Foundations of Computer Graphics (Fall 2012)

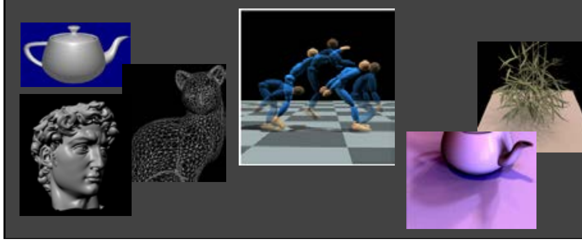
CS 184, Lecture 9: Curves 1

http://inst.eecs.berkeley.edu/~cs184

Course Outline

- 3D Graphics Pipeline

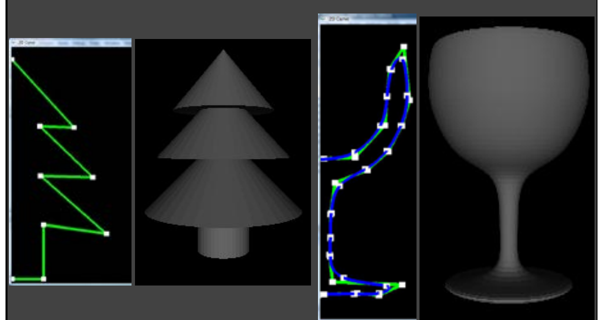
Modeling → Animation → Rendering



Graphics Pipeline

- In HW 1, HW 2, draw, shade objects
- But how to define geometry of objects?
- How to define, edit shape of teapot?
- We discuss *modeling* with spline curves
  - Demo of HW 3 solution

Curves for Modeling



Rachel Shiner, Final Project Spring 2010

Motivation

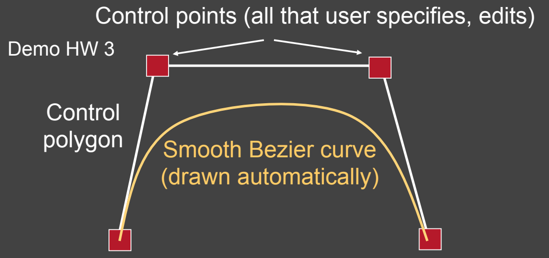
- How do we model complex shapes?
  - In this course, only 2D curves, but can be used to create interesting 3D shapes by surface of revolution, lofting etc
- Techniques known as spline curves
- This unit is about mathematics required to draw these spline curves, as in HW 3
- History: From using computer modeling to define car bodies in auto-manufacturing. Pioneers are Pierre Bezier (Renault), de Casteljau (Citroen)

Outline of Unit

- *Bezier curves*
- deCasteljau algorithm, explicit form, matrix form
- Polar form labeling (next time)
- B-spline curves (next time)
- Not well covered in textbooks (especially as taught here). Main reference will be lecture notes. If you do want a printed ref, handouts from CAGD, Seidel

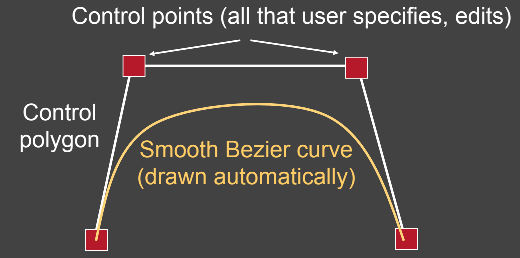
Bezier Curve (with HW2 demo)

- *Motivation: Draw a smooth intuitive curve (or surface) given few key user-specified control points*



Bezier Curve: (Desirable) properties

- Interpolates, is tangent to end points
- Curve within convex hull of control polygon



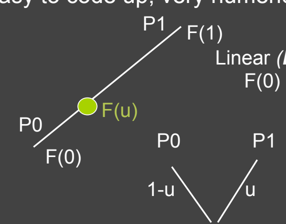
Issues for Bezier Curves

Main question: Given control points and constraints (interpolation, tangent), how to construct curve?

- *Algorithmic: deCasteljau algorithm*
- Explicit: Bernstein-Bezier polynomial basis
- 4x4 matrix for cubics
- Properties: Advantages and Disadvantages

deCasteljau: Linear Bezier Curve

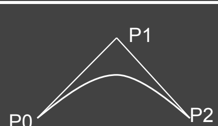
- Just a simple linear combination or interpolation (easy to code up, very numerically stable)



Linear (***Degree 1, Order 2***)
F(0) = P0, F(1) = P1
F(u) = ?

F(u) = (1-u) P0 + u P1

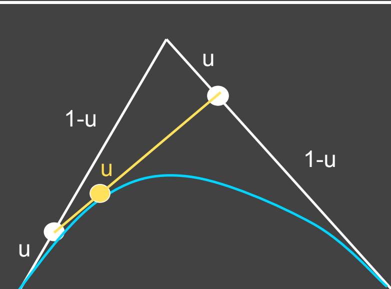
deCasteljau: Quadratic Bezier Curve



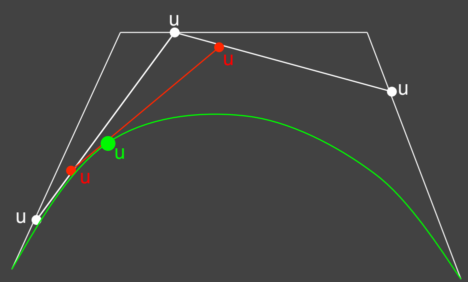
Quadratic
Degree 2, Order 3
F(0) = P0, F(1) = P2
F(u) = ?

$F(u) = (1-u)^2 P0 + 2u(1-u) P1 + u^2 P2$

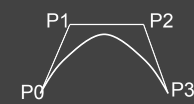
Geometric interpretation: Quadratic



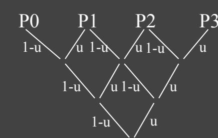
Geometric Interpretation: Cubic



deCasteljau: Cubic Bezier Curve

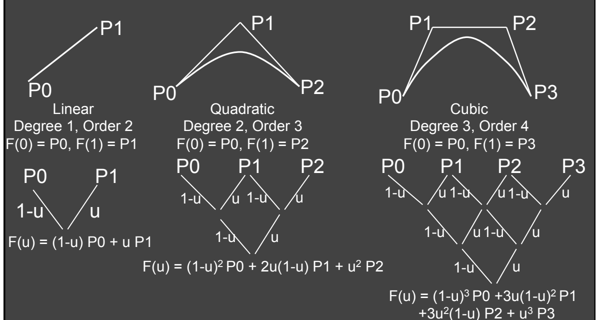


Cubic
Degree 3, Order 4
F(0) = P0, F(1) = P3



F(u) = $(1-u)^3$ P0 +3u$(1-u)^2$ P1 +3u^2(1-u) P2 + u^3 P3

Summary: deCasteljau Algorithm



DeCasteljau Implementation

Input: Control points C_i with $0 \le i \le n$ where n is the degree.
Output: $f(u)$ where u is the parameter for evaluation

```
for (level = n ; level ≥ 0 ; level−−) {
  if (level == n) { // Initial control points
    ∀i : 0 ≤ i ≤ n : p_i^level = C_i ; continue ; }
  for (i = 0 ; i ≤ level ; i++)
    p_i^level = (1 − u) ∗ p_i^(level+1) + u ∗ p_(i+1)^(level+1) ;
}
f(u) = p_0^0
```

- Can be optimized to do without auxiliary storage

Summary of HW2 Implementation

Bezier (Bezier2 and Bspline discussed next time)
- Arbitrary degree curve (number of control points)
- Break curve into detail segments. Line segments for these
- Evaluate curve at locations 0, 1/detail, 2/detail, … , 1
- Evaluation done using deCasteljau

- Key implementation: deCasteljau for arbitrary degree
  - Is anyone confused? About handling arbitrary degree?
- Can also use alternative formula if you want
  - Explicit Bernstein-Bezier polynomial form (next)
- Questions?

Issues for Bezier Curves

Main question: Given control points and constraints (interpolation, tangent), how to construct curve?

- Algorithmic: deCasteljau algorithm
- *Explicit: Bernstein-Bezier polynomial basis*
- 4x4 matrix for cubics
- Properties: Advantages and Disadvantages

Recap formulae

- Linear combination of basis functions

Linear: $F(u) = P_0(1-u) + P_1 u$

Quadratic: $F(u) = P_0(1-u)^2 + P_1[2u(1-u)] + P_2 u^2$

Cubic: $F(u) = P_0(1-u)^3 + P_1[3u(1-u)^2] + P_2[3u^2(1-u)] + P_3 u^3$

Degree n: $F(u) = \sum_k P_k B_k^n(u)$

$B_k^n(u)$ are Bernstein-Bezier polynomials

- Explicit form for basis functions? Guess it?

Recap formulae

- Linear combination of basis functions

Linear: $F(u) = P_0(1-u) + P_1 u$

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Degree n: $F(u) = \sum_k P_k B_k^n(u)$

$B_k^n(u)$ are Bernstein-Bezier polynomials

- Explicit form for basis functions? Guess it?
- ***Binomial coefficients in [(1-u)+u]^n***

Summary of Explicit Form

Linear: $F(u) = P_0(1-u) + P_1 u$

Quadratic: $F(u) = P_0(1-u)^2 + P_1[2u(1-u)] + P_2 u^2$

Cubic: $F(u) = P_0(1-u)^3 + P_1[3u(1-u)^2] + P_2[3u^2(1-u)] + P_3 u^3$

Degree n: $F(u) = \sum_k P_k B_k^n(u)$

$B_k^n(u)$ are Bernstein-Bezier polynomials

$$B_k^n(u) = \frac{n!}{k!(n-k)!}(1-u)^{n-k}u^k$$

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- Algorithmic: deCasteljau algorithm
- Explicit: Bernstein-Bezier polynomial basis
- *4x4 matrix for cubics*
- Properties: Advantages and Disadvantages

Cubic 4x4 Matrix (derive)

$$F(u) = P_0(1-u)^3 + P_1[3u(1-u)^2] + P_2[3u^2(1-u)] + P_3 u^3$$

$$= \begin{pmatrix} u^3 & u^2 & u & 1 \end{pmatrix} \begin{pmatrix} & & & \\ & M = ? & & \\ & & & \\ & & & \end{pmatrix} \begin{pmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \end{pmatrix}$$

Cubic 4x4 Matrix (derive)

$$F(u) = P_0(1-u)^3 + P_1[3u(1-u)^2] + P_2[3u^2(1-u)] + P_3 u^3$$

$$= \begin{pmatrix} u^3 & u^2 & u & 1 \end{pmatrix} \begin{pmatrix} -1 & 3 & -3 & 1 \\ 3 & -6 & 3 & 0 \\ -3 & 3 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} P_0 \\ P_1 \\ P_2 \\ P_3 \end{pmatrix}$$

Issues for Bezier Curves

Main question: Given control points and constraints (interpolation, tangent), how to construct curve?

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- 4x4 matrix for cubics
- *Properties: Advantages and Disadvantages*

Properties (brief discussion)

- Demo of HW 3
- Interpolation: End-points, but approximates others
- Single piece, moving one point affects whole curve (no local control as in B-splines later)
- Invariant to translations, rotations, scales etc. That is, translating all control points translates entire curve
- Easily subdivided into parts for drawing (next lecture): Hence, Bezier curves easiest for drawing