Parametric surfaces

Reading

Required:

- Angel readings for "Parametric Curves" lecture, with emphasis on 11.1.2, 11.1.3, 11.1.5, 11.6.2, 11.7.3, 11.9.4.
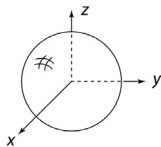
Optional

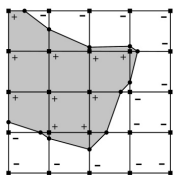- Bartels, Beatty, and Barsky. *An Introduction to Splines for use in Computer Graphics and Geometric Modeling,* 1987.

Mathematical surface representations
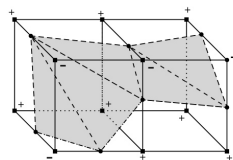
- Explicit $z=f(x,y)$ (a.k.a., a "height field")
  - what if the curve isn't a function, like a sphere?

- Implicit $g(x,y,z) = 0$

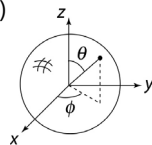Isocontour from "marching squares"   Isocontour from "marching cubes"

- Parametric $S(u,v)=(x(u,v),y(u,v),z(u,v))$
  - For the sphere:

$x(u,v) = r \cos 2\pi v \sin \pi u$

$y(u,v) = r \sin 2\pi v \sin \pi u$

$z(u,v) = r \cos \pi u$

As with curves, we'll focus on parametric surfaces.

Surfaces of revolution

Idea: rotate a 2D **profile curve** around an axis.

What kinds of shapes can you model this way?

Constructing surfaces of revolution

Given: A curve $C(u)$ in the xy-plane:

$$C(u) = \begin{bmatrix} c_x(u) \\ c_y(u) \\ 0 \\ 1 \end{bmatrix}$$

Let $R_x(\theta)$ be a rotation about the x-axis.

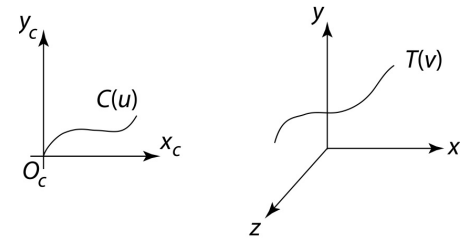**Find:** A surface $S(u,v)$ which is $C(u)$ rotated about the x-axis.

Solution:

General sweep surfaces

The **surface of revolution** is a special case of a **swept surface**.

Idea: Trace out surface $S(u,v)$ by moving a **profile curve** $C(u)$ along a **trajectory curve** $T(v)$.

More specifically:

- Suppose that $C(u)$ lies in an (x_c, y_c) coordinate system with origin O_c.
- For every point along $T(v)$, lay $C(u)$ so that O_c coincides with $T(v)$.
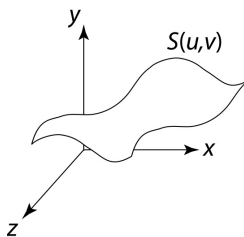
Orientation

The big issue:

- How to orient $C(u)$ as it moves along $T(v)$?

Here are two options:

1. **Fixed** (or **static**): Just translate O_c along $T(v)$.
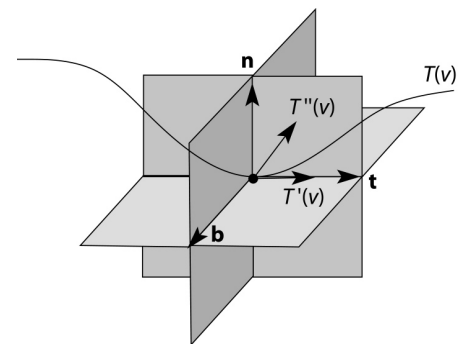

2. Moving. Use the **Frenet frame** of $T(v)$.

- Allows smoothly varying orientation.
- Permits surfaces of revolution, for example.

Frenet frames

Motivation: Given a curve $T(v)$, we want to attach a smoothly varying coordinate system.

To get a 3D coordinate system, we need 3 independent direction vectors.

Tangent: $\mathbf{t}(v) = \text{normalize}[T'(v)]$
Binormal: $\mathbf{b}(v) = \text{normalize}[T'(v) \times T''(v)]$
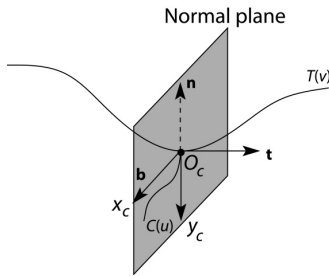Normal: $\mathbf{n}(v) = \mathbf{b}(v) \times \mathbf{t}(v)$

As we move along $T(v)$, the Frenet frame (t,b,n) varies smoothly.

Frenet swept surfaces

Orient the profile curve $C(u)$ using the Frenet frame of the trajectory $T(v)$:

- Put $C(u)$ in the **normal plane** .
- Place O_c on $T(v)$.
- Align x_c for $C(u)$ with **b**.
- Align y_c for $C(u)$ with -**n**.

Normal plane

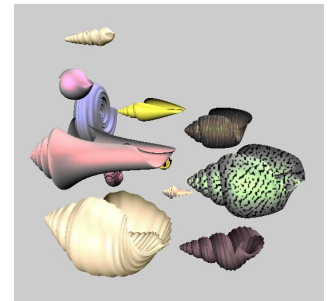If $T(v)$ is a circle, you get a surface of revolution exactly!

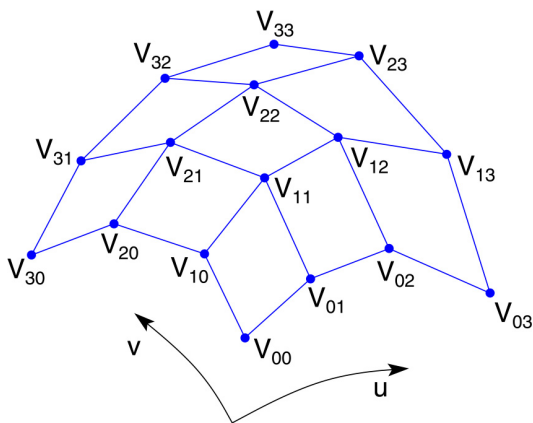Where might these frames be ambiguous or undetermined?

Variations

Several variations are possible:

- Scale $C(u)$ as it moves, possibly using length of $T(v)$ as a scale factor.
- Morph $C(u)$ into some other curve $\tilde{C}(u)$ as it moves along $T(v)$.
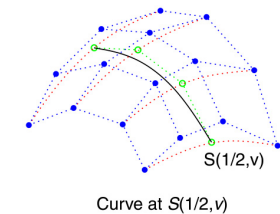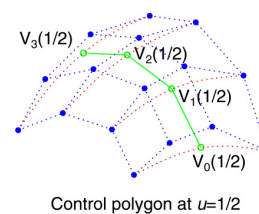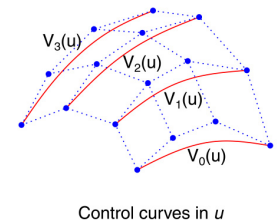- …

Tensor product Bézier surfaces

Given a grid of control points V_{ij}, forming a **control net**, contruct a surface $S(u,v)$ by:

- treating rows of V (the matrix consisting of the V_{ij}) as control points for curves $V_0(u),\ldots, V_n(u)$.
- treating $V_0(u),\ldots, V_n(u)$ as control points for a curve parameterized by v.

Tensor product Bézier surfaces, cont.

Let's walk through the steps:

Control net

Control curves in u

Control polygon at u=1/2

Curve at $S(1/2,v)$

Which control points are interpolated by the surface?

Matrix form of Bézier curves and surfaces

Recall that Bézier curves can be written in terms of the Bernstein polynomials:

$$Q(u) = \sum_{i=0}^{n} V_i b_i(u)$$

They can also be written in a matrix form:

$$Q^T(u) = \begin{bmatrix} u^3 & u^2 & u & 1 \end{bmatrix} \begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 3 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} V_0^T \\ V_1^T \\ V_2^T \\ V_3^T \end{bmatrix}$$

$$= \begin{bmatrix} u^3 & u^2 & u & 1 \end{bmatrix} \mathbf{M}_{\text{Bezier}} \mathbf{V}_{\text{curve}}$$

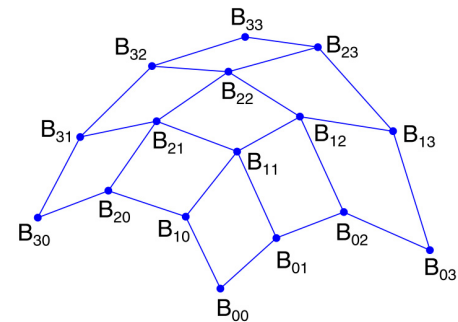Tensor product surfaces can be written out similarly:

$$S(u,v) = \sum_{i=0}^{n} \sum_{j=0}^{n} V_{ij} b_i(u) b_j(v)$$

$$= \begin{bmatrix} u^3 & u^2 & u & 1 \end{bmatrix} \mathbf{M}_{\text{Bézier}} \mathbf{V}_{\text{surface}} \mathbf{M}_{\text{Bézier}}^T \begin{bmatrix} v^3 \\ v^2 \\ v \\ 1 \end{bmatrix}$$

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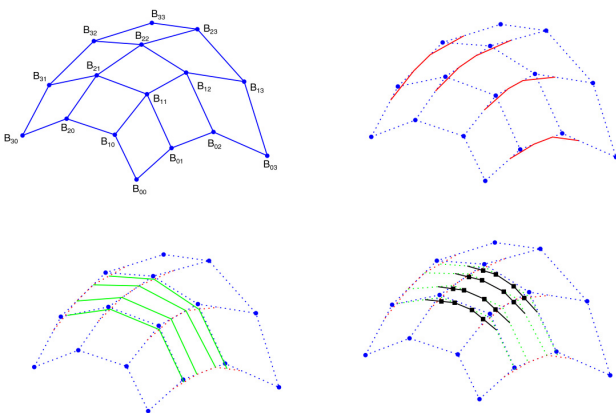## Tensor product B-spline surfaces

As with spline curves, we can piece together a sequence of Bézier surfaces to make a spline surface. If we enforce C^2 continuity and local control, we get B-spline curves:

- ◆ treat rows of B as control points to generate Bézier control points in u.
- ◆ treat Bézier control points in u as B-spline control points in v.
- ◆ treat B-spline control points in v to generate Bézier control points in u.

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Tensor product B-spline surfaces, cont.

Which B-spline control points are interpolated by the surface?

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Matrix form of B-spline surfaces

For curves, we can write a matrix that generates Bezier control points from B-spline control points:

$$\begin{bmatrix} V_0^T \\ V_1^T \\ V_2^T \\ V_3^T \end{bmatrix} = \begin{bmatrix} 1/6 & 2/3 & 1/6 & 0 \\ 0 & 2/3 & 1/3 & 0 \\ 0 & 1/3 & 2/3 & 0 \\ 0 & 1/6 & 2/3 & 1/6 \end{bmatrix} \begin{bmatrix} B_0^T \\ B_1^T \\ B_2^T \\ B_3^T \end{bmatrix}$$

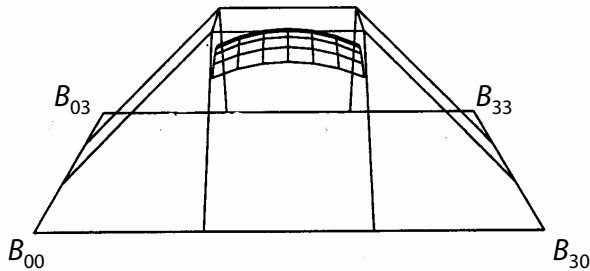$$\mathbf{V}_{\text{curve}} = \mathbf{M}_{\text{B-spline}} \mathbf{B}_{\text{curve}}$$

We can arrive at a similar form for tensor product B-spline surfaces:

$$\mathbf{V}_{\text{surface}} = \mathbf{M}_{\text{B-spline}} \mathbf{B}_{\text{surface}} \mathbf{M}_{\text{B-spline}}^T$$

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Tensor product B-splines, cont.

Another example:
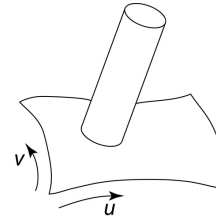

B_{03} B_{33}

B_{00} B_{30}

Trimmed NURBS surfaces

Uniform B-spline surfaces are a special case of NURBS surfaces.

Sometimes, we want to have control over which parts of a NURBS surface get drawn.

For example:

We can do this by **trimming** the u-v domain.

- ◆ Define a closed curve in the u-v domain (a **trim curve**)
- ◆ Do not draw the surface points inside of this curve.

It's really hard to maintain continuity in these regions, especially while animating.

Summary

What to take home:

- ◆ How to construct swept surfaces from a profile and trajectory curve:
  - · with a fixed frame
  - · with a Frenet frame
- ◆ How to construct tensor product Bézier surfaces
- ◆ How to construct tensor product B-spline surfaces