

CS 450: Numerical Analysis¹

Interpolation

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¹*These slides have been drafted by Edgar Solomonik as lecture templates and supplementary material for the book “Scientific Computing: An Introductory Survey” by Michael T. Heath ([slides](#)).*

Interpolation

- ▶ Given $(t_1, y_1), \dots, (t_m, y_m)$ with *nodes* $t_1 < \dots < t_m$ an *interpolant* f satisfies:

$$f(t_i) = y_i \quad \forall i.$$

- ▶ *The number of possible interpolant functions is infinite, but there is a unique degree $m - 1$ polynomial interpolant.*
- ▶ *Error of interpolant can be quantified with knowledge of true function g , (e.g. by considering $\max_{t \in [t_1, t_m]} |f(t) - g(t)|$).*
- ▶ Interpolant is usually constructed as linear combinations of *basis functions* $\{\phi_j\}_{j=1}^n = \phi_1, \dots, \phi_n$ so $f(t) = \sum_j x_j \phi_j(t)$.
 - ▶ *Interpolant exists if $n \geq m$ and is unique for a given basis if $n = m$.*
 - ▶ *Vandermonde matrix $\mathbf{A} = \mathbf{V}(t, \{\phi_j\}_{j=1}^n)$ satisfies $a_{ij} = \phi_j(t_i)$ so $\mathbf{A}\mathbf{x} = \mathbf{y}$.*
 - ▶ *Coefficients x of interpolant are obtained by solving Vandermonde system $\mathbf{A}\mathbf{x} = \mathbf{y}$ for x .*

Polynomial Interpolation

- ▶ The choice of *monomials* as basis functions, $\phi_j(t) = t^{j-1}$ yields a degree $n - 1$ polynomial interpolant:
 - ▶ Corresponding Vandermonde matrix $\mathbf{A} = \mathbf{V}(t, \{t^{j-1}\}_{j=1}^n)$ satisfies $a_{ij} = t_i^{j-1}$.
- ▶ Polynomial interpolants are easy to evaluate and do calculus on:
 - ▶ *Horner's rule* requires n products and $n - 1$ additions:

$$f(t) = x_1 + t(x_2 + t(x_3 + \dots)).$$

- ▶ $O(n)$ work to determine new coefficients for differentiation and integration.

Conditioning of Interpolation

- ▶ Conditioning of interpolation matrix \mathbf{A} depends on basis functions and coordinates t_1, \dots, t_m :
 - ▶ t_i defines the i th column, so columns tend to be nearly linearly-dependent if $t_i \approx t_{i+1}$
 - ▶ ϕ_j defines the j th row, so rows tend to be nearly linearly-dependent if ϕ_j is nearly in the span of the other basis functions: $\text{span}(\{\phi_i\}_{i=1, i \neq j}^n)$
- ▶ The Vandermonde matrix tends to be ill-conditioned:
 - ▶ Monomials of increasing degree increasingly resemble one-another, so rows of \mathbf{A} become nearly the same, and consequently $\kappa(\mathbf{A})$ grows.
 - ▶ The conditioning can be improved somewhat by shifting and scaling points so that each $t_i \in [-1, 1]$.
 - ▶ Consequently, we will consider alternative polynomial bases, seeking to improve the efficiency and conditioning associated with the Vandermonde matrix.
 - ▶ However, generally, we will obtain the same polynomial interpolant. To improve interpolant quality (e.g. avoid oscillations), the nodes and not the basis functions need to be changed.

Lagrange Basis

- ▶ n -points fully define the unique $(n - 1)$ -degree polynomial interpolant in the *Lagrange basis*:

$$\phi_j(t) = \underbrace{\prod_{k=1, k \neq j}^n (t - t_k)}_{\mathbf{num}} / \underbrace{\prod_{k=1, k \neq j}^n (t_j - t_k)}_{\mathbf{den}}$$

- ▶ Note that **den** is never 0,
 - ▶ **num** is 0 whenever $t = t_k$ for some k , so $\phi_j(t_i) = 0$ if $i \neq j$,
 - ▶ when $t = t_j$ then **num** and **den** are the same, so $\phi_j(t_j) = 1$,
 - ▶ consequently, the Lagrange Vandermonde matrix $\mathbf{V}(t, \{\phi_j\}_{j=1}^n) = \mathbf{I}$.
- ▶ Lagrange polynomials yield an ideal Vandermonde system, but the basis functions are hard to evaluate and do calculus on:
 - ▶ Evaluation requires $O(n^2)$ work naively and may incur cancellation error.
 - ▶ Differentiation and integration are also harder than with monomials.

Newton Basis

- ▶ The *Newton basis* functions $\phi_j(t) = \prod_{k=1}^{j-1} (t - t_k)$ with $\phi_1(t) = 1$ seek the best of monomial and Lagrange bases:

- ▶ *Evaluation with Newton basis can use recurrence,*

$$\phi_j(t) = \phi_{j-1}(t)(t - t_j).$$

- ▶ *Divided difference recurrence enables fast computation of coefficients.*

- ▶ The Newton basis yields a triangular Vandermonde system:

- ▶ *Note that $a_{ij} = \phi_j(t_i) = 0$ for all $i < j$, so \mathbf{A} is lower-triangular.*
- ▶ *Given \mathbf{A} , can use back-substitution to obtain the solution in $O(n^2)$ work.*
- ▶ *Can use evaluation recurrence to compute \mathbf{A} with $O(n^2)$ work, but divided difference recurrence is more stable than forming \mathbf{A} .*

Orthogonal Polynomials

- ▶ Recall that good conditioning for interpolation is achieved by constructing a well-conditioned Vandermonde matrix, which is the case when the columns (corresponding to each basis function) are orthonormal. To construct robust basis sets, we introduce a notion of *orthonormal functions*:

- ▶ *To compute overlap between basis functions, use a w -weighted integral as inner product,*

$$\langle p, q \rangle_w = \int_{-\infty}^{\infty} p(t)q(t)w(t)dt.$$

- ▶ *$\{\phi_i\}_{i=1}^n$ are orthonormal with respect to the above inner product if*

$$\langle \phi_i, \phi_j \rangle_w = \delta_{ij} = \begin{cases} 1 & \text{if } i = j \\ 0 & \text{otherwise} \end{cases}.$$

- ▶ *The corresponding norm is given by $\|f\| = \sqrt{\langle f, f \rangle_w}$.*

Legendre Polynomials

- ▶ The Gram-Schmidt orthogonalization procedure can be used to obtain an orthonormal basis with the same span as any given arbitrary basis:

Given orthonormal functions $\{\hat{\phi}_i\}_{i=1}^{k-1}$ obtain k th function from ϕ_k via

$$\hat{\phi}_k(t) = \frac{\hat{\psi}_k(t)}{\|\hat{\psi}_k\|}, \quad \psi_k(t) = \phi_k(t) - \sum_{i=1}^{k-1} \langle \phi_k(t), \hat{\phi}_i(t) \rangle_w \hat{\phi}_i(t)$$

- ▶ The *Legendre polynomials* are obtained by Gram-Schmidt on the monomial basis, with $w(t) = \begin{cases} 1 : -1 \leq t \leq 1 \\ 0 : \text{otherwise} \end{cases}$ and normalized so $\hat{\phi}_i(1) = 1$.

For example, $\{\hat{\phi}_i(t)\}_{i=1}^3 = \{1, t, (3t^2 - 1)/2\}$ since

$$\psi_1(t) = 1, \quad \psi_2(t) = t - \frac{1}{2} \int_{-1}^1 t dt = t$$

$$\psi_3(t) = t^2 - \frac{1}{2} \int_{-1}^1 t^2 dt - t \int_{-1}^1 t^3 dt = t^2 - 1/3$$

Chebyshev Basis

Demo: Chebyshev interpolation
Activity: Chebyshev Interpolation

- ▶ **Chebyshev polynomials** $\phi_j(t) = \cos((j - 1) \arccos(t))$ and **Chebyshev nodes** $t_i = \cos\left(\frac{2i-1}{2n}\pi\right)$ provide a way to pick **nodes** t_1, \dots, t_n along with a basis, to yield perfect conditioning:
 - ▶ They satisfy the recurrence $\phi_1(t) = 1, \phi_2(t) = t, \phi_{i+1}(t) = 2t\phi_i(t) - \phi_{i-1}(t)$
 - ▶ The Chebyshev basis functions are orthonormal with respect to

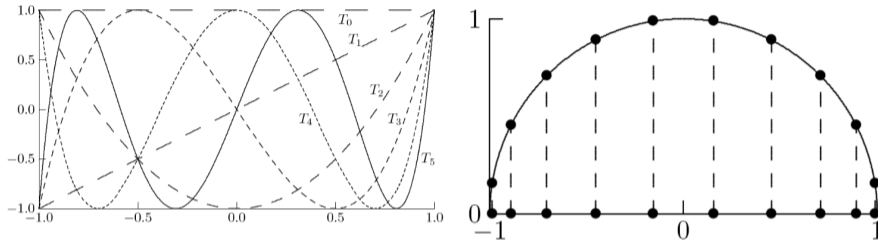
$$w(t) = \begin{cases} 1/(1-t^2)^{1/2} & : -1 \leq t \leq 1 \\ 0 & : \text{otherwise} \end{cases}.$$

- ▶ The Chebyshev nodes ensure orthogonality of the columns of \mathbf{A} , since

$$\sum_{k=1}^n \phi_l(t_k) \phi_j(t_k) = \sum_{k=1}^n \cos\left(\frac{(l-1)(2k-1)}{2n}\pi\right) \cos\left(\frac{(j-1)(2k-1)}{2n}\pi\right)$$

is zero whenever $j \neq l$ due to periodicity of the summands.

Chebyshev Nodes Intuition



- ▶ Note *equi-oscillation* property, successive extrema of $T_k = \phi_k$ have the same magnitude but opposite sign.
- ▶ Set of k Chebyshev nodes are given by zeros of T_k and are abscissas of points uniformly spaced on the unit circle.

Error in Interpolation

We show by induction that given degree n polynomial interpolant \tilde{f} of f the error $E(t) = f(t) - \tilde{f}(t)$ has n zeros t_1, \dots, t_n and there exist y_1, \dots, y_n so

$$E(t) = \int_{t_1}^t \int_{y_1}^{w_0} \cdots \int_{y_n}^{w_{n-1}} f^{(n+1)}(w_n) dw_n \cdots dw_0 \quad (1)$$

$$E(t) = E(t_1) + \int_{t_1}^t E'(w_0) dw_0 \quad (2)$$

Now note that for each of $n - 1$ consecutive pairs t_i, t_{i+1} we have

$$\int_{t_i}^{t_{i+1}} E'(t) dt = E(t_{i+1}) - E(t_i) = 0$$

and so there are $n - 1$ zeros $z_i \in (t_i, t_{i+1})$ such that $E'(z_i) = 0$.

The inductive hypothesis on E' then gives

$$E'(w_0) = \int_{z_1}^{w_0} \int_{y_2}^{w_1} \cdots \int_{y_n}^{w_{n-1}} f^{(n+1)}(w_n) dw_n \cdots dw_1 \quad (3)$$

Substituting (3) into (2), we obtain (1) with $y_1 = z_1$.

Interpolation Error Bounds

- ▶ Consequently, polynomial interpolation satisfies the following error bound:

$$|E(t)| \leq \frac{\max_{s \in [t_1, t_n]} |f^{(n+1)}(s)|}{n!} \prod_{i=1}^n (t - t_i) \quad \text{for } t \in [t_1, t_n]$$

Note that the Choice of Chebyshev nodes decreases this error bound at the extrema, equalizing it with nodes that are in the middle of the interval.

- ▶ Letting $h = t_n - t_1$ (often also achieve same for h as the node-spacing $t_{i+1} - t_i$), we obtain

$$|E(t)| \leq \frac{\max_{s \in [t_1, t_n]} |f^{(n+1)}(s)|}{n!} h^n = O(h^n) \quad \text{for } t \in [t_1, t_n]$$

Suggests that higher-accuracy can be achieved by

- ▶ *adding more nodes (however, high polynomial degree can lead to unwanted oscillations)*
- ▶ *shrinking interpolation interval (suggests piecewise interpolation)*

Piecewise Polynomial Interpolation

- ▶ The k th piece of the interpolant is typically chosen as polynomial on $[t_i, t_{i+1}]$
 - ▶ Typically low-degree polynomial pieces used, e.g. cubic.
 - ▶ Degree of piecewise polynomial is the degree of its pieces.
 - ▶ Continuity is automatic, differentiability can be enforced by ensuring derivative of pieces is equal at knots (nodes at which pieces meet).

$$f(t) = \begin{cases} t \in [t_1, t_2] & : f_1(t) \\ & \vdots \\ t \in [t_{n-1}, t_n] & : f_{n-1}(t) \end{cases}, \forall i \in [2, n-1], f_{i-1}(t_i) = f_i(t_i) = y_i$$

- ▶ **Hermite** interpolation ensures consecutive interpolant pieces have same derivative at each **knot** t_i :
 - ▶ Hermite interpolation ensures differentiability of the interpolant
 $\forall i \in [2, n-1], f'_{i-1}(t_i) = f'_i(t_i)$
 - ▶ Various further constraints can be placed on the interpolant if its degree is at least 3, since otherwise the system is underdetermined.

Spline Interpolation

- ▶ A *spline* is a $(k - 1)$ -time differentiable piecewise polynomial of degree k :
Cubic splines are different from Hermite cubics
 - ▶ $2(n - 1)$ equations needed to interpolate data
 - ▶ $n - 2$ to ensure continuity of derivative
 - ▶ $n - 2$ to ensure continuity of second derivative for cubic splines

Overall there are $4(n - 1)$ coefficients in the interpolant.

- ▶ The resulting interpolant coefficients are again determined by an appropriate *generalized Vandermonde system*:

A natural spline obtains $4(n - 1)$ constraints by forcing $f''(t_1) = f''(t_n) = 0$. Given cubic pieces $p(t)$ and $q(t)$ and nodes t_1, t_2, t_3 (where t_2 is a knot) the generalized Vandermonde system for a two-piece cubic natural spline consists of 8 equations with 8 unknowns:

$$\begin{aligned} p(t_1) &= y_1, & p''(t_1) &= 0 \\ p(t_2) &= y_2, & q(t_2) &= y_2, & p'(t_2) &= q'(t_2), & p''(t_2) &= q''(t_2) \\ q(t_3) &= y_3, & q''(t_3) &= 0 \end{aligned}$$

B-Splines

B-splines provide an effective way of constructing splines from a basis:

- ▶ The basis functions can be defined recursively with respect to degree:

$$v_i^k(t) = \frac{t - t_i}{t_{i+k} - t_i}, \quad \phi_i^0(t) = \begin{cases} 1 & t_i \leq t \leq t_{i+1} \\ 0 & \text{otherwise} \end{cases}$$
$$\phi_i^k(t) = v_i^k(t)\phi_i^{k-1}(t) + (1 - v_{i+1}^k(t))\phi_{i+1}^{k-1}(t), \quad f(t) = \sum_{i=1}^n c_i \phi_i^k(t)$$

- ▶ ϕ_i^1 is a linear hat function that increases from 0 to 1 on $[t_i, t_{i+1}]$ and decreases from 1 to 0 on $[t_{i+1}, t_{i+2}]$.
- ▶ ϕ_i^k is positive on $[t_i, t_{i+k+1}]$ and zero elsewhere.
- ▶ The B-spline basis spans all possible splines of degree k with nodes $\{t_i\}_{i=1}^n$.
- ▶ The B-spline basis coefficients are determined by a Vandermonde system that is lower-triangular and banded (has k subdiagonals), and need not contain differentiability constraints, since $f(t)$ is a sum of ϕ_i^k s.