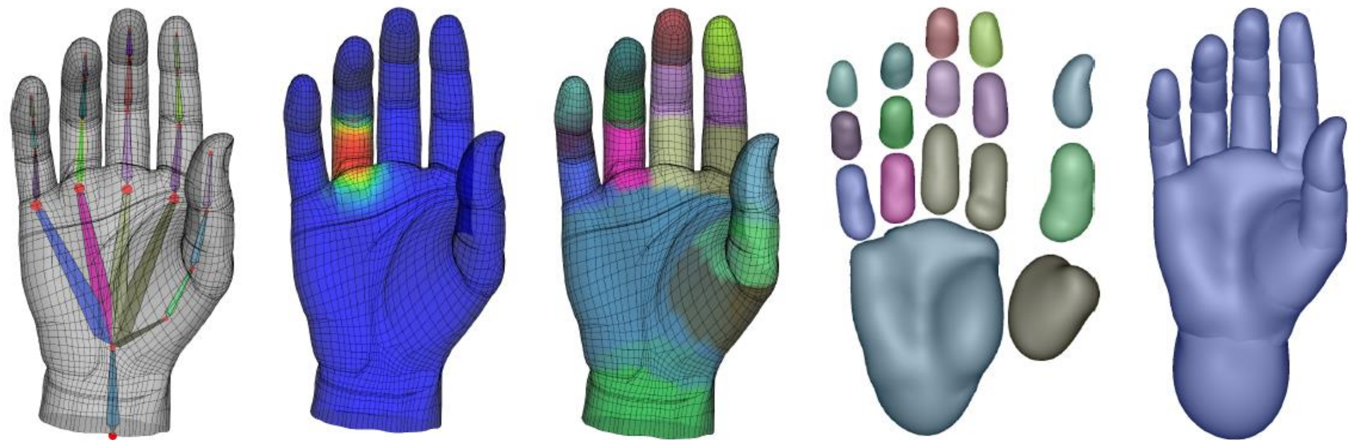


LBS Dual quaternions

- Skeletal motion
- Skin & face
- Clothing & hair

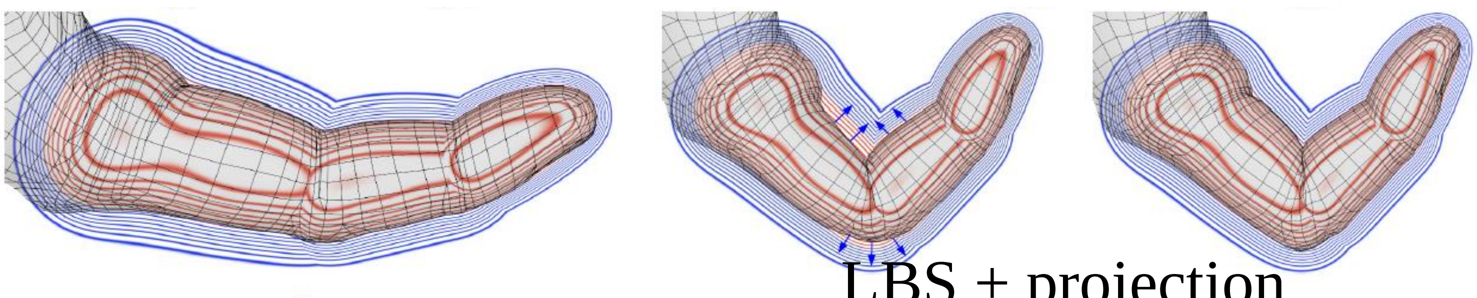
Geometric skinning
Implicit skinning

Volume preserving blending? Which solves for contact surfaces?



Implicit surface

Advanced blending
- Contact
- Bulges



[Vaillant 2013]

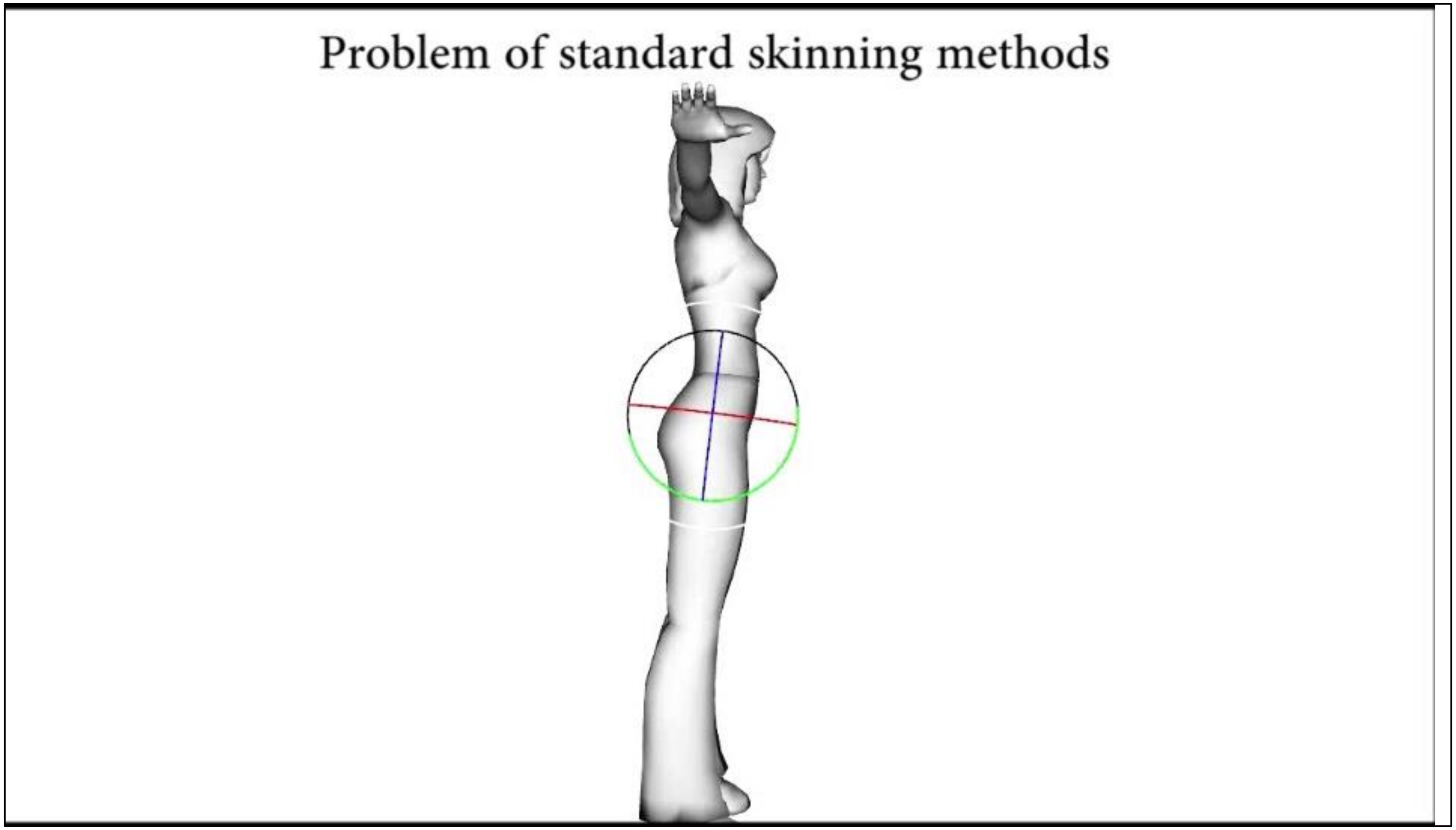
LBS + projection

To preserve details : Maintain mesh points on their own isosurfaces

- Skeletal motion
- Skin & face
- Clothing & hair

Geometric skinning
Implicit skinning

[Vaillant 2013]

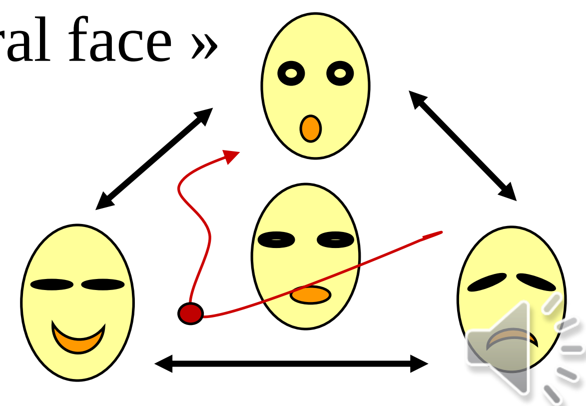


Animating faces
From Physics to Geometry

- **Face dynamics**
  - Requires facial bones motion + muscle activation
  - Complex and costly physically-based simulation
- **Key frames** : Interpolate key-shapes over time
  - Redundancy of successive key-faces

- **Blend Shapes** : Multi-target interpolation
  - Model a few « extreme faces » from a « neutral face »
  - Animate a trajectory in this space : weights(t)

During animation, for each meh point
compute the current barycenter on the fly



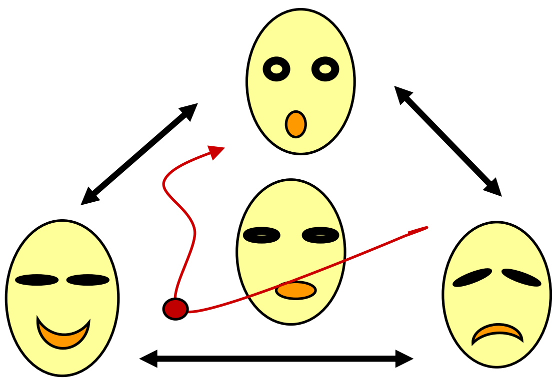
Animating faces

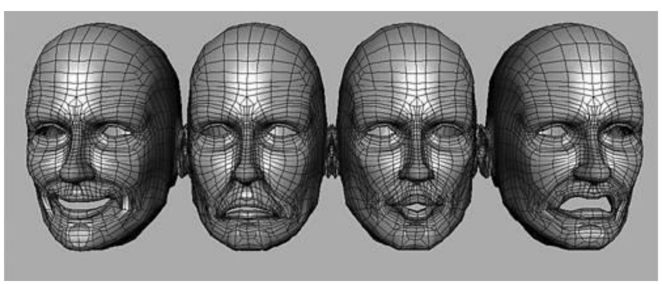
Blend Shapes are most often used

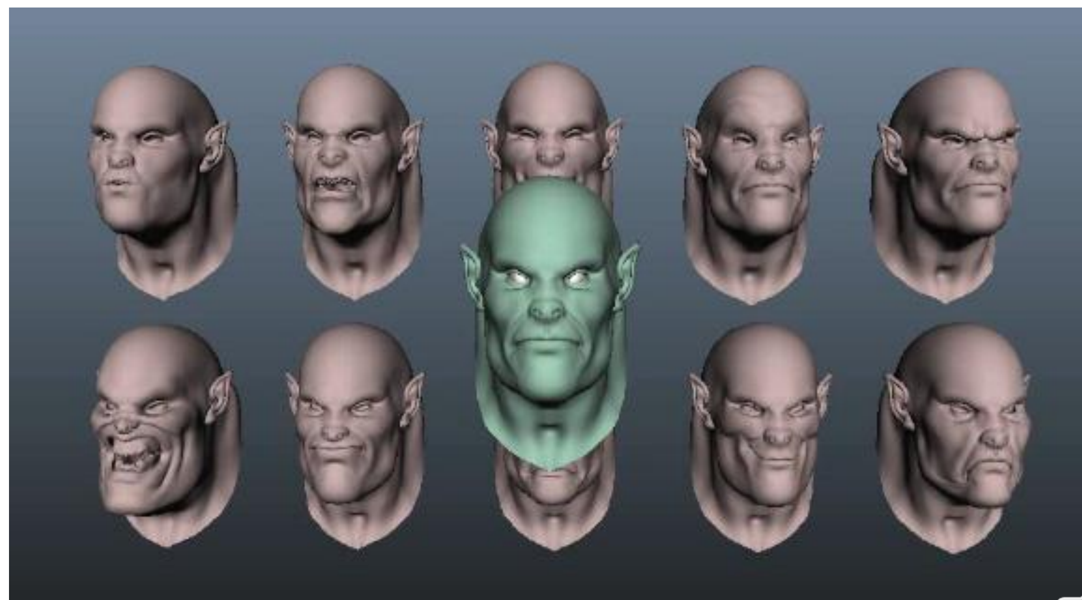
– The same mesh needs to be used to model all expressions

+ Fast mesh interpolation

+ Trajectories in blend-space can be transferred to other characters







Passive layers in a character
Clothes and hair

Passive : Physically-based simulation!

- Difficulties for clothes
  - Collisions between thin surfaces
  - Should fold rather than compress!

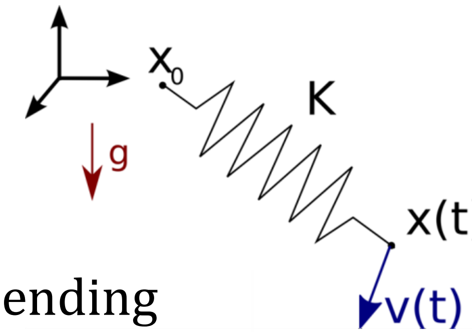
  Numerical integration with stiff springs?
- Difficulties for hair
  - 100 000, non extensible strands
  - Hair shape and dynamic motion

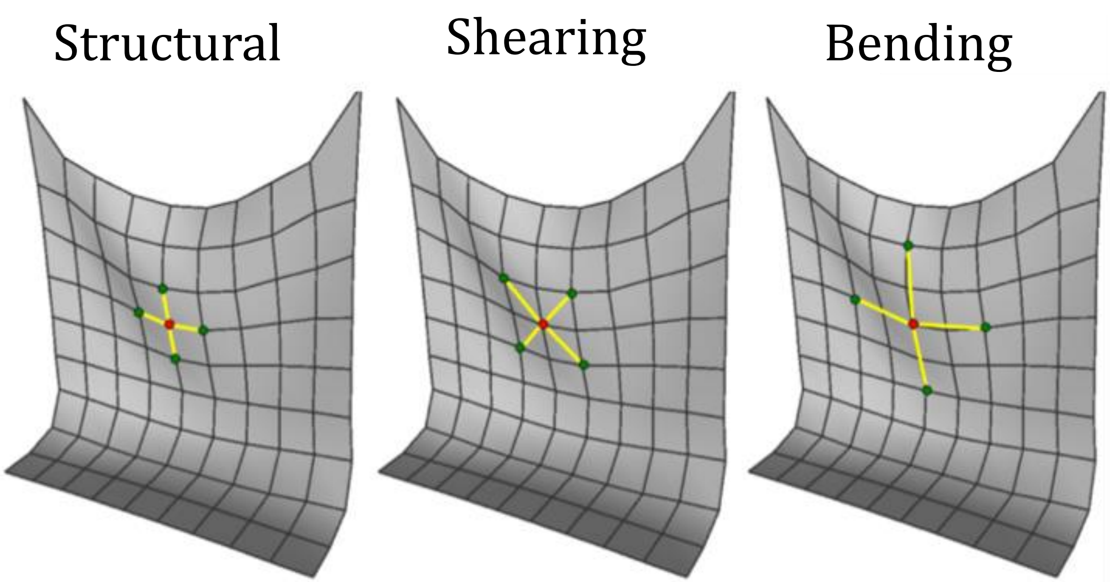
    strongly depend on their interactions!

- Skeletal motion
- Skin & face
- Clothes & hair

Animating clothes Standard…

- Mass-spring system

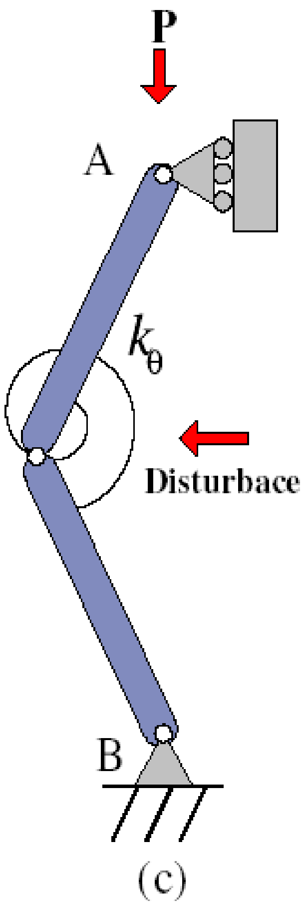


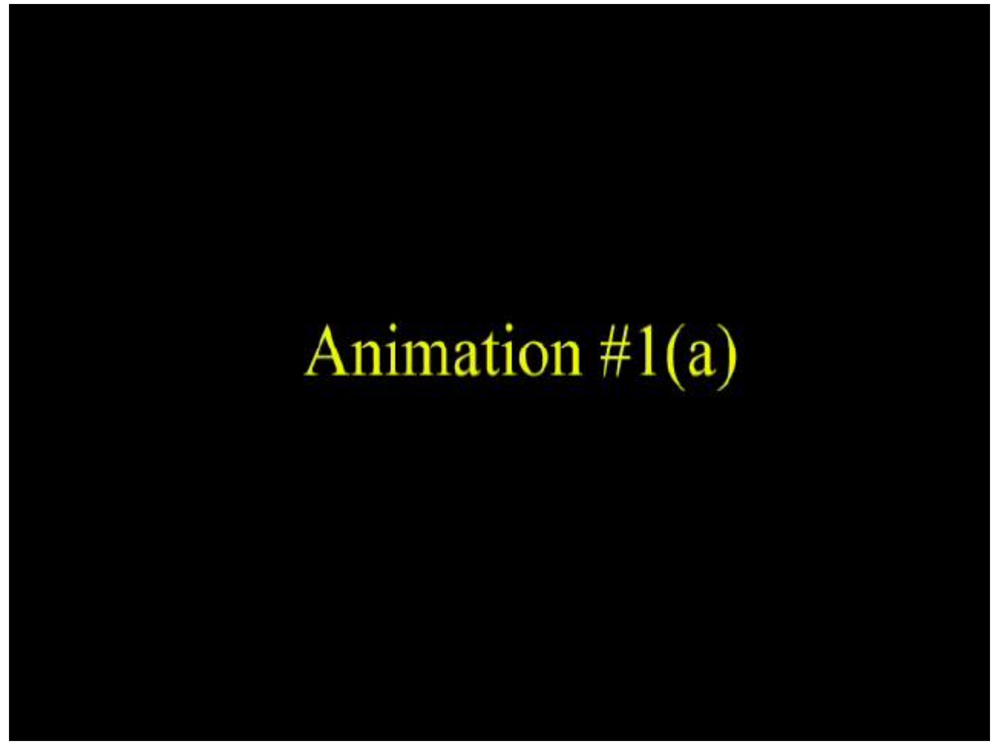


+ Good dynamics
- Results may lack folds

- Skeletal motion
- Skin & face
- Clothes & hair

Animating clothes
Responsive clothes

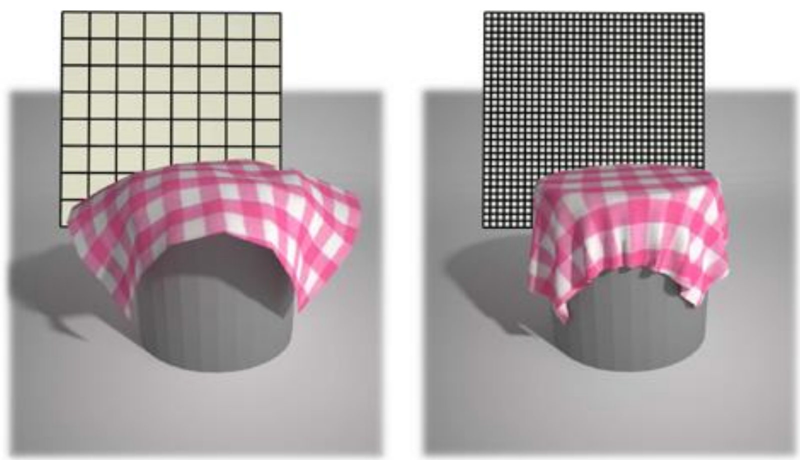




[Choi 2002]

Animating clothes
Drawbacks of simulation…

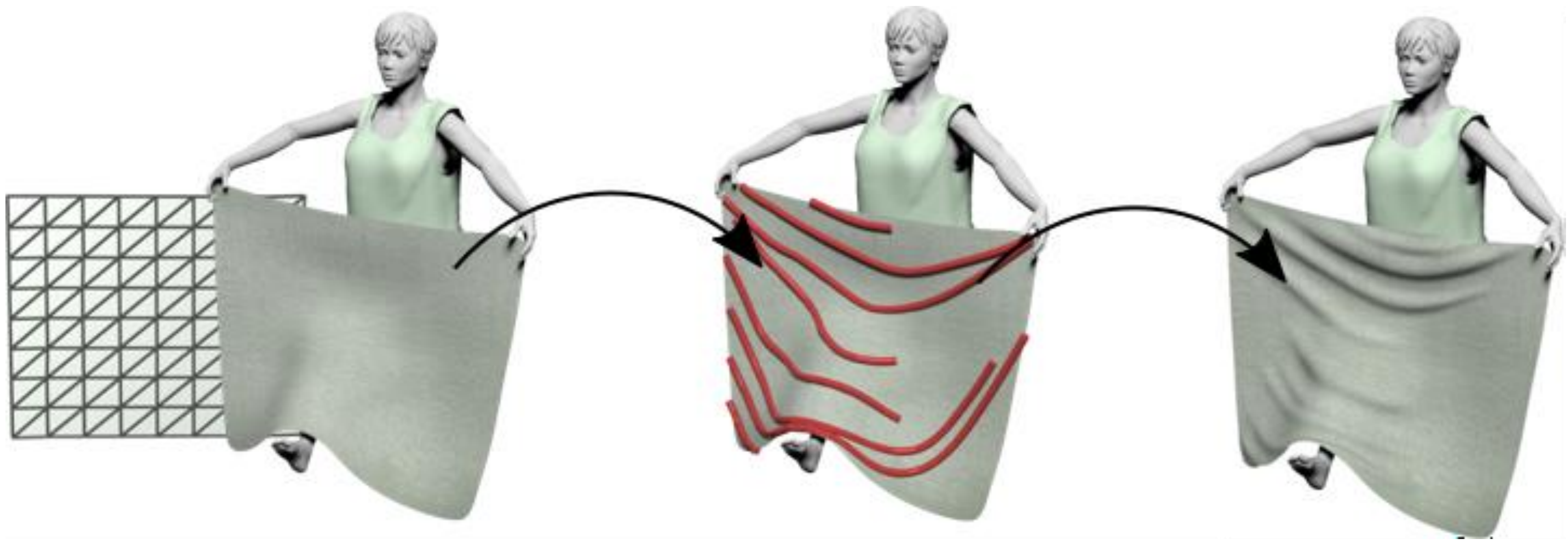
- Physically-based simulation
  - Computational cost : simulation, collisions, self-collisions…
  - Static and dynamic results heavily depend on mesh resolution
  - Springs difficult to tune!
- Many trials and errors …



- Skeletal motion
- Skin & face
- Clothes & hair

Animating clothes
Animation wrinkling

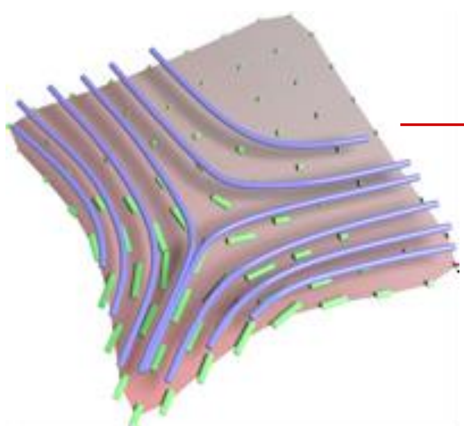
- Layered model *[Rohmer 2010]*
  - Low resolution mesh : dynamics in real time
  - Augmentation with geometric folds in compressed parts



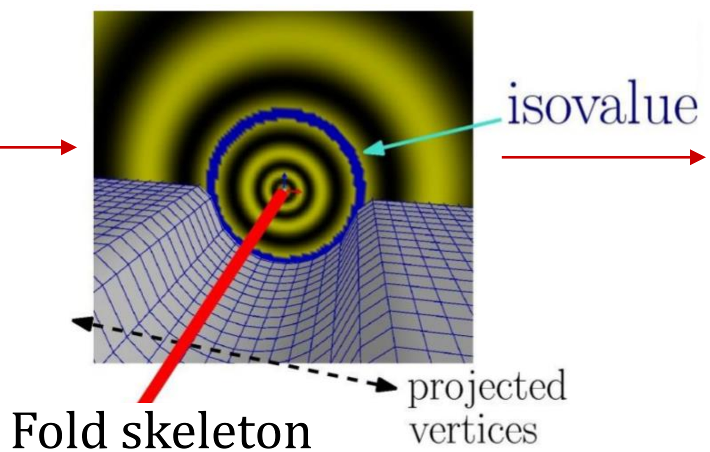
Fast low res simulation **Surface analysis + fold synthesis**

Animating clothes
Animation wrinkling

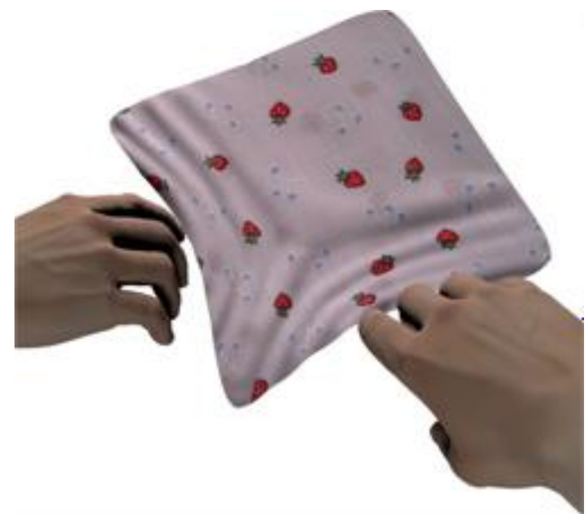
- Fold skeletons : stream-lines of the compression field
- Used to generate implicit surfaces deforming the mesh



Fold skeletons



Implicit deformer



Geometric deformation

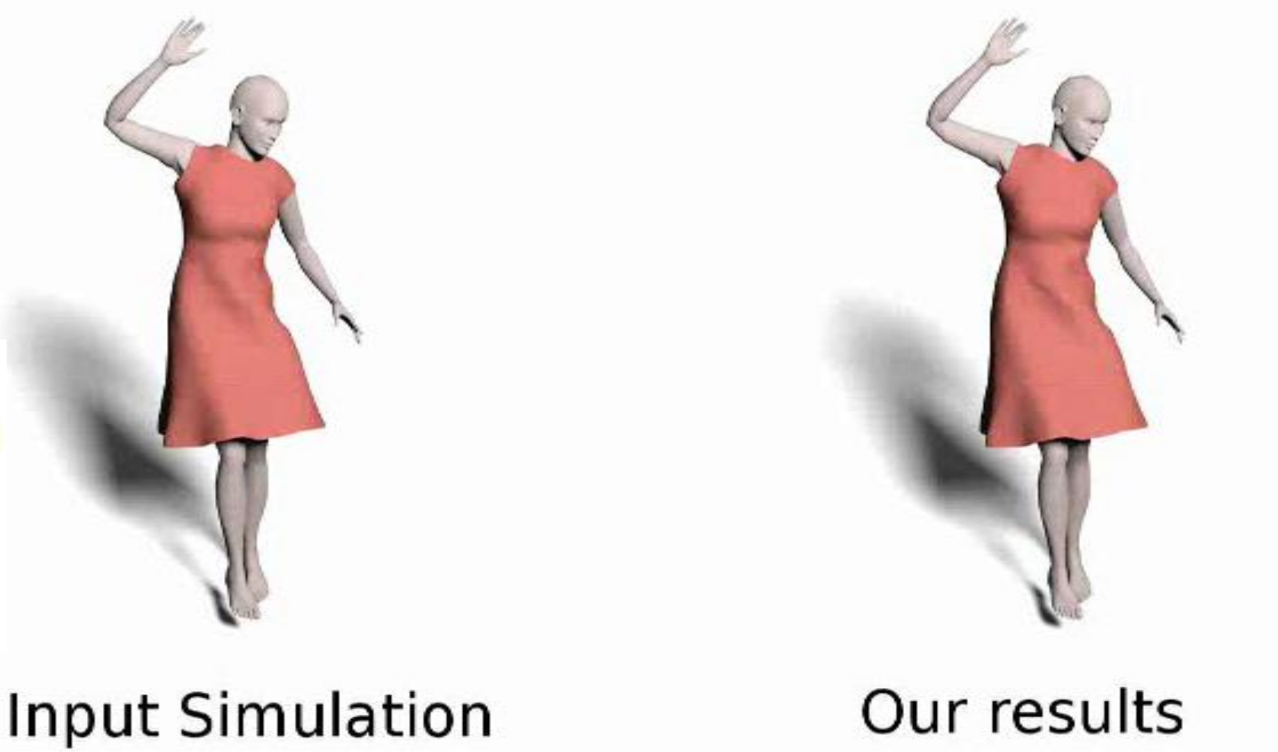
- Skeletal motion
- Skin & face
- Clothes & hair

Animating clothes
Animation wrinkling

Results

- Folds do not collide
- They blend at distance!

[Rohmer 2010]



- Skeletal motion
- Skin & face
- Clothes & hair

[Buffet 2019]

Animating layers of clothes
Implicit « untangling »

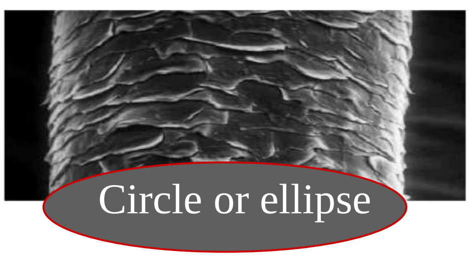
- Skeletal motion
- Skin & face
- Clothes & hair

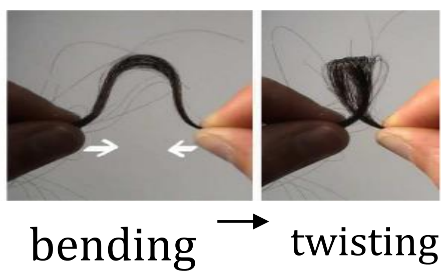
Hair animation Challenges

Full head of hair

- 100 000 non-extensible, interacting hair-strands
- Both static shape and dynamic motion emerge from interactions

First hair model in CG
No self-interaction
[Anjyo 1992]





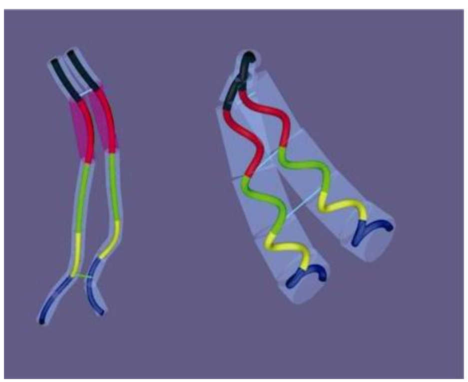
- Skeletal motion
- Skin & face
- Clothes & hair

Hair animation

[Bertails 2006]

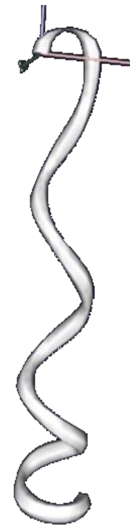
Layered modelling

- Guide strands simulated to capture dynamic motion
- Hair wisps used to model anisotropic interactions
- Geometric stands added at the rendering stage
  - using interpolation or extrapolation…. or both !



- Skeletal motion
- Skin & face
- Clothes & hair

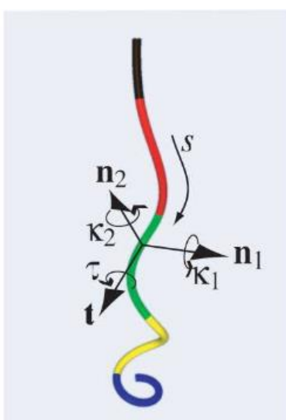
Hair animation
Layered modelling

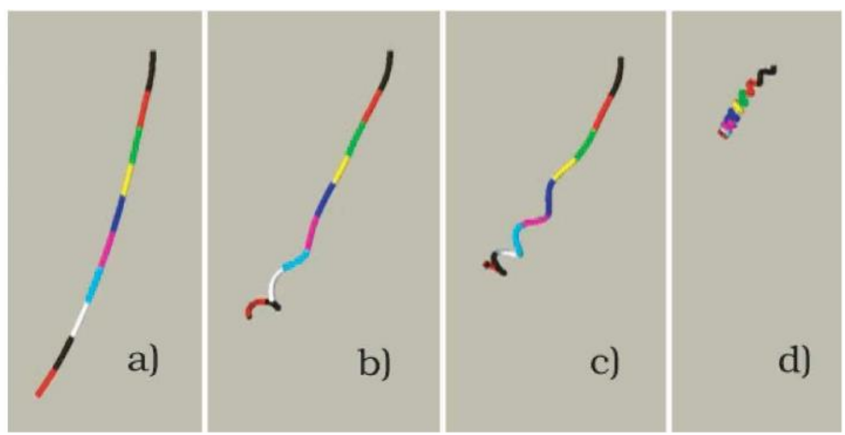


Dynamics for the « guide hairs » ?

"Super helices" (helices by part)

- Un-extensible rods
- Non-zero rest curvature





- Skeletal motion
- Skin & face
- Clothes & hair

Hair animation
Layered modelling with super-helices

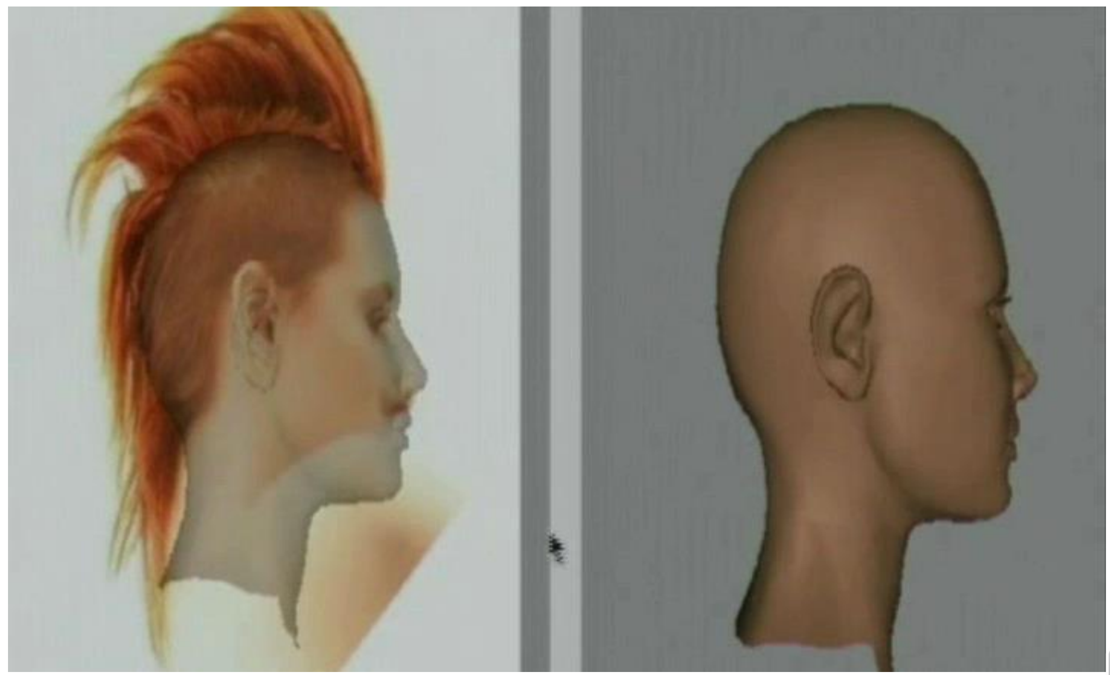
Results
[Bertails 2006]

- Skeletal motion
- Skin & face
- Clothes & hair

Hair animation
Layered modelling with super-helices

- Hair styling using simulation

- *Expressive hair styling [Wither 2008]*



Conclusion

Layered models for individual characters

- Standard methods
  - Kinematics (or physics) for the skeleton
  - Geometric deformation for the skin
  - Dynamics for clothes and hair
- Can we make it easier?
  - Expressive authoring of kinematic animation
  - Towards realism
    - Learning motion control for physically-based characters

References (skeletal motion)

- Beaudoin, Coros, van de Panne, Poulin. 2008. Motion-motif graphs. SCA 2008.
- Choi, Blanco i Ribera, Lewis, Seol, Seokpyo, Eom, Jung, Noh (2016). SketchiMo: sketch-based motion editing for articulated characters. ACM TOG, Siggraph 2016
- Guay, Cani, Ronfard The Line of Action. Siggraph Asia 2013.
- Guay, Ronfard, Gleicher, Cani. Adding dynamics to sketch-based character animations. Sketch-Based Interfaces and Modeling (SBIM), Expressive symposium 2015.
- Guay, Ronfard, Gleicher, Cani. Space-time sketching of character animation. Siggraph 2015
- Hodgins, Wooten, Brogan, O'Brien. Animating human athletics. SIGGRAPH 1995
- Holden, Komura, Saito. 2017. Phase-functioned neural networks for character control. Siggraph 2017.
- Lamouret, Cani. Scripting Interactive Physically-Based Motions, Graphics Interface 1995.
- Liu, Hodgins. Learning Basketball Dribbling Skills Using Trajectory Optimization and Deep Reinforcement Learning. SIGGRAPH 2018
- Miller, "The Motion Dynamics of Snakes and Worms“, SIGGRAPH 1988.
- Naderi, Rajamäki, Hämäläinen. Discovering and synthesizing humanoid climbing movements. SIGGRAPH 2017

References (skeletal motion)

- Peng, Abbeel, Levine, van de Panne. DeepMimic : Example-Guided Deep Reinforcement Learning of Physics-Based Character Skills. SIGGRAPH 2018.
- Z. Ren, P. Charalambous, J. Bruneau, Q. Peng, J. Pettré. . Group Modeling: A Unified Velocity-Based Approach. Computer Graphics Forum (CGF). 2017.
- Reynolds, « Flocks, herds and schools: A distributed behavioral model », SIGGRAPH 1987
- Karl Sims. Evolving virtual creatures. SIGGRAPH 1994
- Van de Panne, Fiume. Sensor actuator networks, SIGGRAPH 1993.
- Witkin and Kass. Spacetime constraints. SIGGRAPH 1988.
- Won, Park, Kim, Lee. 2017. How to train your dragon: example-guided control of flapping flight. Siggraph Asia 2017
- Yin, Loken, van de Panne. SIMBICON: Simple Biped Locomotion Control. ACM Transaction on Graphics. SIGGRAPH 2007
- Yin, Coros, Beaudoin, van de Panne Continuation methods for adapting simulated skills SIGGRAPH 2008
- Yu, Turk, Liu. Learning Symmetry and Low-energy Locomotion. SIGGRAPH 2018
- Zhang, Starke, Komura, Saito. Mode-Adaptive Neural Networks for Quadruped Motion Control. SIGGRAPH 2018

References (skin, clothes and hair)

- Anjyo, Usami, Kurihara. A simple method for extracting the natural beauty of hair. SIGGRAPH 1992.
- Baerlocher, Boulic. An inverse kinematics architecture enforcing an arbitrary number of strict priority levels. The visual computer 20 (6), 402-417. 2004.
- Bertails, Audoly, Cani, Querleux, Lévèque, Leroy, Super helices, SIGGRAPH 2006
- Buffet, Rohmer, Barthe, Boissieux, Cani Implicit Untangling: A Robust Solution for Modeling Layered Clothing, ACM TOG, SIGGRAPH 2019
- Wither Bertails Cani. Hair styling from a sketch. SMI 2008
- Choi, Ko, Stable but responsive cloth. SIGGRAPH 2002.
- Dicko, Liu, Gilles, Kavan, Faure, Palombi, Cani. Anatomy transfer. Siggraph Asia 2013.
- Kavan, Collins, Zara, O'Sullivan. Geometric Skinning with Approximate Dual Quaternion Blending. ACM Trans. on Graphics, SIGGRAPH 2008.
- Rohmer, Hahmann, Cani. Exact volume preserving skinning with shape control. Symposium on Computer Animation (SCA) 2009.
- Vaillant, Barthe, Guennebaud, Cani, Rohmer, Wyvill, Gourmel,Paulin, Implicit Skinning: Real-Time Skin Deformation with Contact Modeling, SIGGRAPH 2013
- Rohmer, Popa, Cani, Hahmann, Sheffer, Animation wrinkling SIGGRAPH Asia 2010