

## Approximation Theory

## Rational Function Approximation

## Lecture Notes #13

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## Advantages of Polynomial Approximation:

- [1] We can approximate any continuous function on a closed interval to within arbitrary tolerance. (*Weierstrass approximation theorem*)
- [2] Easily evaluated at arbitrary values. (*e.g. Horner's method*)
- [3] Derivatives and integrals are easily determined.

## Disadvantage of Polynomial Approximation:

- [1] Polynomials tend to be oscillatory, which causes errors. This is sometimes, but not always, fixable: — *E.g.* if we are free to select the node points we can minimize the interpolation error (*Chebyshev polynomials*), or optimize for integration (*Gaussian Quadrature*).

## Moving Beyond Polynomials: Rational Approximation.

We are going to use rational functions,  $r(x)$ , of the form

$$r(x) = \frac{p(x)}{q(x)} = \frac{\sum_{i=0}^n p_i x^i}{1 + \sum_{j=1}^m q_j x^j}$$

and say that the degree of such a function is  $N = n + m$ .

Since this is a richer class of functions than polynomials — rational functions with  $q(x) \equiv 1$  are polynomials, we expect that *rational approximation of degree  $N$  gives results that are at least as good as polynomial approximation of degree  $N$ .*

## Padé Approximation

Extension of **Taylor expansion** to rational functions; selecting the  $p_i$ 's and  $q_i$ 's so that  $r^{(k)}(x_0) = f^{(k)}(x_0) \forall k = 0, 1, \dots, N$ .

$$f(x) - r(x) = f(x) - \frac{p(x)}{q(x)} = \frac{f(x)q(x) - p(x)}{q(x)}$$

Now, use the Taylor expansion  $f(x) \sim \sum_{i=0}^{\infty} a_i (x - x_0)^i$ , for simplicity  $x_0 = 0$ :

$$f(x) - r(x) = \frac{\sum_{i=0}^{\infty} a_i x^i \sum_{i=0}^m q_i x^i - \sum_{i=0}^n p_i x^i}{q(x)}.$$

Next, we choose  $p_0, p_1, \dots, p_n$  and  $q_1, q_2, \dots, q_m$  so that the numerator has no terms of degree  $\leq N$ .

For simplicity we (sometimes) define the “indexing-out-of-bounds” coefficients:

$$\begin{cases} p_{n+1} = p_{n+2} = \dots = p_N = 0 \\ q_{m+1} = q_{m+2} = \dots = q_N = 0, \end{cases}$$

so we can express the **coefficients of  $x^k$**  in

$$\sum_{i=0}^{\infty} a_i x^i \sum_{i=0}^m q_i x^i - \sum_{i=0}^n p_i x^i = 0, \quad k = 0, 1, \dots, N$$

as

$$\sum_{i=0}^k a_i q_{k-i} = p_k, \quad k = 0, 1, \dots, N.$$

Find the Padé approximation of  $f(x)$  of degree 5, where  $f(x) \sim a_0 + a_1x + \dots + a_5x^5$  is the Taylor expansion of  $f(x)$  about the point  $x_0 = 0$ .

The corresponding equations are:

$x^0$	$a_0$	–	$p_0 = 0$
$x^1$	$a_0q_1 + a_1$	–	$p_1 = 0$
$x^2$	$a_0q_2 + a_1q_1 + a_2$	–	$p_2 = 0$
$x^3$	$a_0q_3 + a_1q_2 + a_2q_1 + a_3$	–	$p_3 = 0$
$x^4$	$a_0q_4 + a_1q_3 + a_2q_2 + a_3q_1 + a_4$	–	$p_4 = 0$
$x^5$	$a_0q_5 + a_1q_4 + a_2q_3 + a_3q_2 + a_4q_1 + a_5$	–	$p_5 = 0$

**Note:**  $p_0 = a_0!!!$  (This reduces the number of unknowns and equations by one (1).)

We get a linear system for  $p_1, p_2, \dots, p_N$  and  $q_1, q_2, \dots, q_N$ :

$$\begin{bmatrix} a_0 & & & & \\ a_1 & a_0 & & & \\ a_2 & a_1 & a_0 & & \\ a_3 & a_2 & a_1 & a_0 & \\ a_4 & a_3 & a_2 & a_1 & a_0 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ q_3 \\ q_4 \\ q_5 \end{bmatrix} - \begin{bmatrix} p_1 \\ p_2 \\ p_3 \\ p_4 \\ p_5 \end{bmatrix} = - \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \end{bmatrix}.$$

If we want  $n = 3, m = 2$ :

$$\begin{bmatrix} a_0 & 0 & -1 & & \\ a_1 & a_0 & 0 & -1 & \\ a_2 & a_1 & 0 & 0 & -1 \\ a_3 & a_2 & 0 & 0 & 0 \\ a_4 & a_3 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ p_1 \\ p_2 \\ p_3 \end{bmatrix} = - \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \end{bmatrix}.$$

The Taylor series expansion for  $e^{-x}$  about  $x_0 = 0$  is  $\sum_{k=0}^{\infty} \frac{(-1)^k}{k!} x^k$ , hence  $\{a_0, a_1, a_2, a_3, a_4, a_5\} = \{1, -1, \frac{1}{2}, -\frac{1}{6}, \frac{1}{24}, -\frac{1}{120}\}$ .

$$\begin{bmatrix} 1 & 0 & -1 & & \\ -1 & 1 & 0 & -1 & \\ 1/2 & -1 & 0 & 0 & -1 \\ -1/6 & 1/2 & 0 & 0 & 0 \\ 1/24 & -1/6 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} q_1 \\ q_2 \\ p_1 \\ p_2 \\ p_3 \end{bmatrix} = - \begin{bmatrix} -1 \\ 1/2 \\ -1/6 \\ 1/24 \\ -1/120 \end{bmatrix},$$

which gives  $\{q_1, q_2, p_1, p_2, p_3\} = \{2/5, 1/20, -3/5, 3/20, -1/60\}$ , i.e.

$$r_{3,2}(x) = \frac{1 - \frac{3}{5}x + \frac{3}{20}x^2 - \frac{1}{60}x^3}{1 + \frac{2}{5}x + \frac{1}{20}x^2}$$

All the possible Padé approximations of degree 5 are:

$$r_{5,0}(x) = 1 - x + \frac{1}{2}x^2 - \frac{1}{6}x^3 + \frac{1}{24}x^4 - \frac{1}{120}x^5$$

$$r_{4,1}(x) = \frac{1 - \frac{4}{5}x + \frac{3}{10}x^2 - \frac{1}{15}x^3 + \frac{1}{120}x^4}{1 + \frac{1}{5}x}$$

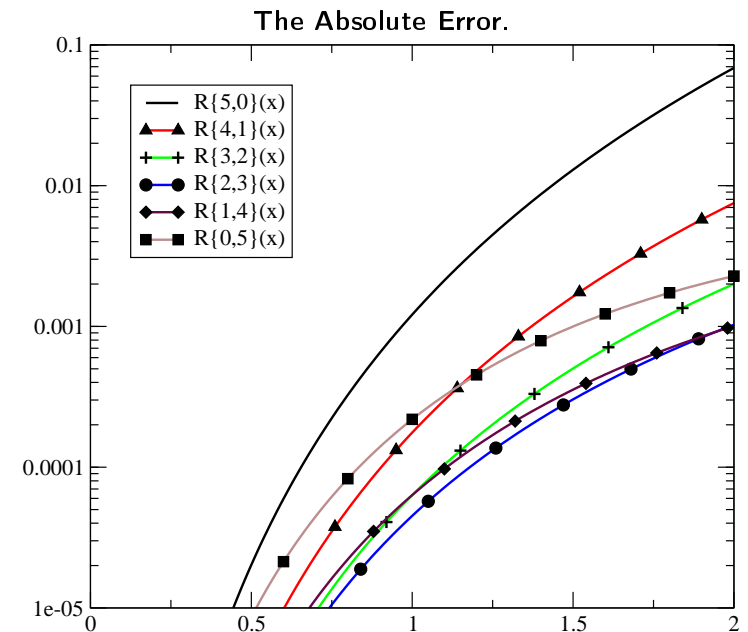
$$r_{3,2}(x) = \frac{1 - \frac{3}{5}x + \frac{3}{20}x^2 - \frac{1}{60}x^3}{1 + \frac{2}{5}x + \frac{1}{20}x^2}$$

$$r_{2,3}(x) = \frac{1 - \frac{2}{5}x + \frac{1}{20}x^2}{1 + \frac{3}{5}x + \frac{3}{20}x^2 + \frac{1}{60}x^3}$$

$$r_{1,4}(x) = \frac{1 - \frac{1}{5}x}{1 + \frac{4}{5}x + \frac{3}{10}x^2 + \frac{1}{15}x^3 + \frac{1}{120}x^4}$$

$$r_{0,5}(x) = \frac{1}{1 + x + \frac{1}{2}x^2 + \frac{1}{6}x^3 + \frac{1}{24}x^4 + \frac{1}{120}x^5}$$

**Note:**  $r_{5,0}(x)$  is the Taylor polynomial of degree 5.



### Padé Approximation: Matlab Code.

The algorithm in the book looks very frightening! If we think in terms of the matrix problem defined earlier, it is easier to figure out what is going on:

```
% The Taylor Coefficients, a_0, a_1, a_2, a_3, a_4, a_5
a = [1 -1 1/2 -1/6 1/24 -1/120]';
N = length(a); A = zeros(N-1,N-1);
% m is the degree of q(x), and n the degree of p(x)
m = 3; n = N-1-m;
% Set up the columns which multiply q_1 through q_m
for i=1:m
    A(i:(N-1),i) = a(1:(N-i));
end
% Set up the columns that multiply p_1 through p_n
A(1:n,m+(1:n)) = -eye(n)
% Set up the right-hand-side
b = - a(2:N);
% Solve
c = A\b;
Q = [1 ; c(1:m)]; % Select q_0 through q_m
P = [a_0 ; c((m+1):(m+n))]; % Select p_0 through p_n
```

### Optimal Padé Approximation?

	One Point	Optimal Points
Polynomials	Taylor	Chebyshev
Rational Functions	Padé	???

From the example  $e^{-x}$  we can see that Padé approximations suffer from the *same problem* as Taylor polynomials – they are very accurate near *one point*, but away from that point the approximation degrades.

“Chebyshev-placement” of interpolating points for polynomials gave us an optimal (uniform) error bound over the interval.

Can we do something similar for rational approximations???

### Chebyshev Basis for the Padé Approximation!

We use the *same* idea — instead of expanding in terms of the basis functions  $x^k$ , we will use the **Chebyshev polynomials**,  $T_k(x)$ , as our basis, *i.e.*

$$r_{n,m}(x) = \frac{\sum_{k=0}^n p_k T_k(x)}{\sum_{k=0}^m q_k T_k(x)}$$

where  $N = n + m$ , and  $q_0 = 1$ .

We also need to expand  $f(x)$  in a series of Chebyshev polynomials:

$$f(x) = \sum_{k=0}^{\infty} a_k T_k(x),$$

so that

$$f(x) - r_{n,m}(x) = \frac{\sum_{k=0}^{\infty} a_k T_k(x) \sum_{k=0}^m q_k T_k(x) - \sum_{k=0}^n p_k T_k(x)}{\sum_{k=0}^m q_k T_k(x)}.$$

### The Resulting Equations

Again, the coefficients  $p_0, p_1, \dots, p_n$  and  $q_1, q_2, \dots, q_m$  are chosen so that the numerator has zero coefficients for  $T_k(x)$ ,  $k = 0, 1, \dots, N$ , *i.e.*

$$\sum_{k=0}^{\infty} a_k T_k(x) \sum_{k=0}^m q_k T_k(x) - \sum_{k=0}^n p_k T_k(x) = \sum_{k=N+1}^{\infty} \gamma_k T_k(x).$$

We will need the following relationship:

$$T_i(x)T_j(x) = \frac{1}{2} [T_{i+j}(x) + T_{|i-j|}(x)].$$

Also, we must compute (usually numerically)

$$a_0 = \frac{1}{\pi} \int_{-1}^1 \frac{f(x)}{\sqrt{1-x^2}} dx \quad \text{and} \quad a_k = \frac{2}{\pi} \int_{-1}^1 \frac{f(x)T_k(x)}{\sqrt{1-x^2}} dx, \quad k \geq 1.$$

### Example: Revisiting $e^{-x}$ with Chebyshev-Padé Approximation 1/5

The 8<sup>th</sup> order Chebyshev-expansion (ALL PRAISE MAPLE) for  $e^{-x}$  is

$$\begin{aligned} P_8^{\text{CT}}(x) &= 1.266065878 T_0(x) - 1.130318208 T_1(x) + 0.2714953396 T_2(x) \\ &\quad - 0.04433684985 T_3(x) + 0.005474240442 T_4(x) \\ &\quad - 0.0005429263119 T_5(x) + 0.00004497732296 T_6(x) \\ &\quad - 0.000003198436462 T_7(x) + 0.0000001992124807 T_8(x) \end{aligned}$$

and using the same strategy — building a matrix and right-hand-side utilizing the coefficients in this expansion, we can solve for the Chebyshev-Padé polynomials of degree  $(n + 2m) \leq 8$ : —

Next slide shows the matrix set-up for the  $r_{3,2}^{\text{CP}}(x)$  approximation.

**Note:** Due to the “folding”,  $T_i(x)T_j(x) = \frac{1}{2} [T_{i+j}(x) + T_{|i-j|}(x)]$ , we need  $n + 2m$  Chebyshev-expansion coefficients. (Burden-Faires do not mention this, but it is “obvious” from algorithm 8.2; Example 2 (p. 519) is broken, – it needs  $\tilde{P}_7(x)$ .)

### Example: Revisiting $e^{-x}$ with Chebyshev-Padé Approximation 2/5

$$\begin{aligned} T_0(x) &: \frac{1}{2} \begin{bmatrix} a_1 q_1 & + & a_2 q_2 & - & 2p_0 & = & 2a_0 \end{bmatrix} \\ T_1(x) &: \frac{1}{2} \begin{bmatrix} (2a_0 + a_2)q_1 & + & (a_1 + a_3)q_2 & - & 2p_1 & = & 2a_1 \end{bmatrix} \\ T_2(x) &: \frac{1}{2} \begin{bmatrix} (a_1 + a_3)q_1 & + & (2a_0 + a_4)q_2 & - & 2p_2 & = & 2a_2 \end{bmatrix} \\ T_3(x) &: \frac{1}{2} \begin{bmatrix} (a_2 + a_4)q_1 & + & (a_1 + a_5)q_2 & - & 2p_3 & = & 2a_3 \end{bmatrix} \\ T_4(x) &: \frac{1}{2} \begin{bmatrix} (a_3 + a_5)q_1 & + & (a_2 + a_6)q_2 & - & 0 & = & 2a_4 \end{bmatrix} \\ T_5(x) &: \frac{1}{2} \begin{bmatrix} (a_4 + a_6)q_1 & + & (a_3 + a_7)q_2 & - & 0 & = & 2a_5 \end{bmatrix} \end{aligned}$$

### Example: Revisiting $e^{-x}$ with Chebyshev-Padé Approximation 3/5

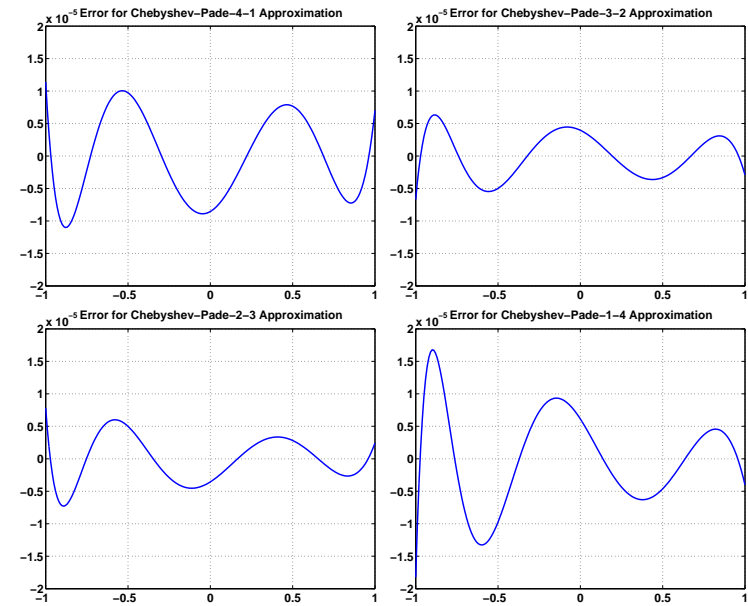
$$R_{4,1}^{\text{CP}}(x) = \frac{1.155054 T_0(x) - 0.8549674 T_1(x) + 0.1561297 T_2(x) - 0.01713502 T_3(x) + 0.001066492 T_4(x)}{T_0(x) + 0.1964246628 T_1(x)}$$

$$R_{3,2}^{\text{CP}}(x) = \frac{1.050531166 T_0(x) - 0.6016362122 T_1(x) + 0.07417897149 T_2(x) - 0.004109558353 T_3(x)}{T_0(x) + 0.3870509565 T_1(x) + 0.02365167312 T_2(x)}$$

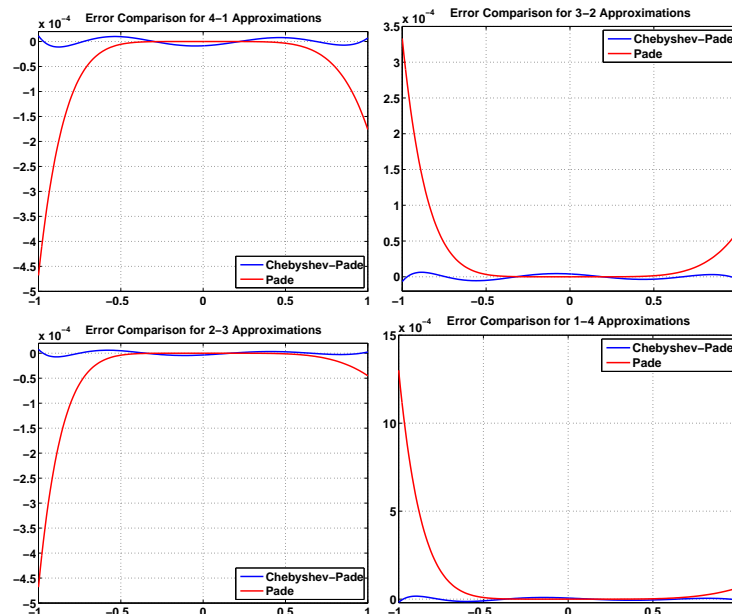
$$R_{2,3}^{\text{CP}}(x) = \frac{0.9541897238 T_0(x) - 0.3737556255 T_1(x) + 0.02331049609 T_2(x)}{T_0(x) + 0.5682932066 T_1(x) + 0.06911746318 T_2(x) + 0.003726440404 T_3(x)}$$

$$R_{1,4}^{\text{CP}}(x) = \frac{0.8671327116 T_0(x) - 0.1731320271 T_1(x)}{T_0(x) + 0.73743710 T_1(x) + 0.13373746 T_2(x) + 0.014470654 T_3(x) + 0.00086486509 T_4(x)}$$

### Example: Revisiting $e^{-x}$ with Chebyshev-Padé Approximation 4/5



### Example: Revisiting $e^{-x}$ with Chebyshev-Padé Approximation 5/5



### The Bad News — It's Not Optimal!

The Chebyshev basis does not give an optimal (in the min-max sense) rational approximation. However, the result can be used as a starting point for [the second Remez algorithm](#). It is an iterative scheme which converges to the best approximation.

A discussion of how and why (and why not) you may want to use the second Remez' algorithm can be found in [Numerical Recipes in C: The Art of Scientific Computing](#) (Section 5.13). [You can read it for free on the web — just Google for it!]