Advanced 3D Graphics

… where Computer Graphics meets AI

Marie-Paule Cani

GeoViC team, LIX/DIX
Ecole Polytechnique

Advanced 3D Graphics
Focus : where Computer Graphics meets AI

***Part 1. "Creative AI"** – Intelligent systems helping users in creative tasks*

1. Expressive 3D modeling : smart geometry controlled by gestures
    - Shape representations for constructive modeling
    - Sculpting, sketching, transfer metaphors
2. Extension to virtual worlds
    - Modeling and animating natural scenes
    - Expressive creation & control of animated scenes

***Part 2. Autonomous characters** – animation & control*

3. Motion planning for characters and crowds
4. Animating and controlling individual characters

3D Computer Graphics
See and touch imaginary worlds ?

@Grenoble-INP avec Lyon 1, Inria

- Design, refine and fabricate imaginary 3D shapes
- Give life and explore animated virtual worlds…

Playful dimension… and a wonderful tool!

Digital creation in 3D

Computer Graphics

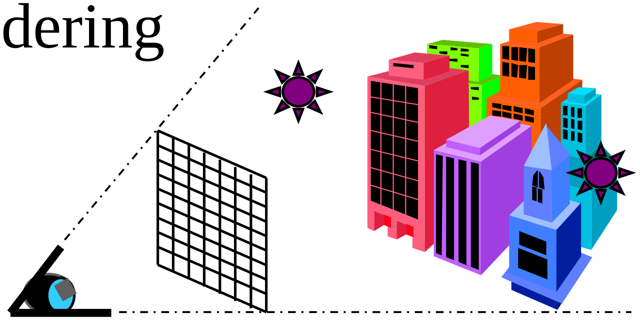
How can we help the user create them?

Not “image processing”, not “imaging”

– Input: mathematical models… Output: images!

3 steps

1. Geometric modeling
2. Animation
3. Rendering



Advanced 3D Graphics
Focus : where Computer Graphics meets AI

Part 1. "Creative AI" *– Intelligent systems helping users in creative tasks*

1. Expressive 3D modeling : smart geometry controlled by gestures
   - Section 1: Shape representations for constructive modeling
   - Section 2: Sculpting, sketching, & transfer metaphors
2. Extension to virtual worlds
   - Modeling and animating natural scenes
   - Expressive creation & control of animated scenes

Part 2. Autonomous characters *– animation & control*

3. Motion planning for characters and crowds
4. Animating and controlling individual characters

Part 1, Chapter 1: Expressive modeling
Section 1: Shape representations

Objectives

- Creating new shapes (no reconstruction)
- User control (no automatic generation)

→ *Interactive 3D modeling*

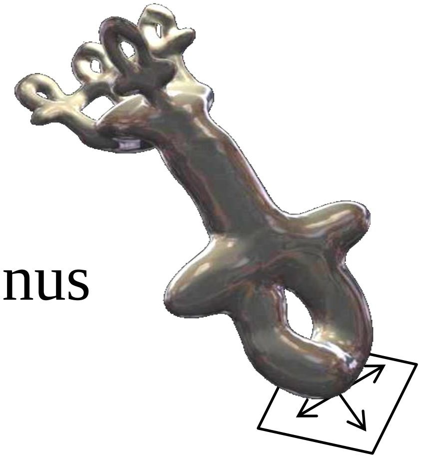
In this section

- Notion of « constructive modeling »
- Reminder on different shape representations
- Recent advances in **implicit modeling**

3D Shapes : a few definitions

Shape : Geometric Structure in a 3D space

- 1D (curve), 2D (surface), 3D (volume)
- Any combination of the above!

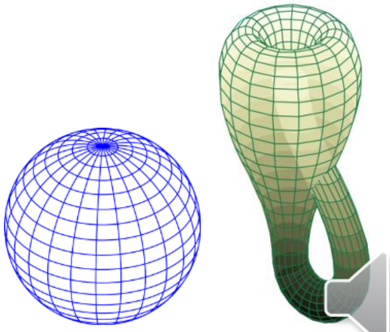


Free form shape : arbitrary geometry and topological genus

Smooth shape:

- C^1 : tangent continuity
- C^2 : curvature continuity

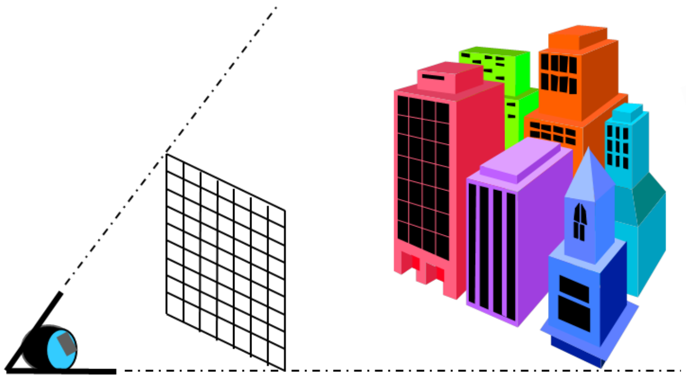
3D shapes: ***Volume*** vs. ***Border Representation*** *(B-Rep)*



3D shapes

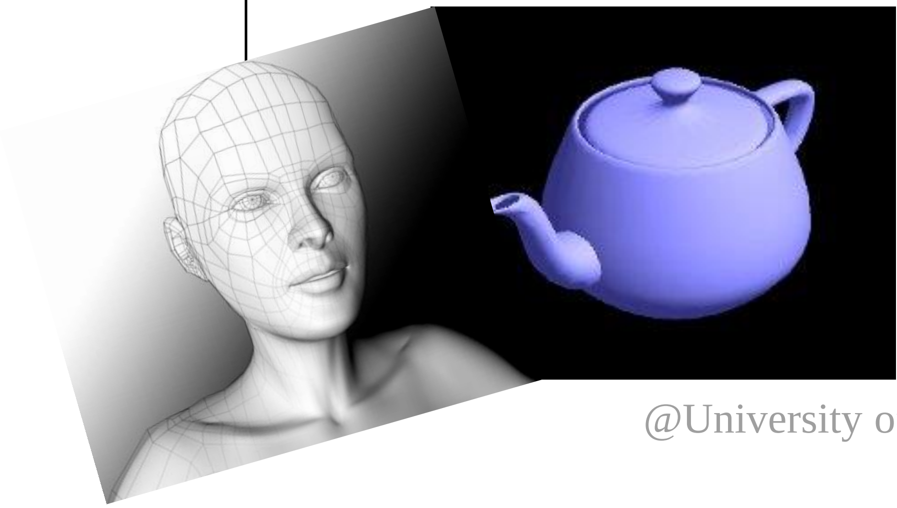
Machines view-point / Human view-point

- Mathematical model
  - Enumerated (list of faces)
  - Equation to compute them
- Rendering : projection of faces



[M. Leyton – cognitive sciences]

- Shape = assembly of parts
- Part = deformation of a symmetrical « primitive shape »



[A generative theory of shapes. M. Leyton, Springer]

@University of Utah, 1982

3D shapes

Machines view-point / Human view-point

- Mathematical model
  - Enumerated (list of faces)
  - Equation to compute them

→ **Specify degrees of freedom**

- Give the list of faces
- or parameter values

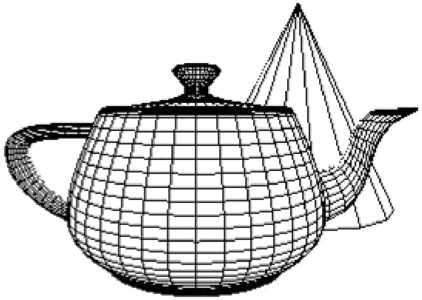
Wins in the end!

- Shape = assembly of parts
- Part = deformation of a symmetrical « primitive shape »

→ **« constructive » modeling**

= series of operations :

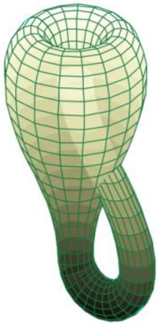
- Create
- Deform
- Assemble

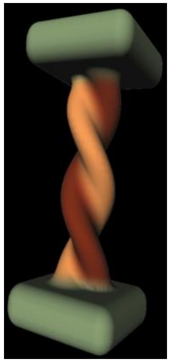


Source of misunderstanding!

Constructive modeling
The needs

1. Being able to create free form shapes
2. Remaining in the space of « valid shapes »
   - No Klein bottle
   - Avoid self-intersections
3. Progressive modeling and refinement
4. Real-time display
   - Whatever the duration of the modeling session





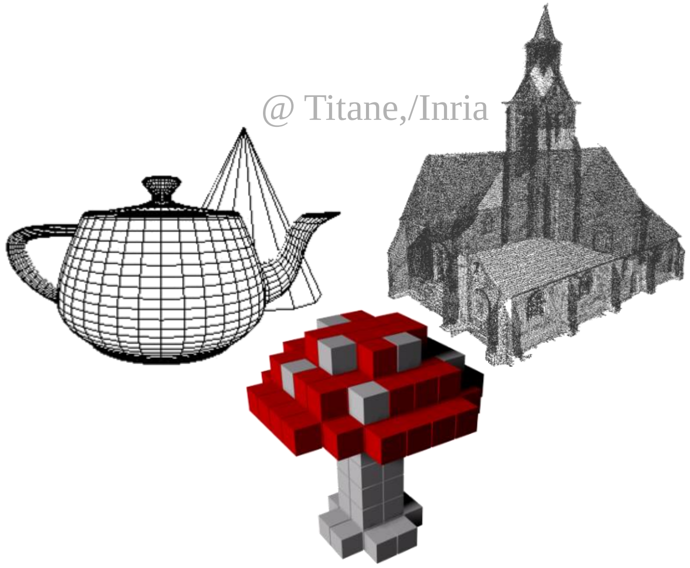
→ ***Choice of an adapted representation ?***

- ✓ *Constructive modeling*
- ✓ ***Choice of a representation***
- ✓ *Zoom : implicit surfaces*

Discrete Representations

Enumerations

- points 0D, segments 1D
- faces 2D (***meshes*** if connectivity info)
- voxels 3D : volumes



@ Titane,/Inria

Non-smooth representations

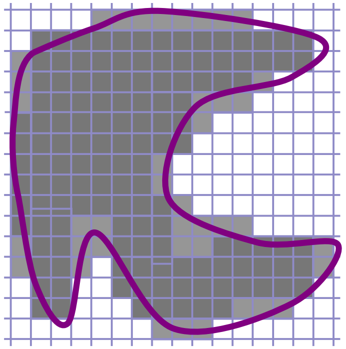
- Well suited to automatic creation
- Not adapted to manual creation

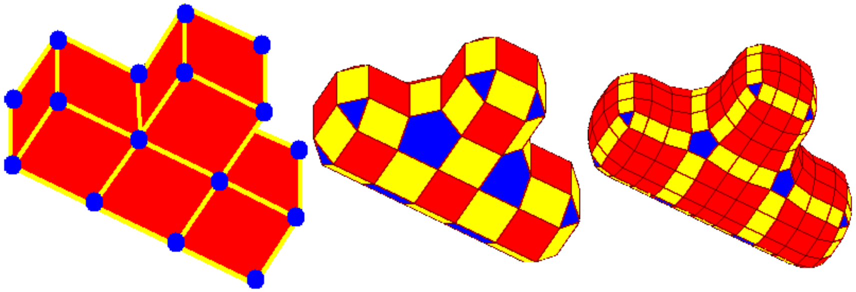
(Except as a game!)

Algorithmic representations

Discrete representation + automatic smoothing

- *Voxels* : Interpolate a scalar density in a grid
  - Display the 0.5 iso-surface
- *Mesh* : Subdivision surfaces
  - Difficulty : controlling the limit shape





Recursively « cut corners »

Continuous representations

Shape (curve, surface, volume) defined by an equation

- **Parametric** vs **implicit formulation**

Exemple : Sphere of radius r

Parametric surface

$$S(u,v) = (r\ Sin(u)Cos(v),\ r\ Sin(u)Sin(v),\ r\ Cos(u))$$

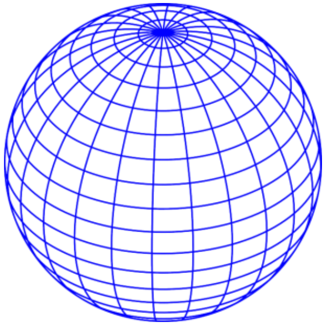
$$u \in [0,\pi],\ v \in [0, 2\pi]$$

Implicit surface

$$I = \{P \in \mathbb{R}^3 / x^2+y^2+z^2 = r^2\}$$

Implicit volume

$$V = \{P \in \mathbb{R}^3 / x^2+y^2+z^2 \leq r^2\}$$



- ✓ *Constructive modeling*
- ✓ ***Choice of a representation***
- ✓ *Zoom : implicit surfaces*

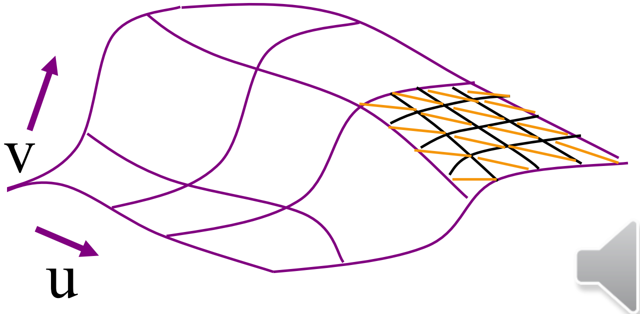
Constructive Modeling
Choice of representation ?

Advantages of continuous representations

- Less parameters to define (ex sphere : radius, center)
- A smooth shape remains smooth at any scale
  - can be converted into different discrete representations

Ex: Parametric surface $S(u, v) = (S_x (u, v), S_y (u, v), S_z (u, v))$

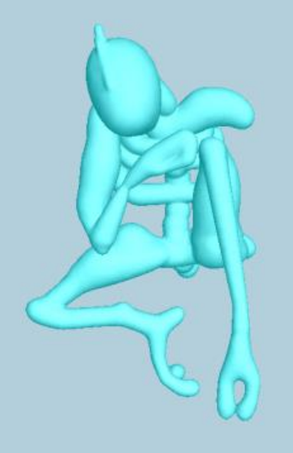
- Compute a grid of sample points
- Triangulate it (planar faces)



Constructive Modeling
Choosing a representation ?

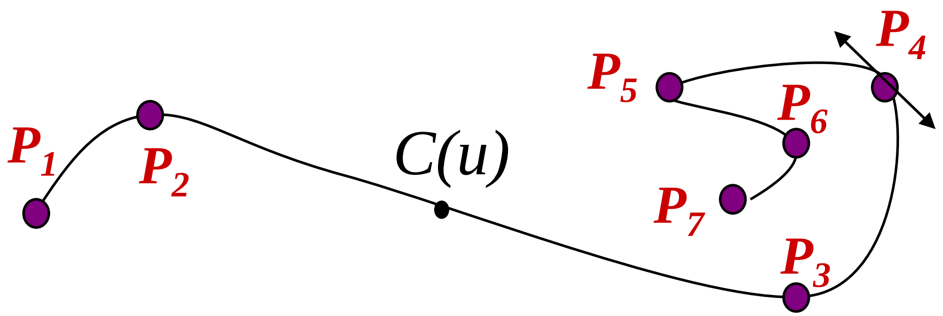
Constructive modeling loop

1. Create primitive shapes
2. Deform – should be intuitive, local or global
3. Assemble – Seamless if possible



Can this be done with parametric surfaces ?

Parametric modeling
Spline curves



Creation

- List of « control points » P_i
- To be interpolated or approximated : $C(u) = \sum F_i(u)\, P_i$

Deformation

- Need for local control!
- F_i low degree polynomials (degree 3), compact support

Assembly

- C^1 or C^2 at joints

- ✓ *Constructive modeling*
- ✓ ***Choice of a representation***
- ✓ *Zoom : implicit surfaces*

Interpolation curve

“Cardinal Spline”

C^1 at joints

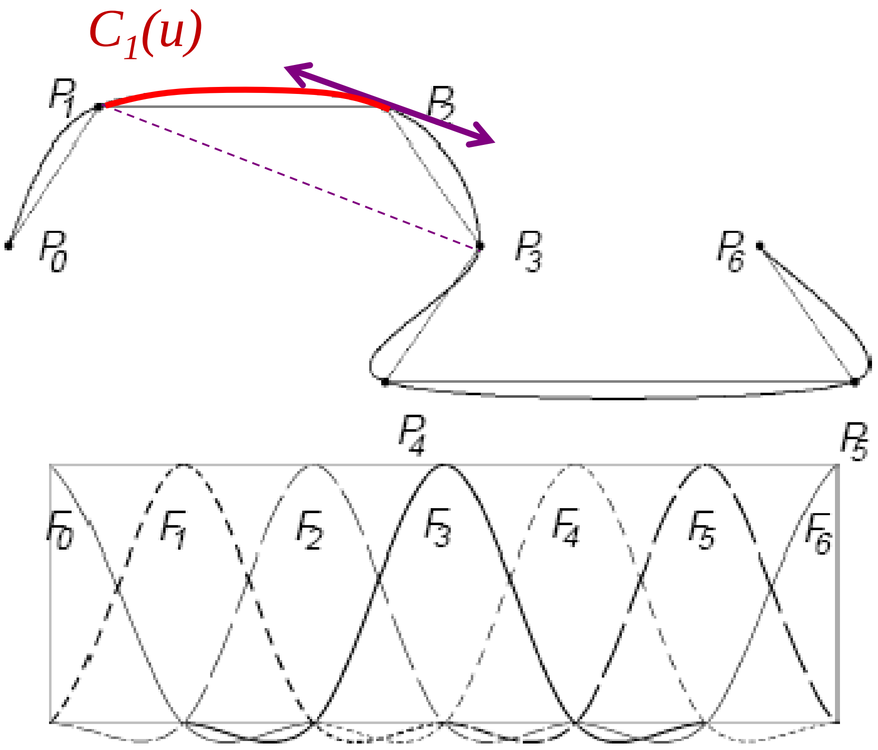
$$C_i(0) = P_i$$
$$C_i(1) = P_{i+1}$$
$$C'_i(0) = k\,(P_{i+1} - P_{i-1})$$
$$C'_i(1) = k\,(P_{i+2} - P_i)$$

$$\mathbf{C_i(u) = \sum F_i(u)\, P_i}$$

Single solution with $F_i(u)$ of degree 3

- Local control of order 4
- $F_i(u)$ not always positive

  $C(u)$ goes outside of the convex hull



Approximation curve
Uniform cubic Bspline

C^2 continuity with F_i local, of d°3 ?

Curve segment defined by:

- F_i built from 4 d°3 polynomials
- Local control of order 4

  F_i continuously vanishes outside support
- Convex hull
- Regularizing curve

$C_i(u) = \sum F_i(u) P_i$

For all u, $F_i(u) \geq 0$, $\sum F_i(u) = 1$

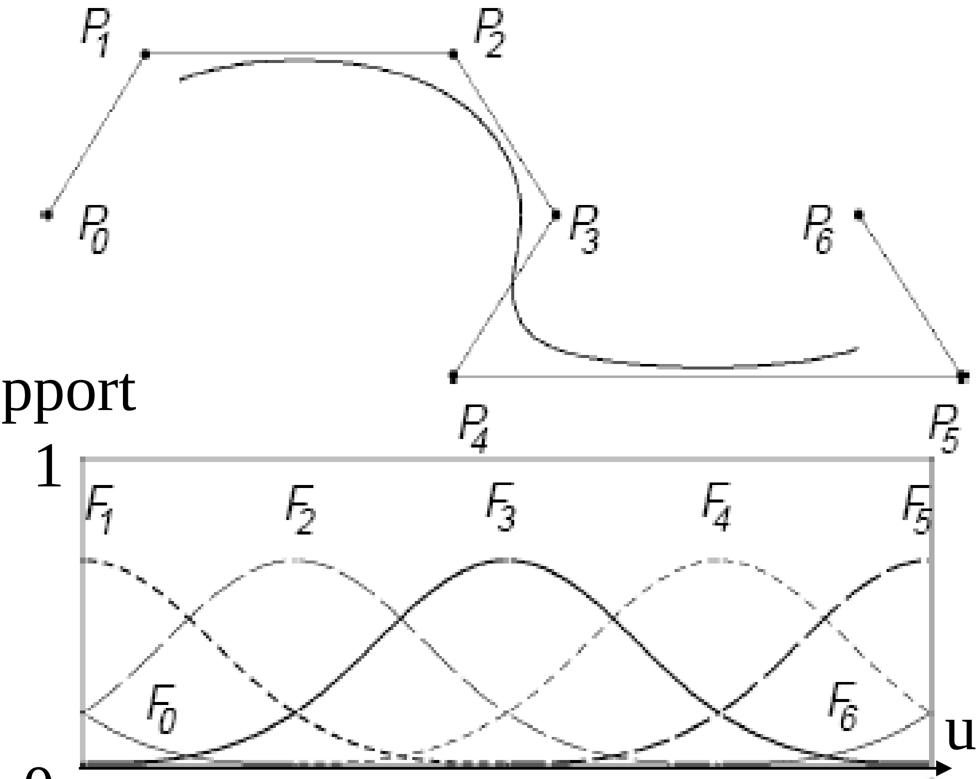
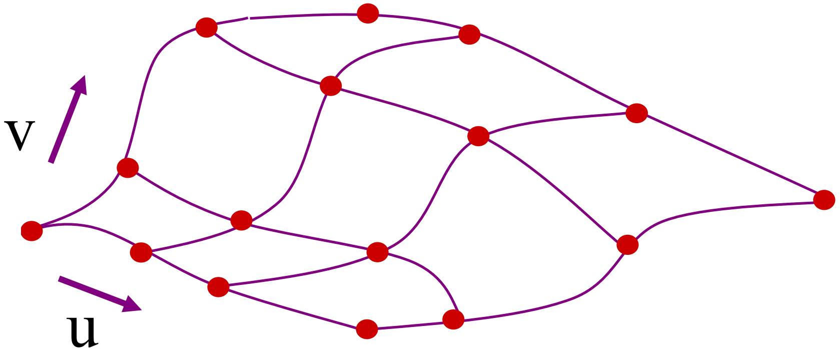


Figure 1: *Uniform B-spline curve*

Parametric Modeling
Spline surface

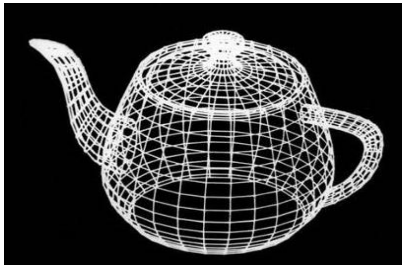
- Product of spline curves in u and v

$$S_{i,j}\,(u, v) = \sum F_i\,(u)\; F_j\,(v)\; P_{ij}$$



- Need of a ***grid*** of control points

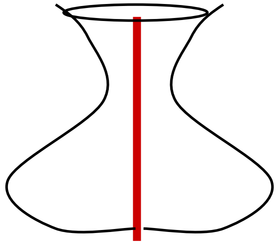
- How can we create complex shapes?



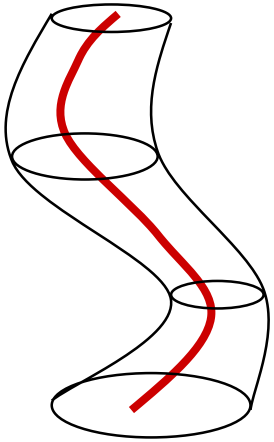
@Université de l'Utah, 1982

Parametric modeling
Spline surfaces: Creation

- **Surfaces of revolution**
  - Rotate a planar curve around an axis



- **Extrusion**
  - A skeleton curve
  - A section swept along the skeleton
  - A profile curve giving the scaling factor



✓ *Constructive modeling*
✓ ***Choice of a representation***
✓ *Zoom : implicit surfaces*

Parametric modeling
Spline surfaces: Deformation

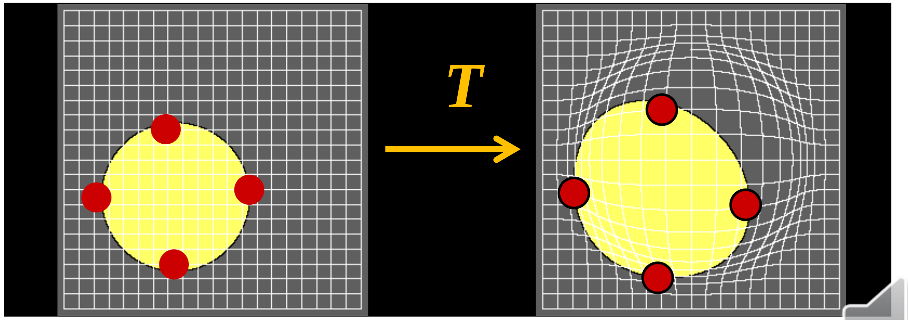
- Local deformation
  - Move control points

- Global deformation?

Use a « space deformation » $T: \mathbb{R}^3 \rightarrow \mathbb{R}^3$

Control points move

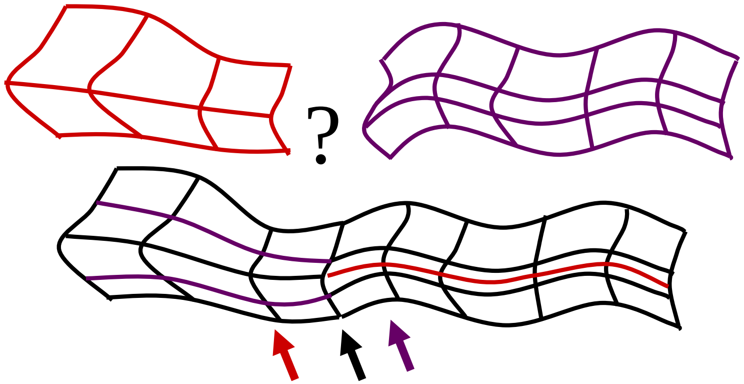
The surface deforms



(See part on « sculpture »)

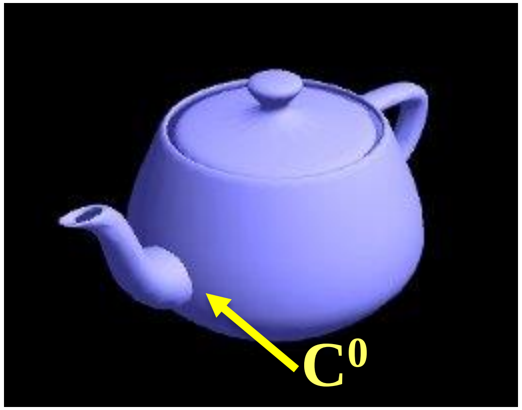
Parametric modeling
Spline surface: Assembly

- Along borders… OK
  - Same number of patches needed
  - 3 common rows of control points

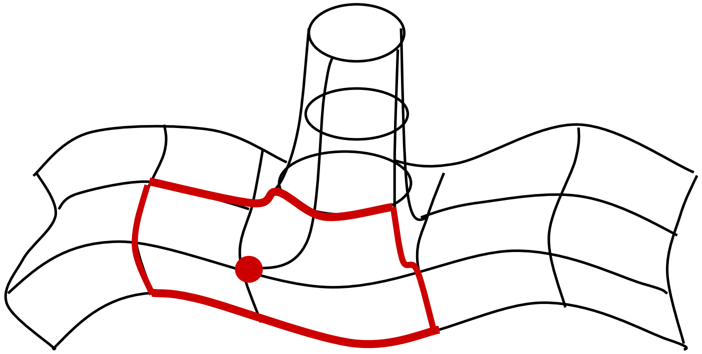


- Handles, branchings?

  Very difficult!



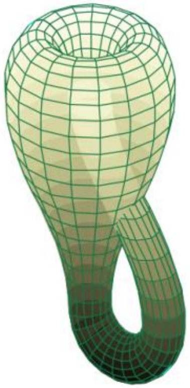
@Université de l’Utah, 1982



Rational S-patch [Loop90]

Parametric surfaces
Limitations

- B-Rep only
  - No constraint against incorrect shapes (eg. Klein bottle…)



- Hard to model
  - Arbitrary topological genus
  - Smooth branchings

Continuous representations
Implicit surfaces

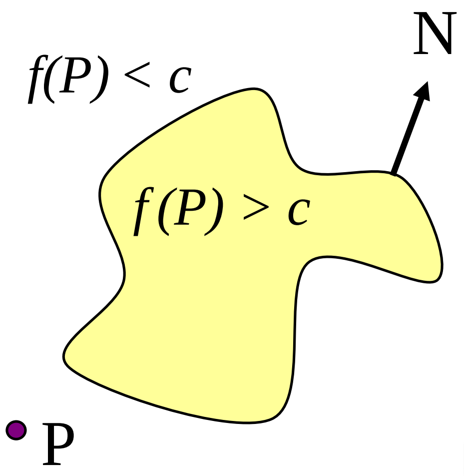
$\boldsymbol{I = \{ P \ / \ f(P) = c \}}$ $f : \mathbb{R}^3 \rightarrow \mathbb{R}$ scalar field

(ex sphere : $f(P) = x^2+y^2+z^2$, $c = r^2$)

Hyp: I separates space into two parts - one of finite size

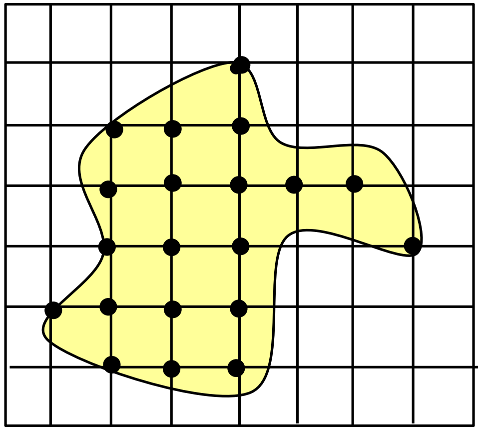
- Inside volume $f(P) > c$
- Surface normal $N = - \nabla f$
- *f* et *I* have the same degree of continuity!
- Difficult to list surface points…

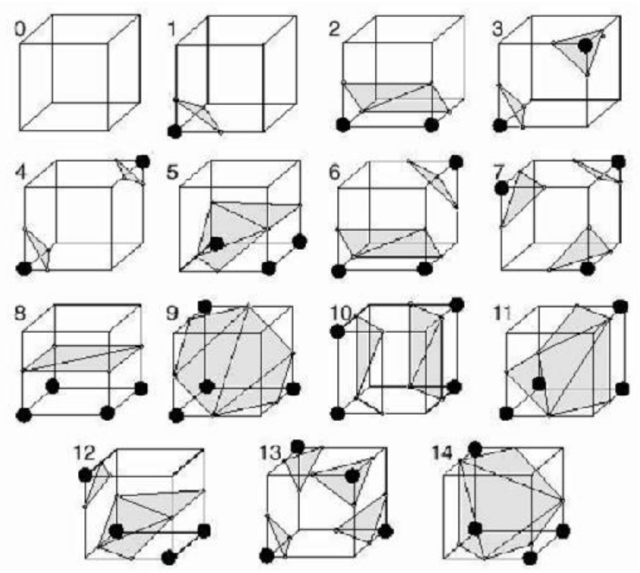
  but « inside / outside» test ($f(P) > c$?)

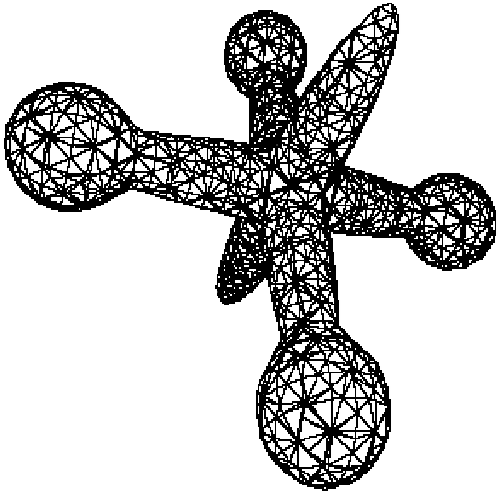


Implicit surfaces
Sampling for display

- « **Marching cubes** » **method** *[Lorensen 1991]*
  - Inside/outside classification of grid points: $f(P) \geq c \rightarrow black$
  - Extract cubes that cut the surface
  - Triangulate their intersection with the surface



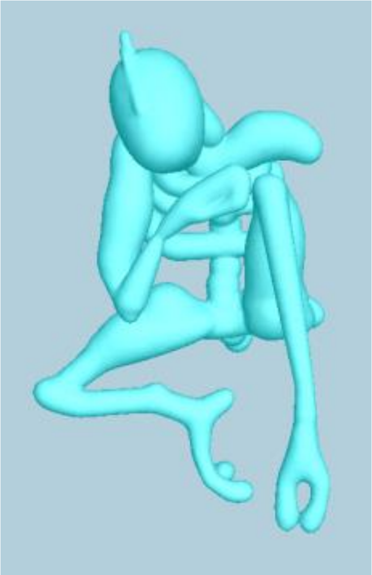




Constructive modeling
Choosing a representation?

Constructive modeling loop

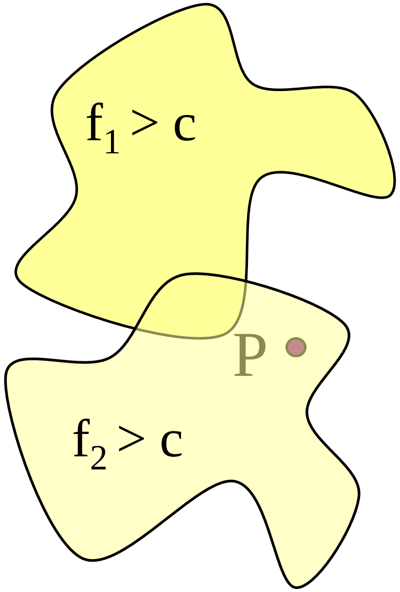
1. Create simple shapes
2. Deform them – should be intuitive
3. Assemble them – seamlessly if possible



Attempt with implicit surfaces ?

Implicit surfaces
Assembling

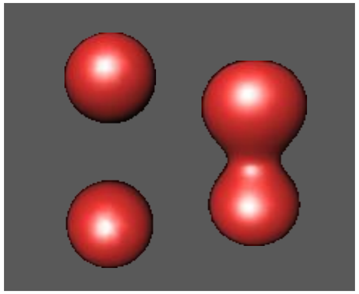
Given $I_1 = \{ P \ / \ f_1(P) = c \}$, $I_2 = \{ P \ / \ f_2(P) = c \}$
f_1 and f_2 of class at least C^1



Assembling : compute $I = \{ P \ / \ f(P) = c \}$

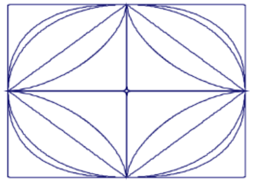
- $f = max\,(f_1, f_2)$ → **Union**
- $f = min\,(f_1, f_2)$ → **Intersection**
- $f = f_1 + f_2$ → « **Blending** »

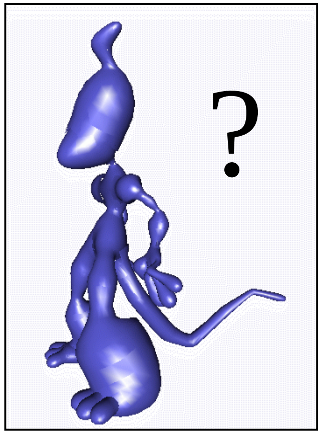
Preserves the degree of continuity!



Implicit surfaces
Creation ?

- Use of an equation quite limited…





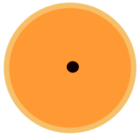
Spheres : $f(P) = x^2+y^2+z^2 = r^2$

Super-ellipsoïds : $f(P) = \frac{x^n}{a^n}+\frac{y^n}{b^n}+\frac{z^n}{c^n}=1$

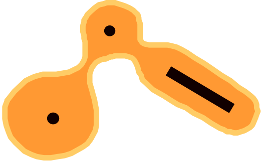
- Solution : **skeleton-based implicit surfaces**

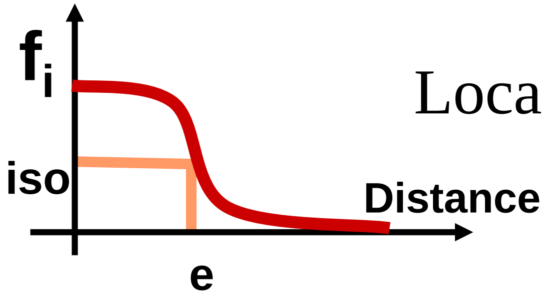
f_i : decreasing function of $d(P, S_i)$ → *density of matter* around S_i

Skeletons :
points, curves
surfaces…



$f(P) = \sum f_i(P) = c$





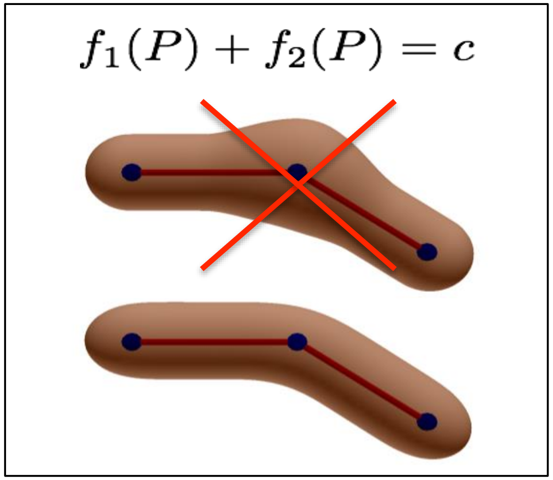
Locality!

Skeleton-based implicit surfaces

Convolution surfaces *[Bloomethal 91]*

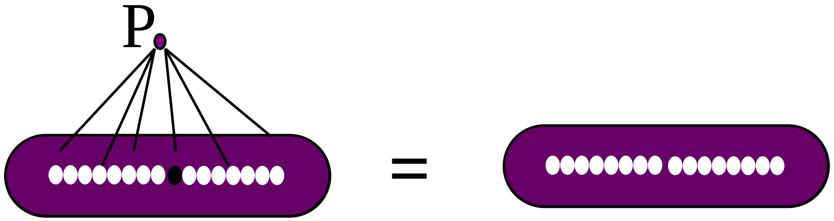
- Skeleton made of several segments

  Bulge at joints !

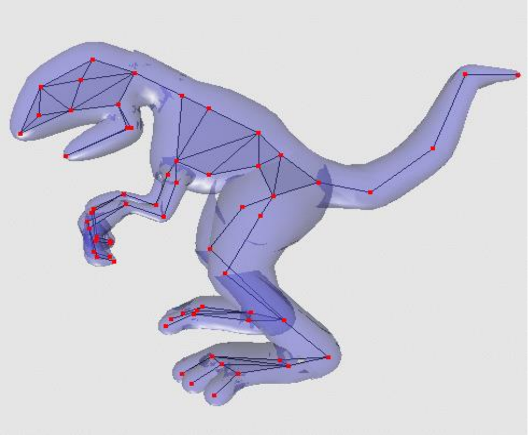


Convolution surface

$$f_i(P) = \int_S r(s)\, K(d(P,S))\, ds$$



2 skeletons one skeleton



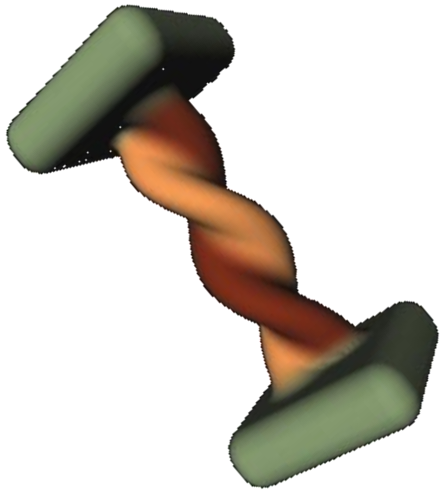
✓ *Constructive modeling*

✓ ***Choice of a representation***

✓ *Zoom : implicit surfaces*

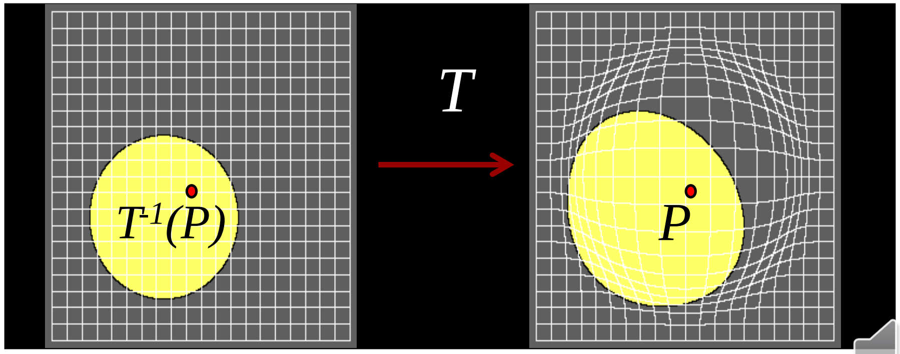
Implicit surface Deform?

- **Local deformation**
  - Deform skeletons
  - Edit thickness

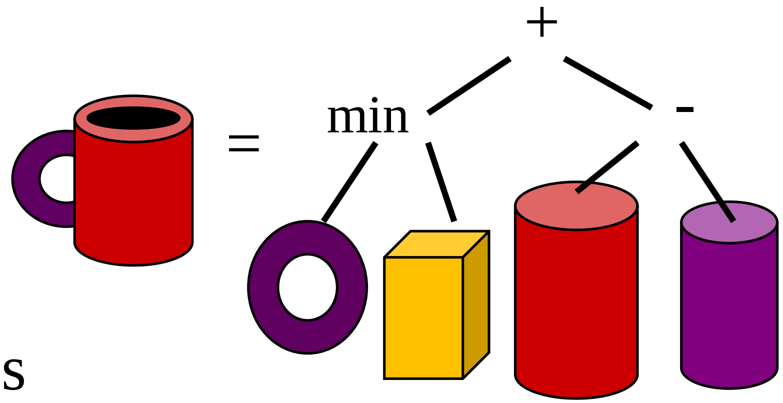


- **Global deformation**
  - Space deformation $T: \mathbb{R}^3 \to \mathbb{R}^3$

$$\hat{f}(P) = f\,(T^{-1}(P))$$

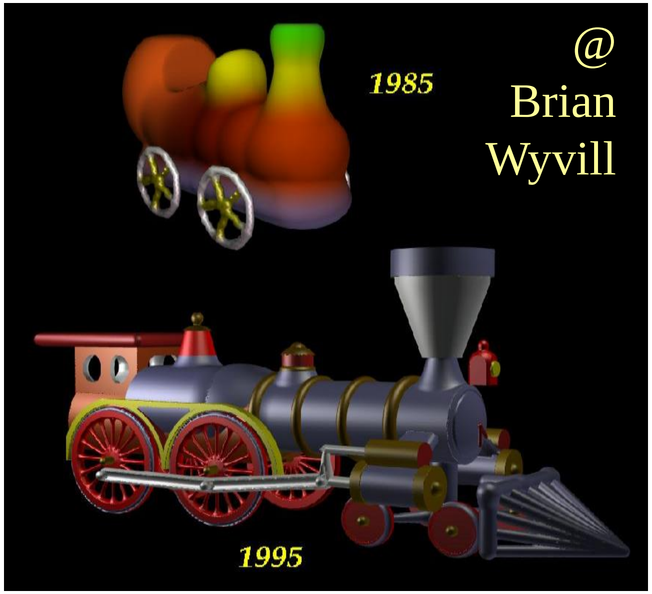


Constructive implicit modeling
Construction trees



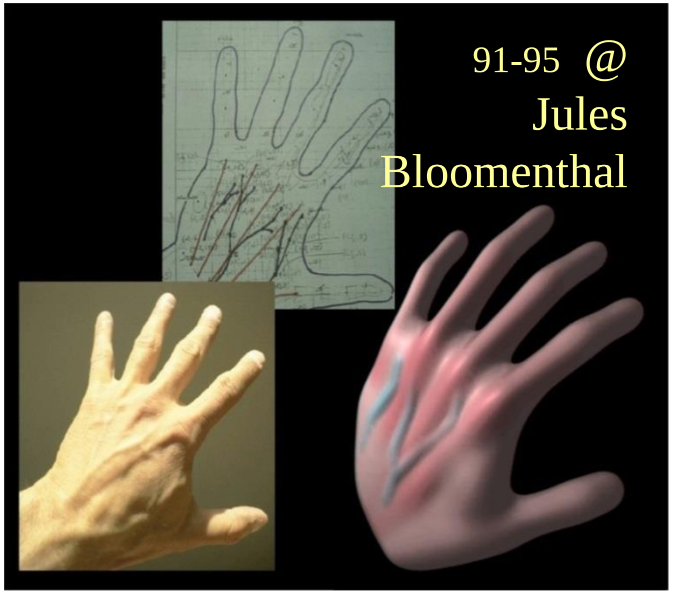
'BlobTrees' extending CSG trees

- Assembling nodes: +, -, max, min, …
- Unary nodes for deformation
- Leaves = Skeleton-based implicit primitives



1985 @ Brian Wyvill

1995



91-95 @ Jules Bloomenthal

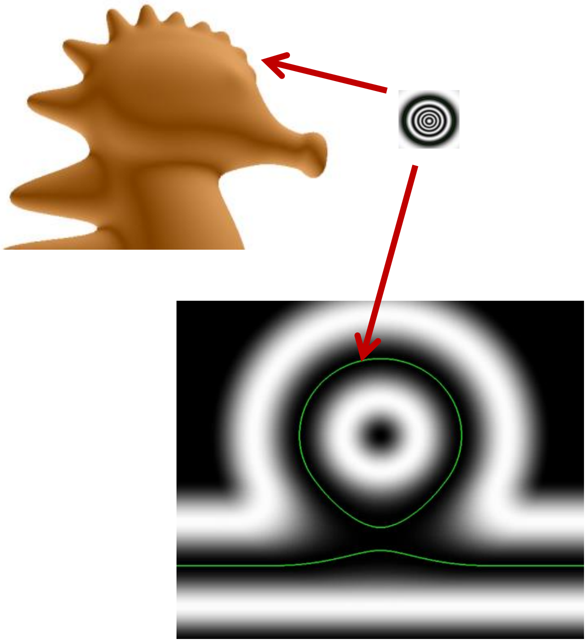
1998 @Eric Galin

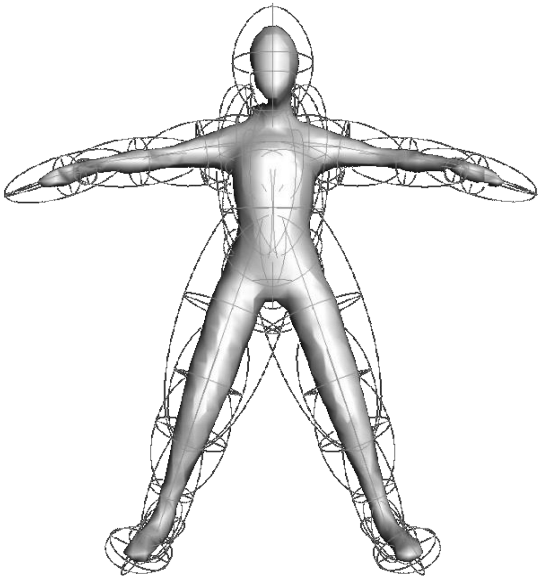
Recent research on implicit surfaces

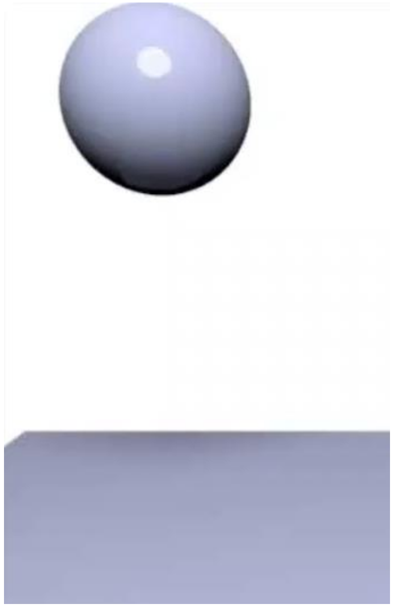
Challenging unsolved problems until 2010

1. Small details vanish : “blobby” shapes
2. Non-local blends, that start at a distance

→ *shapes and animations hard to control !*







Problem 1
Small details vanish

Solution [Zanni 2013]

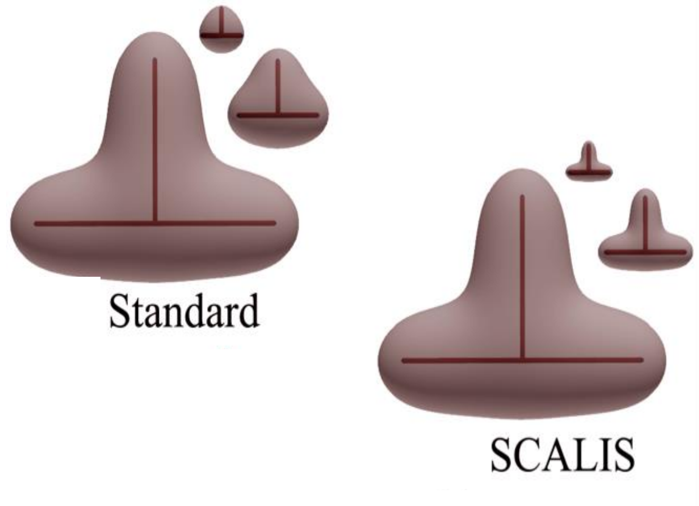
SCALIS - normalized integral surface

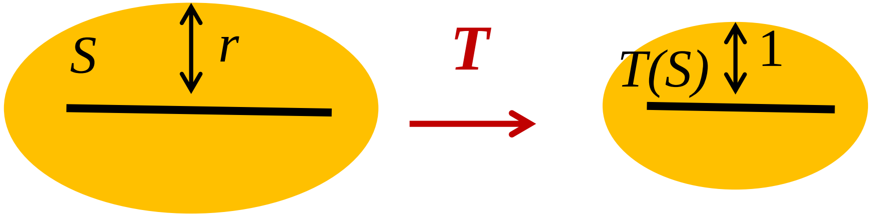
- T: Scaling factor *1/r*
- Normalized convolution

$$f_S(P) = \tilde{f}_{T(S)}(T(\mathrm{P}))$$

Radius 1

Scaling





Reference space

- ✓ *Constructive modeling*
- ✓ *Choice of a representation*
- ✓ ***Zoom : implicit surfaces***

Problem 1
Small details vanish

Convolution :

$$f_S(P) = \int_S r(s) \;\; K(d(P,S)) \;\; ds$$

General case : varying weight r!

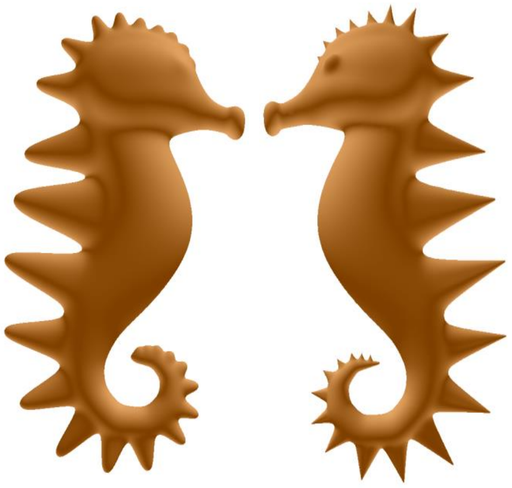
SCALIS *[Zanni 2013]*

$$f_S(P) = \frac{1}{N(K,c)} \int_S K\left(\frac{d(P,S)}{r(s)}\right) \frac{ds}{r(s)}$$

So that weight
= radius

Scaling point

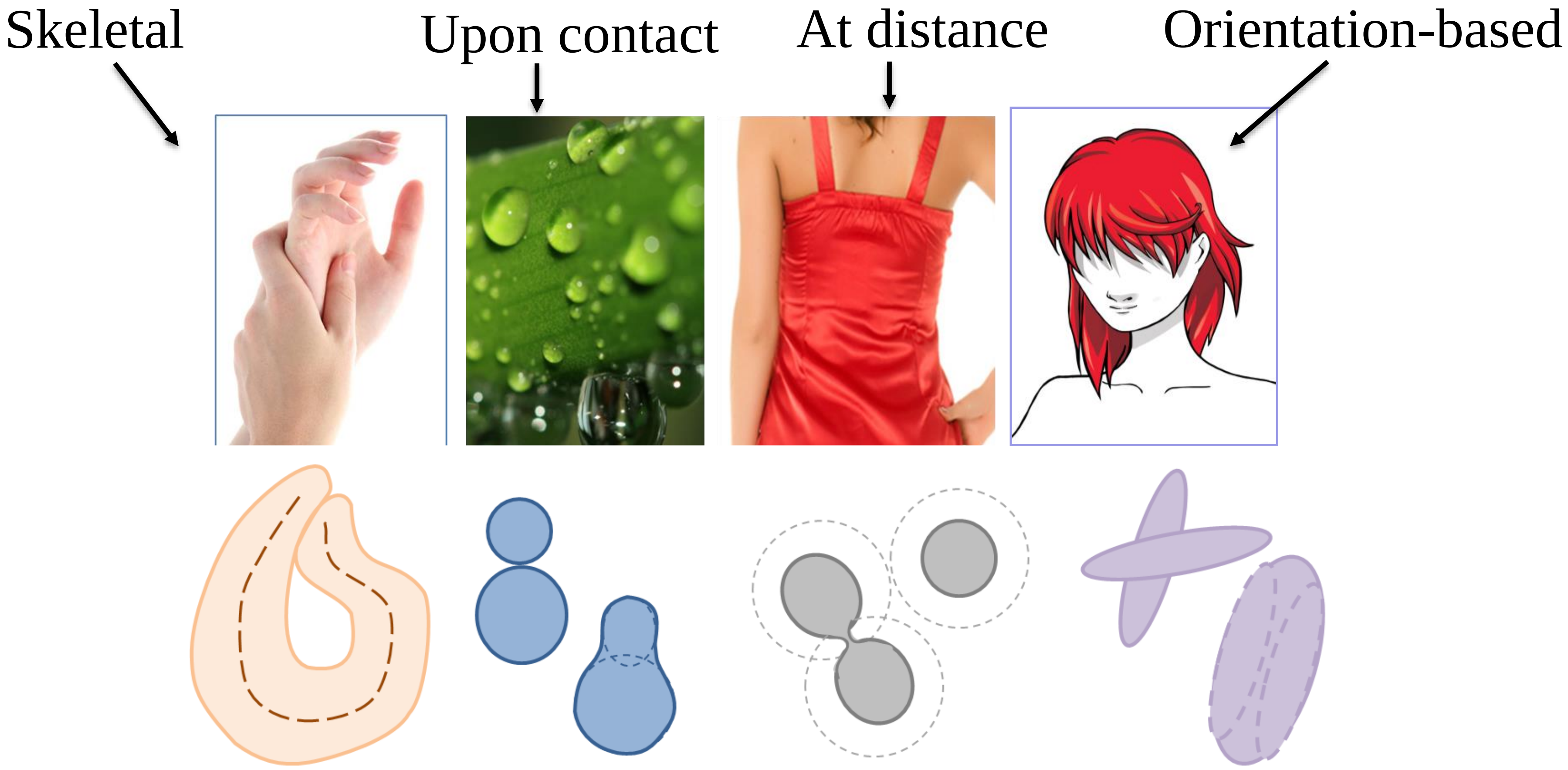
Scaling skeleton


Convolution SCALIS

- ✓ *Constructive modeling*
- ✓ *Choice of a representation*
- ✓ ***Zoom : implicit surfaces***

Problem 2

Which blending would we like?



Skeletal

Upon contact

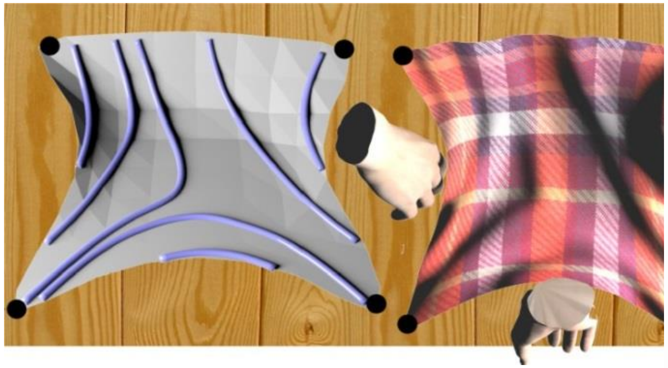
At distance

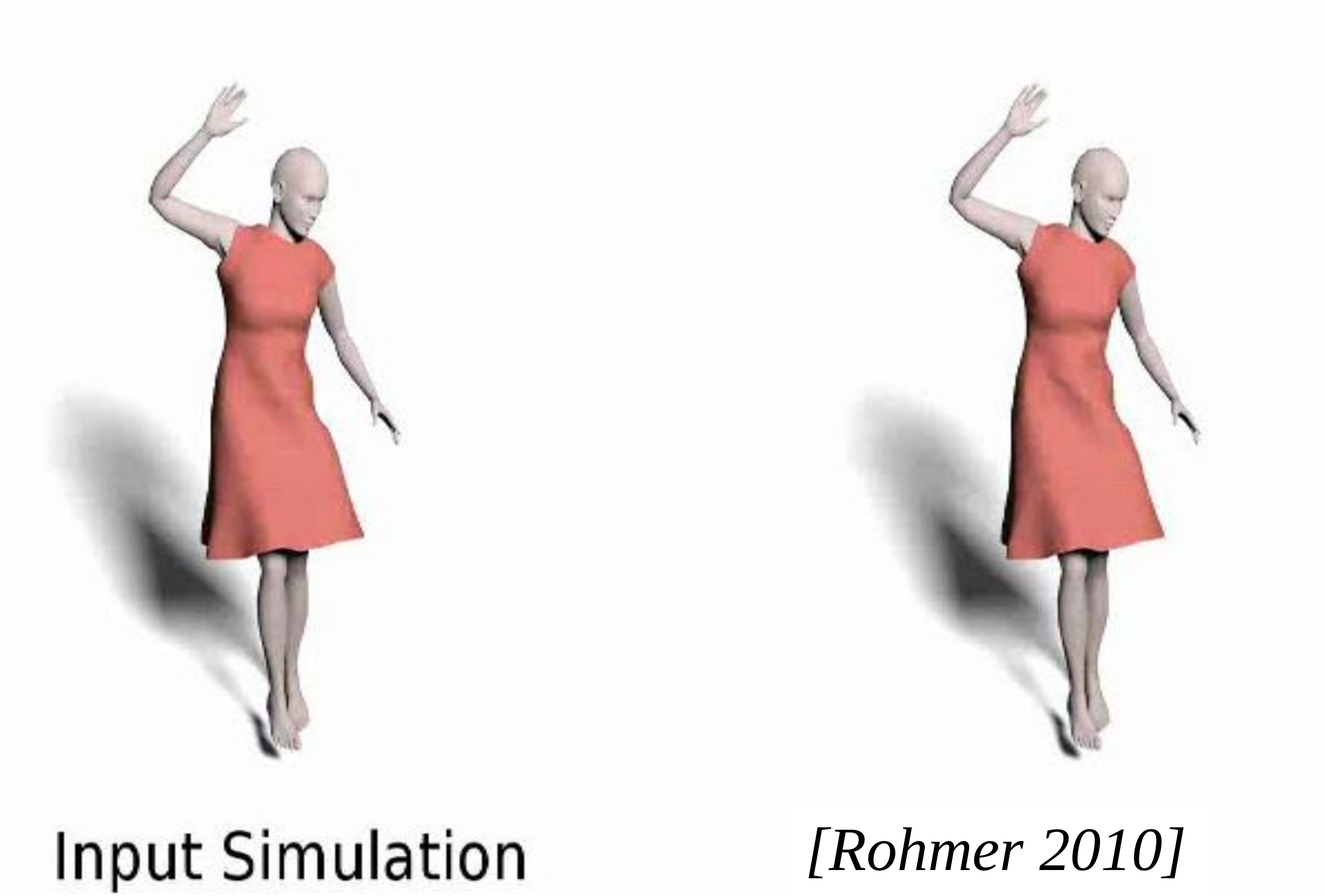
Orientation-based

Problem 2
Blending at distance : Garment folds

If compression

- Fold skeletons
- Implicit surfaces
- Deform cloth mesh





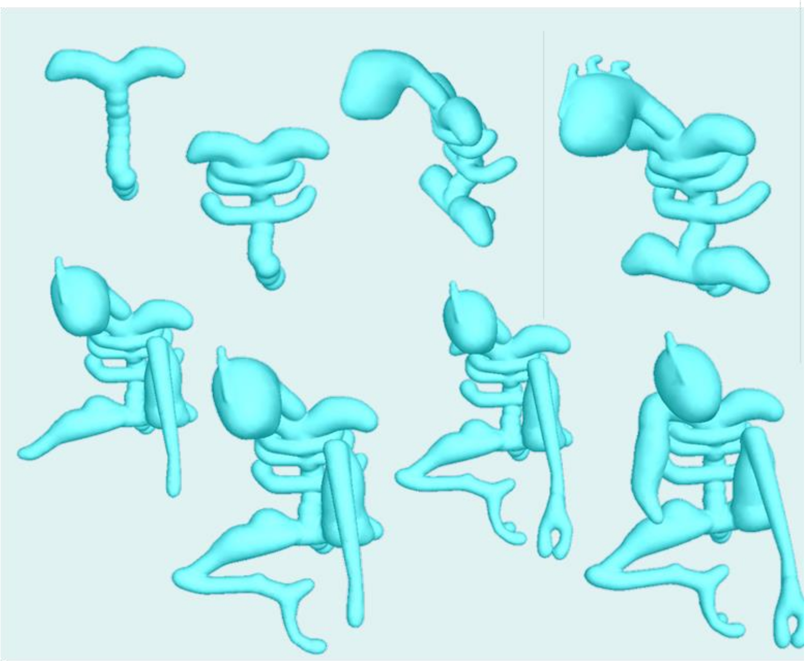
[Rohmer 2010]

- ✓ *Constructive modeling*
- ✓ *Choice of a representation*
- ✓ ***Zoom : implicit surfaces***

Problem 2

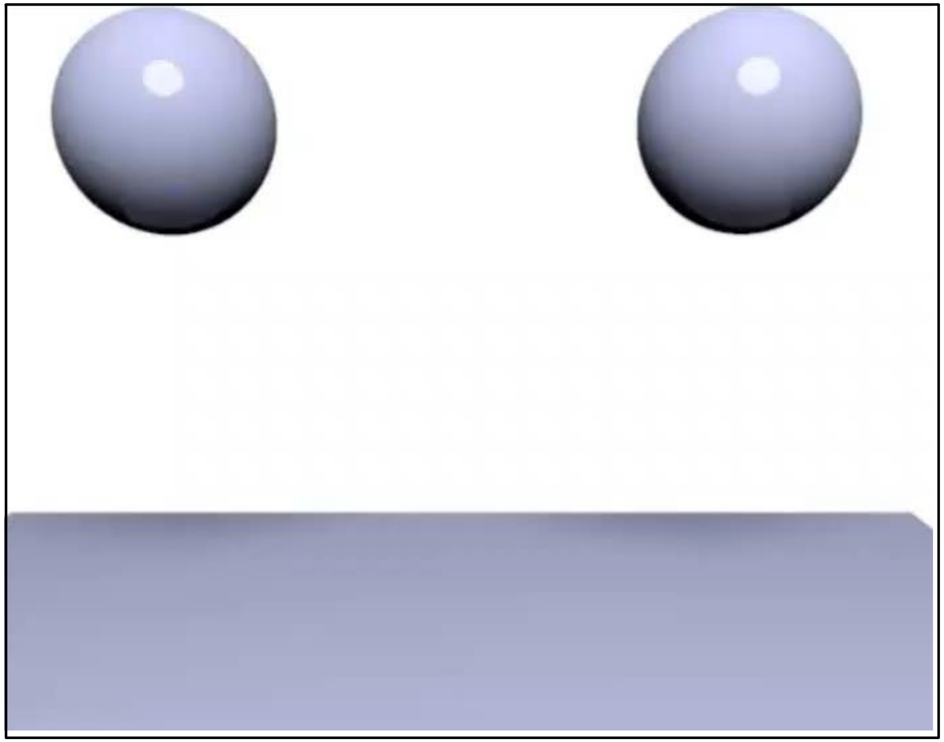
Blending upon contact

Constructive modeling

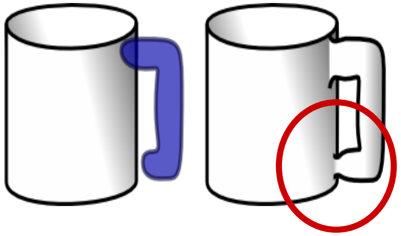


Animated water droplets

Before After



Solution: Gradient-based blends



$f = f_{1,} + f_2$ blending at distance

Idea: blending should depend on

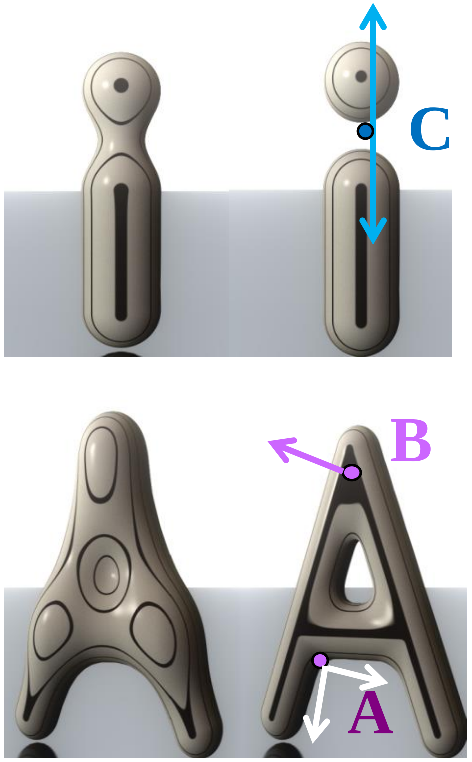
field values ***and gradients***

Desired behavior

- Blend where **gradients are orthogonal**
- Union if **aligned** or **opposed**

Method: $f = g\,(f_1, f_2, \nabla f_1, \nabla f_2)$

g interpolates between union and blending



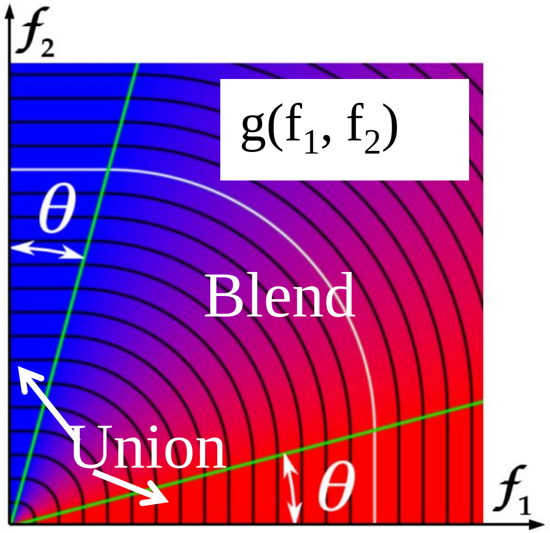
\+ Gradient blend

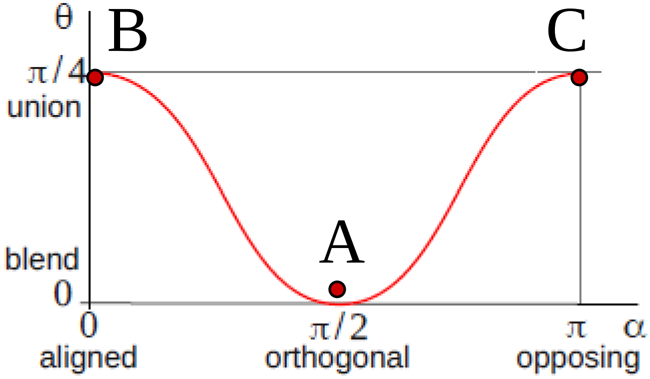
✓ *Constructive modeling*
✓ *Choice of a representation*
✓ ***Zoom : implicit surfaces***

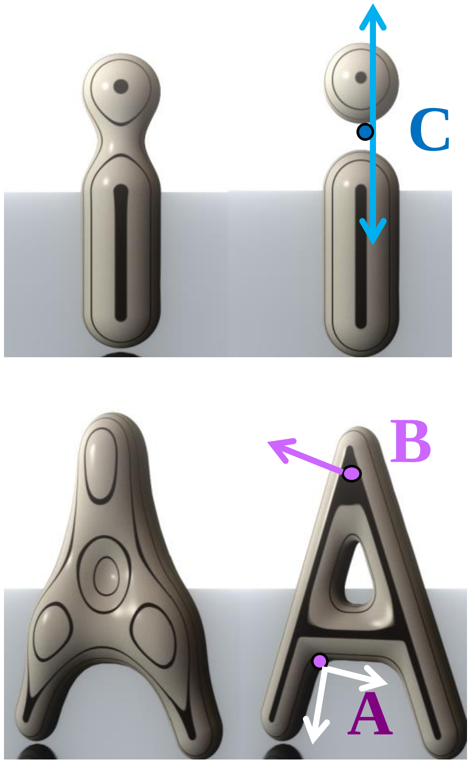
Solution: Gradient-based blends

Solution *[Gourmel 2013]*

- Blending operator with a blending angle Θ
- Θ function of angle between gradients





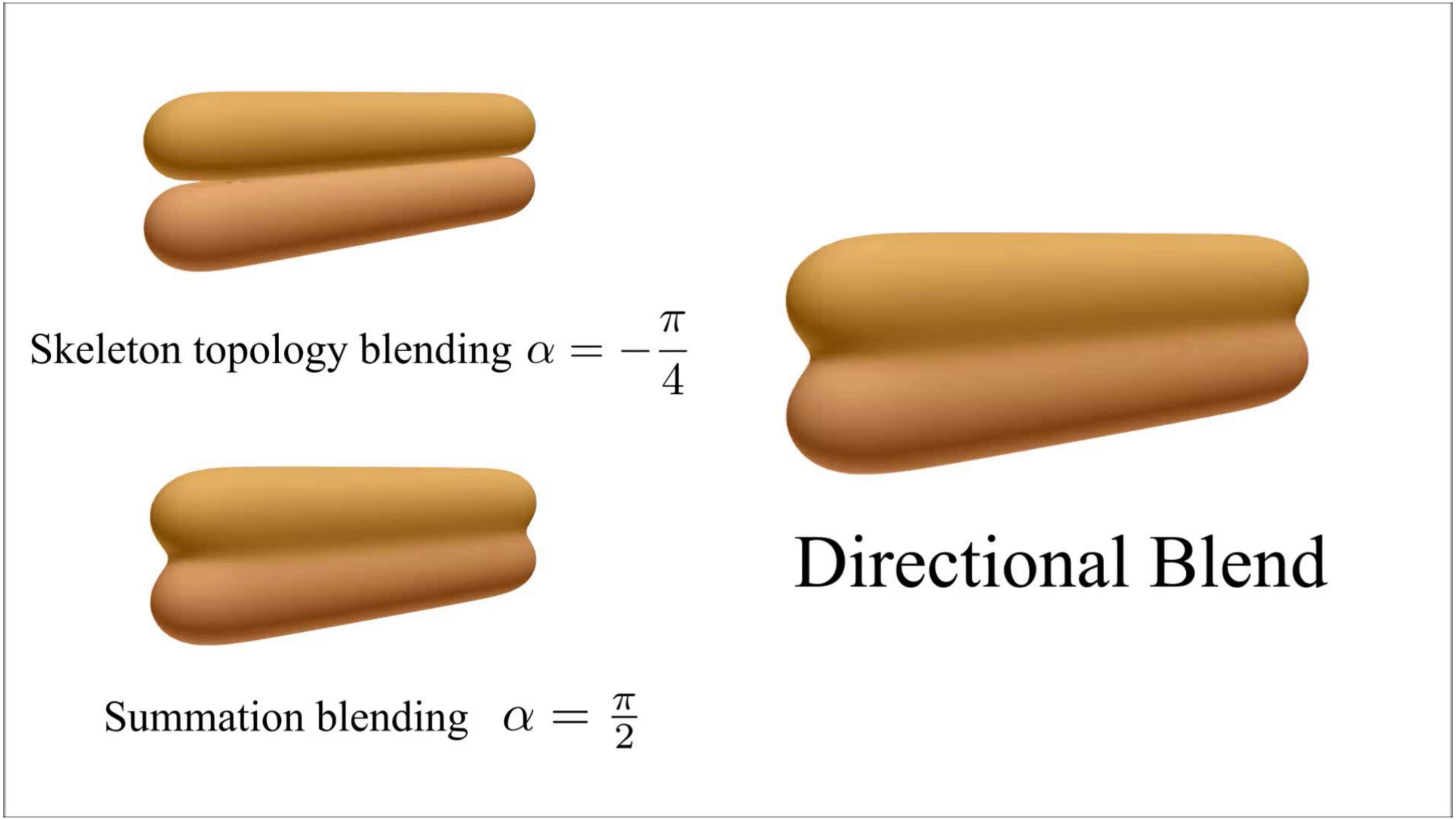


\+ Gradient blend

✓ *Constructive modeling*
✓ *Choice of a representation*
✓ ***Zoom : implicit surfaces***

Directional blending

[Zanni 2015]



Separating shapes instead of assembly?

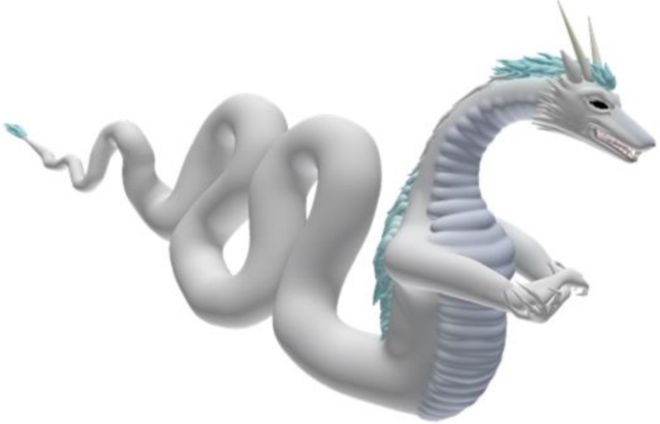
Implicit untangling *[Buffet 2019]*

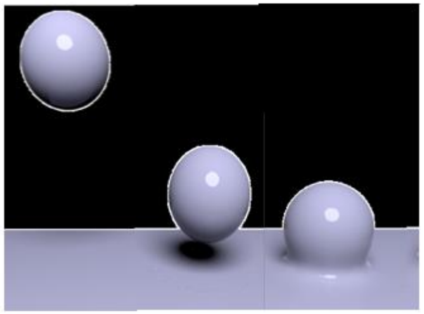
Conclusion

Continuous shape representations for Constructive modeling

- Spline surfaces good for 2D shapes
- 3D shapes easier with implicit surfaces
  - ✓ Intuitive control using skeletons
  - ✓ Precise blending control is mandatory

Jweel @Skimlab





References

- Leyton (2001). A generative theory of shape (Vol. 2145). Springer Science & Business Media.
- Beatty & Barsky (1987). An introduction to splines for use in computer graphics and geometric modeling. Morgan Kaufmann.
- Loop & DeRose (1990). Generalized b-spline surfaces of arbitrary topology. ACM Computer Graphics, Siggraph.
- Lorensen & Cline (1987). Marching cubes: A high resolution 3D surface construction algorithm. ACM Computer Graphics, Siggraph.
- Bloomenthal (1997) Introduction to Implicit Surfaces, Morgan Kaufmann.
- Wyvill, Guy, Galin (1999). Extending the CSG Tree - Warping, Blending and Boolean Operations in an Implicit Surface Modeling System. Comput. Graph. Forum 18(2).
- Zanni, Bernhardt, Quiblier, Cani (2013). SCALe-invariant Integral Surfaces Computer Graphics Forum, Wiley-Blackwell, 32 (8).
- Rohmer, Popa, Cani, Hahmann, Sheffer (2010). Animation Wrinkling: Augmenting Coarse Cloth Simulations with Realistic-Looking Wrinkles. ACM Transactions on Graphics, 29 (5).
- Gourmel, Barthe, Cani, Wyvill, Bernhardt, Paulin, Grasberger (2013). A Gradient-Based Implicit Blend. ACM Transactions on Graphics, 32 (2).
- Zanni, Cani, Gleicher (2014). N-ary implicit blends with topology control. Computers and Graphics (proceedings of Shape Modeling International), Elsevier.
- Buffet, Rohmer, Barthe,Cani, Implicit untangling, ACM Transactions on Greaphics, Siggraph 2019.