

# Topics

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1. Introduction: What is Computer Graphics?
2. Raster Images (image input/output devices and representation)
3. Scan conversion (pixels, lines, triangles)
4. Ray Casting (camera, visibility, normals, lighting, Phong illumination)
5. Ray Tracing (shadows, supersampling, global illumination)
6. Spatial Data Structures (AABB trees, OBB, bounding spheres, octree)
7. Meshes (connectivity, smooth interpolation, uv-textures, subdivision, Laplacian smoothing)
8. 2D/3D Transformations (Translate, Rotate, Scale, Affine, Homography, Homogeneous coordinates)
9. Viewing and Projection (matrix composition, perspective, Z-buffer)
10. Shader Pipeline (Graphics Processing Unit)
11. Animation (kinematics, keyframing, Catmull-Rom interpolation, physical simulation)
12. 3D curves and objects (Hermite, Bezier, cubic curves, curve continuity, extrusion/revolve surfaces)
13. Advanced topics overview

# Topic 12.

## 3D Curves and Objects

# Interactive Design of Curves

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Goal: Expand the capabilities of shapes beyond lines and conics, simple analytic functions and to allow design constraints.

Design Issues:

- Continuity (smoothness)
- Control (local vs. global)
- Interpolation vs. approximation of constraints
- Other geometric properties  
(planarity, tangent/curvature control)
- Efficient analytic representation

# Parametric Polynomial Curves

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Recall a linear curve (line) is:

$$p(t) = a_1t + a_0$$

A cubic curve is similarly:

$$\begin{aligned}x(t) &= a_3t^3 + a_2t^2 + a_1t + a_0 \\y(t) &= b_3t^3 + b_2t^2 + b_1t + b_0 \\z(t) &= c_3t^3 + c_2t^2 + c_1t + c_0\end{aligned}$$

...or  $p(t) = d_3t^3 + d_2t^2 + d_1t + d_0$ , where  $d_i = [a_i, b_i, c_i]^T$

Cubics are commonly used in graphics because curves of lower order commonly have too little flexibility (only planar, no curvature control), while curves of higher order are unnecessarily complex and make it easy to introduce undesired wiggles.

# Designing Polynomial Curves from constraints

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$p(t) = TA$ , where  $T$  is powers of  $t$ . for a cubic  $T=[t^3 \ t^2 \ t^1 \ 1]$ .

Written with geometric constraints  $p(t) = TMG$ , where  $M$  is the **Basis matrix** of a design curve and  $G$  the specific design constraints.

An example of constraints for a cubic Hermite for eg. are end points and end tangents. i.e.  $P_1, R_1$  at  $t=0$  and  $P_4, R_4$  at  $t=1$ . Plugging these constraints into  $p(t) = TA$  we get.

$B$

$$p(0) = P_1 = [0 \ 0 \ 0 \ 1] A_h$$

$$p(1) = P_4 = [1 \ 1 \ 1 \ 1] A_h$$

$$p'(0) = R_1 = [0 \ 0 \ 1 \ 0] A_h \quad \Rightarrow \quad G=BA, \ A=MG \Rightarrow M=B^{-1}$$

$$p'(1) = R_4 = [3 \ 2 \ 1 \ 0] A_h$$

# Designing Polynomial Curves from constraints

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An example of constraints for a cubic Hermite for eg. are end points and end tangents. i.e.  $p_0, p'_0$  at  $t=0$  and  $p_1, p'_1$  at  $t=1$ . Plugging these constraints into  $p(t) = TA$  we get.

$$\begin{aligned} & \text{B} \\ p(0) = p_0 &= [0 \ 0 \ 0 \ 1] A_h \\ p(1) = p_1 &= [1 \ 1 \ 1 \ 1] A_h \\ p'(0) = p'_0 &= [0 \ 0 \ 1 \ 0] A_h \\ p'(1) = p'_1 &= [3 \ 2 \ 1 \ 0] A_h \end{aligned} \quad \Rightarrow \quad G=BA, A=MG \Rightarrow M=B^{-1}$$

# Hermite Basis Matrix

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$$\begin{bmatrix} 0 & 0 & 0 & 1 \end{bmatrix}^{-1}$$
$$\begin{bmatrix} 1 & 1 & 1 & 1 \end{bmatrix}$$
$$\begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix}$$
$$\begin{bmatrix} 3 & 2 & 1 & 0 \end{bmatrix}$$

$$= M_{\text{hermite}}$$

$$\begin{bmatrix} 2 & -2 & 1 & 1 \end{bmatrix}$$
$$\begin{bmatrix} -3 & 3 & -2 & -1 \end{bmatrix}$$
$$\begin{bmatrix} 0 & 0 & 1 & 0 \end{bmatrix}$$
$$\begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}$$

The columns of the Basis Matrix form Basis Functions such that:

$$p(t) = (2t^3 - 3t^2 + 1)p_0 + (-2t^2 + 3t^2)p_1 + (t^3 - 2t^2 + t)p'_0 + (t^3 - t^2)p'_1.$$

# Bezier Basis Matrix

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A cubic Bezier can be defined with four points where:

$p_0, p'_0$  at  $t=0$  and  $p_3, p'_3$  at  $t=1$  for a Hermite.

$p'_0 = 3(p_1 - p_0)$  and  $p'_3 = 3(p_3 - p_2)$ .

We can thus compute the Bezier Basis Matrix by finding the matrix that transforms  $[p_0 \ p_1 \ p_2 \ p_3]^T$  into  $[p_0 \ p_3 \ p'_0 \ p'_3]^T$  i.e.

$$B_H = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ -3 & 3 & 0 & 0 \\ 0 & 0 & -3 & 3 \end{bmatrix}$$

$$M_{\text{bezier}} = M_{\text{hermite}} * B_H$$



# Bezier Basis Functions

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$$\begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 3 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

The columns of the Basis Matrix form Basis Functions such that:  
 $p(t) = f_0(t)p_0 + f_1(t)p_1 + f_2(t)p_2 + f_3(t)p_3.$

From the matrix:

$$f_i(t) = \binom{n}{i} * (1-t)^{(n-i)} * t^i$$

These are also called Bernstein polynomials.

# Basis Functions

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Basis functions can be thought of as interpolating functions.

Note: actual interpolation of any point only happens if its Basis function is 1 and all others are zero at some  $t$ .

Often Basis functions for design curves sum to 1 for all  $t$ .

This gives the curve some nice properties like affine invariance and the convex hull property when the function are additionally non-negative.

# Geometric continuity at a joint of two curves

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## *Geometric Continuity*

$G_0$ : curves are joined

$G_1$ : first derivatives are proportional at the join point

The curve tangents thus have the same direction,  
but not necessarily the same magnitude.

i.e.,  $C_1'(1) = (a, b, c)$  and  $C_2'(0) = (k*a, k*b, k*c)$ .

$G_2$ : first and second derivatives are proportional at join point

## *Parametric Continuity*

$C_0$ : curves are joined

$C_1$ : first derivatives equal

$C_2$ : first and second derivatives are equal

If  $t$  is taken to be time, the acceleration is continuous.

$C_n$ :  $n$ th derivatives are equal

# Local vs. Global control

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Changing a point on the Bezier changes the curve mostly near the point, but a little bit everywhere...

Precise local control can be handled by splines where the Basis functions of points symmetrically increase from 0 to a maximum value over a window and then decrease to 0.

The curve is strictly affected by the point over this parameter range or window.

# 3D parametric surfaces

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- Extrude
- Revolve
- Loft
- Square

Demo...

# 3D parametric surfaces: Coons interpolation

