Modeling Complex Shapes

- We want to build models of very complicated objects
- An equation for a sphere is possible, but how about an equation for a telephone, or a face?
- Complexity is achieved using simple pieces
  - polygons, parametric curves and surfaces, or implicit curves and surfaces
  - This lecture: parametric curves
Parametric Curves

Modeling:
• parametric curves (Splines)
• polygonal meshes
Roller coaster

- We must model the 3D curve describing the roller coaster, but how?
- How to make the simulation obey the laws of gravity?
What Do We Need From Curves in Computer Graphics?

- Local control of shape (so that easy to build and modify)
- Stability
- Smoothness and continuity
- Ability to evaluate derivatives
- Ease of rendering
Curve Representations

- Explicit: $y = f(x)$
  
  $y = mx + b$
  
  - Easy to generate points
  - Must be a function: big limitation—vertical lines?
Curve Representations

• Explicit: \( y = f(x) \)
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• Implicit: \( f(x,y) = 0 \)
  \[ x^2 + y^2 - r^2 = 0 \]
  +Easy to test if on the curve
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- **Parametric:** \( (x,y) = (f(u), g(u)) \)
  \[
  (x, y) = (\cos u, \sin u)
  \]
  + Easy to generate points
Parameterization of a Curve

- *Parameterization* of a curve: how a change in $u$ moves you along a given curve in $xyz$ space.
Polynomial Interpolation

- An \( n \)-th degree polynomial fits a curve to \( n+1 \) points
  - called Lagrange Interpolation
  - result is a curve that is too wiggly, change to any control point affects entire curve (nonlocal) – *this method is poor*

- We usually want the curve to be as smooth as possible
  - minimize the wiggles
  - high-degree polynomials are bad
Splines: Piecewise Polynomials

• A spline is a *piecewise polynomial* - many low degree polynomials are used to interpolate (pass through) the control points

• *Cubic piecewise* polynomials are the most common:
  – piecewise definition gives local control
Piecewise Polynomials

- Spline: lots of little polynomials pieced together
- Want to make sure they fit together nicely

C₀ continuity
Continuous in position

C₀ & C₁ continuity
Continuous in position and tangent vector

C₀ & C₁ & C₂ continuity
Continuous in position, tangent, and curvature
Splines

• Types of splines:
  – Hermite Splines
  – Catmull-Rom Splines
  – Bezier Splines
  – Natural Cubic Splines
  – B-Splines
  – NURBS
Hermite Curves

- Cubic Hermite Splines

That is, we want a way to specify the end points and the slope at the end points!
Splines

chalkboard
The Cubic Hermite Spline Equation

• Using some algebra, we obtain:

\[ p(u) = \begin{bmatrix} u^3 & u^2 & u & 1 \end{bmatrix} \begin{bmatrix} 2 & -2 & 1 & 1 \\ -3 & 3 & -2 & -1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \\ \nabla p_1 \\ \nabla p_2 \end{bmatrix} \]

point that gets drawn

basis control matrix (what the user gets to pick)

• This form typical for splines
  – basis matrix and meaning of control matrix change with the spline type
The Cubic Hermite Spline Equation

• Using some algebra, we obtain:

\[ p(u) = \begin{bmatrix} u^3 & u^2 & u \end{bmatrix} \begin{bmatrix} 2 & -2 & 1 & 1 \\ -3 & 3 & -2 & -1 \\ 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \\ \nabla p_1 \\ \nabla p_2 \end{bmatrix} \]

Point that gets drawn

Basis

Control matrix (what the user gets to pick)

\[ p(u) = \begin{bmatrix} u^3 - 3u^2 + 1 \\ -2u^3 + 3u^2 \\ u^3 - 2u^2 + u \\ u^3 - u^2 \end{bmatrix}^T \begin{bmatrix} p_1 \\ p_2 \\ \nabla p_1 \\ \nabla p_2 \end{bmatrix} \]

4 Basis Functions
Four Basis Functions for Hermite splines

\[ p(u) = \begin{bmatrix} 2u^3 - 3u^2 + 1 \\ -2u^3 + 3u^2 \\ u^3 - 2u^2 + u \\ u^3 - u^2 \end{bmatrix}^\top \begin{bmatrix} p_1 \\ p_2 \\ \nabla p_1 \\ \nabla p_2 \end{bmatrix} \]

4 Basis Functions

Every cubic Hermite spline is a linear combination (blend) of these 4 functions
Piecing together Hermite Curves

- It's easy to make a multi-segment Hermite spline
  - each piece is specified by a cubic Hermite curve
  - just specify the position and tangent at each “joint”
  - the pieces fit together with matched positions and first derivatives
  - gives C1 continuity

- The points that the curve has to pass through are called knots or knot points
Catmull-Rom Splines

- With Hermite splines, the designer must specify all the tangent vectors.
- Catmull-Rom: an interpolating cubic spline with *built-in* $C^1$ continuity.
Catmull-Rom Splines

- With Hermite splines, the designer must specify all the tangent vectors.
- Catmull-Rom: an interpolating cubic spline with built-in $C^1$ continuity.

\[ \text{tangent at } p_i = s(p_{i+1} - p_{i-1}) \]
Catmull-Rom Spline Matrix

\[ p(u) = \begin{bmatrix} u^3 & u^2 & u \end{bmatrix} \begin{bmatrix} -s & 2s & s-2 & s \\ 2s & s-3 & 3-2s & -s \\ -s & 0 & s & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \end{bmatrix} \]

- spline coefficients
- CR basis
- control vector

- Derived similarly to Hermite
- Parameter \( s \) is typically set to \( s=1/2 \).
Cubic Curves in 3D

- Three cubic polynomials, one for each coordinate
  - \( x(u) = a_x u^3 + b_x u^2 + c_x u + d_x \)
  - \( y(u) = a_y u^3 + b_y u^2 + c_y u + d_y \)
  - \( z(u) = a_z u^3 + b_z u^2 + c_z u + d_z \)

- In matrix notation

\[
\begin{bmatrix}
  x(u) \\
  y(u) \\
  z(u)
\end{bmatrix} =
\begin{bmatrix}
  u^3 & u^2 & u & 1
\end{bmatrix}
\begin{bmatrix}
  a_x & a_y & a_z \\
  b_x & b_y & b_z \\
  c_x & c_y & c_z \\
  d_x & d_y & d_z
\end{bmatrix}
\]
Catmull-Rom Spline Matrix in 3D

\[
\begin{bmatrix}
  x(u) \\
  y(u) \\
  z(u)
\end{bmatrix} =
\begin{bmatrix}
  u^3 & u^2 & u & 1
\end{bmatrix}
\begin{bmatrix}
  -s & 2 - s & s - 2 & s \\
  2s & s - 3 & 3 - 2s & -s \\
  -s & 0 & s & 0 \\
  0 & 1 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
  x_1 & y_1 & z_1 \\
  x_2 & y_2 & z_2 \\
  x_3 & y_3 & z_3 \\
  x_4 & y_4 & z_4
\end{bmatrix}
\]

CR basis
control vector
Beziers Curves

- Another variant of the same game
- Instead of endpoints and tangents, four control points
  - points $P_0$ and $P_3$ are on the curve: $P(u=0) = P_0$, $P(u=1) = P_3$
  - points $P_1$ and $P_2$ are off the curve
    - $P'(u=0) = 3(P_1 - P_0)$, $P'(u=1) = 3(P_3 - P_2)$
- Convex Hull property
  - curve contained within convex hull of control points
- Gives more control knobs (series of points) than Hermite
- Scale factor (3) is chosen to make “velocity” approximately constant
The Bezier Spline Matrix*

\[
\begin{bmatrix}
 x \\
 y \\
 z
\end{bmatrix} =
\begin{bmatrix}
 u^3 & u^2 & u & 1
\end{bmatrix}
\begin{bmatrix}
 -1 & 3 & -3 & 1 \\
 3 & -6 & 3 & 0 \\
 -3 & 3 & 0 & 0 \\
 1 & 0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
 x_1 & y_1 & z_1 \\
 x_2 & y_2 & z_2 \\
 x_3 & y_3 & z_3 \\
 x_4 & y_4 & z_4
\end{bmatrix}
\]

Beziers basis \hspace{1cm} \text{Beziers control vector}
Beziers Blending Functions

\[ p(t) = \begin{bmatrix} (1-t)^3 \\ 3t(1-t)^2 \\ 3t^2(1-t) \\ t^3 \end{bmatrix}^T \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \end{bmatrix} \]

Also known as the order 4, degree 3 Bernstein polynomials
Nonnegative, sum to 1
The entire curve lies inside the polyhedron bounded by the control points
Splines with More Continuity?

• How could we get $C^2$ continuity at control points?

• Possible answers:
  – Use higher degree polynomials
    degree 4 = quartic, degree 5 = quintic, … but these get computationally expensive, and sometimes wiggly
  – Give up local control natural cubic splines
    A change to any control point affects the entire curve
  – Give up interpolation cubic B-splines
    Curve goes near, but not through, the control points
Piecewise Polynomials

- Spline: lots of little polynomials pieced together
- Want to make sure they fit together nicely

1. $C_0$ continuity
   - Continuous in position

2. $C_0$ & $C_1$ continuity
   - Continuous in position and tangent vector

3. $C_0$ & $C_1$ & $C_2$ continuity
   - Continuous in position, tangent, and curvature
# Comparison of Basic Cubic Splines

<table>
<thead>
<tr>
<th>Type</th>
<th>Local Control</th>
<th>Continuity</th>
<th>Interpolation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hermite</td>
<td>YES</td>
<td>C1</td>
<td>YES</td>
</tr>
<tr>
<td>Bezier</td>
<td>YES</td>
<td>C1</td>
<td>YES</td>
</tr>
<tr>
<td>Catmull-Rom</td>
<td>YES</td>
<td>C1</td>
<td>YES</td>
</tr>
<tr>
<td>Natural</td>
<td>NO</td>
<td>C2</td>
<td>YES</td>
</tr>
<tr>
<td>B-Splines</td>
<td>YES</td>
<td>C2</td>
<td>NO</td>
</tr>
</tbody>
</table>

- **Summary**
  - Can’t get C2, interpolation and local control with cubics
Natural Cubic Splines*

- If you want 2nd derivatives at joints to match up, the resulting curves are called \textit{natural cubic splines}.
- It’s a simple computation to solve for the cubics' coefficients. (See \textit{Numerical Recipes in C} book for code.)
- Finding all the right weights is a \textit{global} calculation (solve tridiagonal linear system).
B-Splines*

- Give up interpolation
  - the curve passes near the control points
  - best generated with interactive placement (because it’s hard to guess where the curve will go)

- Curve obeys the convex hull property

- C2 continuity and local control are good compensation for loss of interpolation
B-Spline Basis

- We always need 3 more control points than spline pieces

\[ M_{Bs} = \frac{1}{6} \begin{bmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 0 & 3 & 0 \\ 1 & 4 & 1 & 0 \end{bmatrix} \]

\[ G_{Bs_i} = \begin{bmatrix} P_{i-3} \\ P_{i-2} \\ P_{i-1} \\ P_i \end{bmatrix} \]
How to Draw Spline Curves

- Basis matrix eqn. allows same code to draw any spline type
- **Method 1**: brute force
  - Calculate the coefficients
  - For each cubic segment, vary $u$ from 0 to 1 (fixed step size)
  - Plug in $u$ value, matrix multiply to compute position on curve
  - Draw line segment from last position to current position

\[
\begin{bmatrix}
  x \\ y \\ z 
\end{bmatrix} =
\begin{bmatrix}
  u^3 & u^2 & u & 1 \\
\end{bmatrix}
\begin{bmatrix}
  -s & 2-s & s-2 & s \\
  2s & s-3 & 3-2s & -s \\
  -s & 0 & s & 0 \\
  0 & 1 & 0 & 0 \\
\end{bmatrix}
\begin{bmatrix}
  x_1 & y_1 & z_1 \\
  x_2 & y_2 & z_2 \\
  x_3 & y_3 & z_3 \\
  x_4 & y_4 & z_4 \\
\end{bmatrix}
\]

CR basis
control vector
How to Draw Spline Curves

- What’s wrong with this approach?
  - Draws in even steps of u
  - Even steps of u ≠ even steps of x
  - Line length will vary over the curve
  - Want to bound line length
    » too long: curve looks jagged
    » too short: curve is slow to draw
Method 2: recursive subdivision - vary step size to draw short lines

Subdivide(u0, u1, maxlinelength)
  umid = (u0 + u1)/2
  x0 = P(u0)
  x1 = P(u1)
  if |x1 - x0| > maxlinelength
     Subdivide(u0, umid, maxlinelength)
     Subdivide(umid, u1, maxlinelength)
  else drawline(x0, x1)

Variant on Method 2 - subdivide based on curvature
- replace condition in “if” statement with straightness criterion
- draws fewer lines in flatter regions of the curve
In Summary...

- **Summary:**
  - piecewise cubic is generally sufficient
  - define conditions on the curves and their continuity

- **Things to know:**
  - basic curve properties (what are the conditions, controls, and properties for each spline type)
  - generic matrix formula for uniform cubic splines \( x(u) = uB \)
  - given definition derive a basis matrix