

## Chapter 3

# POLYNOMIAL EVALUATION

### 3.1 Power Basis

Horner's algorithm can evaluate a power basis polynomial

$$y(t) = \sum_{i=0}^n p_i t^i$$

using  $n$  multiplies and adds as follows:

$$h_n = p_n; \quad h_{i-1} = t \times h_i + p_{i-1}; \quad y(t) = h_0.$$

In C, this can be written

```
float p_horner(float *p,int n, float t)
{
float h;
int i;

    h = p[n];
    for(i=n-1; i<=0; i--)
        h = t*h + p[i];
    return (h)
}
```

This is the fastest algorithm for evaluating a power basis polynomial at a single point. For evaluating a polynomial at several evenly spaced intervals ( $f(0)$ ,  $f(a)$ ,  $f(2a)$ ,  $f(3a)$ , etc.) forward differences work faster though are numerically unstable.

### 3.2 Bernstein Basis

For evaluating a Bézier curve, one option is to convert to power basis (see section 3.3) and then use Horner's algorithm. Alternatively, Horner's algorithm can be modified to work directly on Bernstein basis polynomials. We can use the recurrence relation for binomial coefficient

$$\binom{n}{i} = \frac{n-i+1}{i} \binom{n}{i-1}$$

to derive a nested multiplication which does not involve the binomial coefficients directly:

```
float b_horner(float *b, int n, float t)
{
float u, bc, tn, tmp;
int i;

    u = 1.0 - t;
    bc = 1;
    tn = 1;
    tmp = b[0]*u;
    for(i=1; i<n; i++){
        tn = tn*t;
        bc = bc*(n-i+1)/i;
        tmp = (tmp + tn*bc*b[i])*u;
    }
return (tmp + tn*t*b[n]);
}
```

### 3.3 Basis Conversion

A fundamental problem in CAGD is that of polynomial basis conversion. We here consider the common case of conversion between power and Bernstein bases. For example, given a Bézier curve of any degree, we want to find the equivalent power basis equation and vice versa.

Denote a polynomial in Bernstein form

$$B(t) = \sum_{i=0}^n b_i \binom{n}{i} (1-t)^{n-i} t^i$$

and a polynomial in power form

$$P(t) = \sum_{i=0}^n p_i t^i.$$

The problem we consider is, given the  $b_i$  of a polynomial in Bernstein basis, find the  $p_i$  for the equivalent power basis polynomial (Bernstein to power basis conversion) or given the  $p_i$  from the  $b_i$  (power to Bernstein conversion).

An elegant solution to this problem can be obtained by performing a Taylor's series expansion. The Taylor's expansion of  $B(t)$  is:

$$B(t) \equiv B(0) + B'(0)t + \frac{B''(0)t^2}{2} + \dots + \frac{B^{(i)}(0)t^i}{i!} + \dots$$

A power basis polynomial is equivalent to a Bernstein basis polynomial ( $P(t) \equiv B(t)$ ) if and only if

$$\frac{P^{(i)}(0)t^i}{i!} \equiv \frac{B^{(i)}(0)t^i}{i!}, \quad i = 0, \dots, n.$$

But, for power basis,

$$\frac{P^{(i)}(0)}{i!} = p_i$$

so

$$(3.1) \quad p_i = \frac{B^{(i)}(0)}{i!}, \quad i = 0, \dots, n.$$

The terms  $B^{(i)}(0)$  can be found by setting up a difference table. Remember from our study of hodographs that the coefficients of the derivative of a polynomial in Bernstein form (for example, the  $x$  or  $y$  component of a Bézier curve) are:

$$n(b_1 - b_0), \quad n(b_2 - b_1), \dots, n(b_n - b_{n-1}).$$

The coefficients of the second derivative are:

$$n(n-1)(b_2 - 2b_1 + b_0), \quad n(n-1)(b_3 - 2b_2 + b_1), \dots, n(n-1)(b_n - 2b_{n-1} + b_{n-2}).$$

Since  $B(0) = \sum_{i=0}^n b_i \binom{n}{i} (1-0)^{n-i} 0^i = b_0$ , we have

$$B'(0) = n(b_1 - b_0), \quad B''(0) = n(n-1)(b_2 - 2b_1 + b_0)$$

$$B^{(i)}(0) = n(n-1) \cdots (n-i+1) \sum_{j=0}^i (-1)^{(i-j+1)} \binom{i}{j} b_j.$$

This can be written more neatly if we define the recurrence

$$b_i^j = b_{i+1}^{j-1} - b_i^{j-1}$$

with  $b_i^0 \equiv b_i$ . Then

$$B^{(i)}(0) = n(n-1) \cdots (n-i+1) b_0^i = \frac{n!}{(n-i)!} b_0^i.$$

From equation 3.1,

$$p_i = \frac{n!}{(n-i)!i!} b_0^i = \binom{n}{i} b_0^i.$$

Thus, the problem reduces to one of finding the values  $b_0^i$ . This is easily done using a difference table:

$b_0^0 = b_0 = p_0$	$b_1^0 = b_1$	$\dots$	$b_n^0 = b_n$	Thus, to perform
$b_0^1 = b_1^0 - b_0^0 = p_1 / \binom{n}{1}$	$b_1^1 = b_2^0 - b_1^0$	$\dots$	$b_n^1 = b_n^0 - b_{n-1}^0$	
$b_0^2 = b_1^1 - b_0^1 = p_2 / \binom{n}{2}$	$b_1^2 = b_2^1 - b_1^1$	$\dots$	$b_n^2 = b_n^1 - b_{n-1}^1$	
$\dots$	$\dots$	$\dots$	$\dots$	
$b_0^{n-1} = b_1^{n-2} - b_0^{n-2} = p_{n-1} / \binom{n}{n-1}$	$b_1^{n-1} = b_2^{n-2} - b_1^{n-2}$	$\dots$	$\dots$	
$b_0^n = b_1^{n-1} - b_0^{n-1} = p_n$				

Bernstein to power basis conversion, load the Bernstein coefficients into the top row and compute the difference table. Scale the left column by  $\binom{n}{i}$ , and you have the power coefficients.

To perform power to Bernstein conversion, divide the power coefficients by  $\binom{n}{i}$ , load them into the left column, compute the difference table backwards, and read the Bernstein coefficients off the top row.

### 3.3.1 Example

Convert to power basis the degree 4 Bernstein form polynomial with coefficients (1, 3, 4, 6, 8). This is done by setting up the difference table

1	3	4	6	8
2	1	2	2	
-1	1	0		
2	-1			
-3				

so the power coefficient are taken from the left column, times the binomial coefficients:

$$p_0 = 1 \binom{4}{0} = 1$$

$$p_1 = 2 \binom{4}{1} = 8$$

$$p_2 = -1 \binom{4}{2} = -6$$

$$p_3 = 2 \binom{4}{3} = 8$$

$$p_4 = -3 \binom{4}{4} = -3$$

### 3.3.2 Closed Form Expression

The conversion from Bernstein to power basis can be written concisely as follows:

$$p_i = \sum_{k=0}^i b_k \binom{n}{i} \binom{i}{k} (-1)^{i-k}.$$