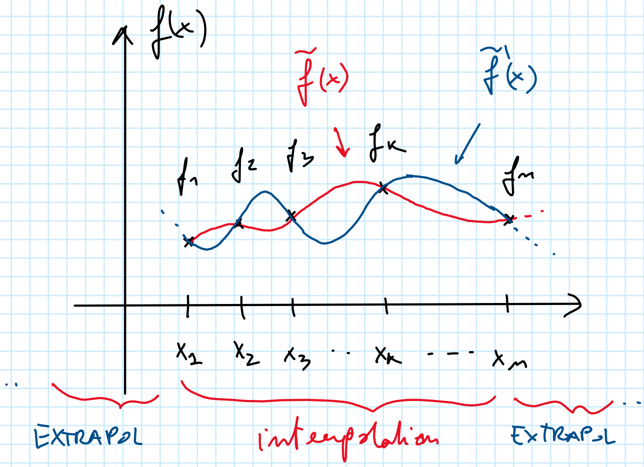
Interpolation

Def given $f(x)$, known only at certaint points $x_1, x_2, \dots, x_n$ (DATA POINTS)

$f(x_1) = f_1,\ f(x_2) = f_2, \dots f(x_k) = f_k \dots$

interpolation is the process of constructing $\tilde{f}(x)$ such that.

$$\underbrace{\tilde{f}(x_k)}_{\text{DATA POINT}} = \underbrace{f_k}_{f(x_k)}, \quad \forall\ k = 1, \dots, n \quad (1)$$



$\Rightarrow$ $\tilde{f}(x)$ can be used to ESTIMATE $f(x)$ $\forall \in [x_1, \dots x_n]$

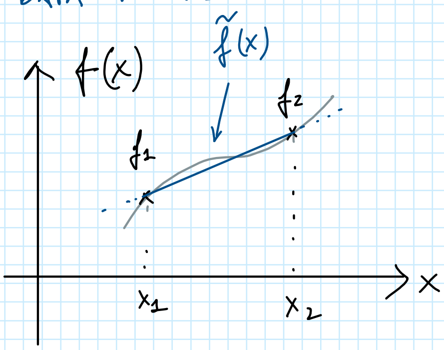
NOTE: $\tilde{f}(x)$ is not UNIQUE $\rightarrow$ ∞ of $\tilde{f}(x)$ that satisfy the CONDITION (1)

for UNIQUENESS $\Rightarrow$ RESTRICTION of $\tilde{f}(x)$

Polynomial interpolation

- restrict $\tilde{f}(x)$ polynomial of degree $n-1$ (n - DATA POINTS)

2 DATA POINTS



$$\tilde{f}(x) = \underbrace{a_0 + a_1 x}_{\text{coefficients}} \leftarrow \text{Polynomial of order 1}$$

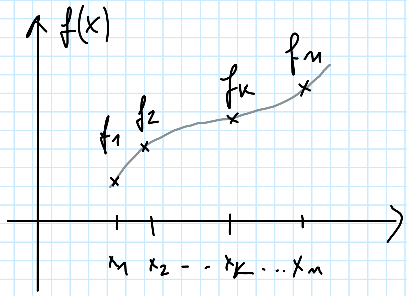
$\Downarrow$

"find a_0 and a_1 such that".

$$\begin{cases} \tilde{f}(x_1) = a_0 + a_1 x_1 = f_1 \\ \tilde{f}(x_2) = a_0 + a_1 x_2 = f_2 \end{cases}$$

n DATA POINTS

n DATA POINTS



$$\tilde{f}(x) = a_0 + a_1 x + a_2 x^2 + a_3 x^3 + \cdots + a_{n-1} x^{n-1}$$

"find $a_0, a_1, \ldots, a_{n-1}$ such that:"

$$\begin{cases} \tilde{f}(x_1) = a_0 + a_1 x_1 + a_2 x_1^2 + \cdots + a_{n-1} x_1^{n-1} = f_1 \\ \tilde{f}(x_2) = a_0 + a_1 x_2 + a_2 x_2^2 + \cdots + a_{n-1} x_2^{n-1} = f_2 \\ \vdots \\ \tilde{f}(x_n) = a_0 + a_1 x_n + a_2 x_n^2 + \cdots + a_{n-1} x_n^{n-1} = f_n \end{cases}$$

matrix form:

$$\underbrace{\begin{bmatrix} 1 & x_1 & x_1^2 & \cdots & x_1^{n-1} \\ 1 & x_2 & x_2^2 & \cdots & x_2^{n-1} \\ & & \vdots & & \\ 1 & x_n & x_n^2 & \cdots & x_n^{n-1} \end{bmatrix}}_{[V]} \begin{bmatrix} a_0 \\ a_1 \\ \vdots \\ a_{n-1} \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{bmatrix}$$

$[V]$ VANDERMONDE MATRIX

$\Rightarrow$ Solve $[V]\{a\} = \{f\}$ $\Rightarrow$ find $[V^{-1}]$ inverse of $[V]$

$$\underbrace{[V^{-1}][V]}_{[I_d]}\{a\} = [V^{-1}]\{f\}$$

$$\begin{bmatrix} 1 & & 0 \\ & 1 & \\ 0 & & \ddots\ 1 \end{bmatrix} \rightarrow \underbrace{[I_d]\{a\}}_{\{a\}}$$

$$\{f\} = \begin{Bmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{Bmatrix}$$

$$\{a\} = [V^{-1}]\{f\}$$

$[V]$ is invertible if $\operatorname{Det}[V] \neq 0$ $\Rightarrow$ $[V]$ is linearly independent. ✓

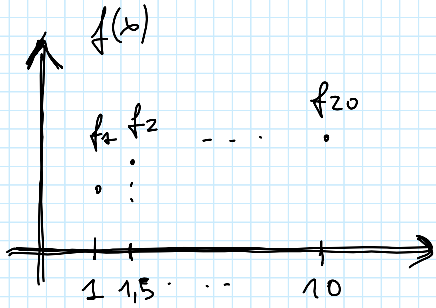
. numerically .

numerically.

$[V]$ often ILL-CONDITIONED matrix

EXAMPLE: $f(x) \rightarrow \tilde{f}(x)$

$n = 20$
$x_1 = 1$
$x_{20} = 10$



$$[V] = \begin{bmatrix} 1 & 1 & 1^2 & \cdots & 1^{19} \\ 1 & 1{,}5 & 1{,}5^2 & \cdots & 1{,}5^{19} \\ \vdots & & & & \vdots \\ 1 & 10 & 10^2 & \cdots & 10^{19} \end{bmatrix}$$

V_k: k-th entry of $[V]$

$$\frac{\min(V_k)}{\max(V_k)} = \frac{1}{10^{19}} = 10^{-19}$$

$\varepsilon \sim 2{,}2 \; 10^{-16}$

$\Rightarrow$ first rows are "AS IF" they were ZERO

$\Downarrow$

MATRIX is "numerically" SINGULAR

κ

CONDITION number (of a matrix)

unified measure of the sensitivity of the solution of $[A]\{x\}=\{b\}$ to SMALL PERTURBATIONS in $[A]$ or $\{b\}$

internal perturbations (roundoff errors)

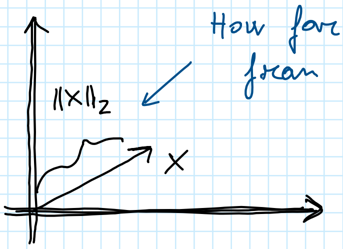
external perturbations

ILL-conditioned linear system
HUGE VARIATIONS in $\{x\}$ for small variations in $\{b\}$

Def: $\kappa([A]) = \|A\|_2 \, \|A^{-1}\|_2$

2-NORM (EUCLIDEAN NORM) of a VECTOR

$$\|x\|_2 = \sqrt{\sum_{k=1}^{n} x_k^2}$$

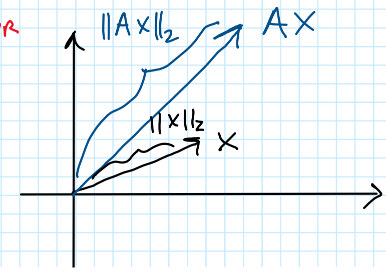


How far $\{x\}$ extends from origin

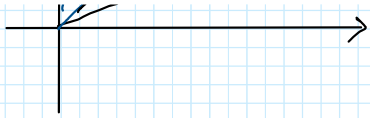
2-NORM of a matrix

Ax = VECTOR

$$\|A\|_2 = \max \left(\underbrace{\frac{\|Ax\|_2}{\|x\|_2}}_{} \right) = M$$

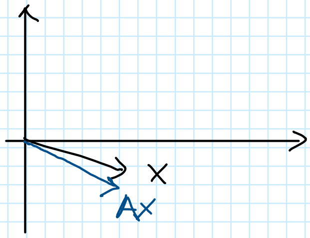


$$\left(\|x\|_2 \right)$$



STRETCHING of x induced by A

$$\frac{1}{\|A^{-1}\|_2} = \min \left(\frac{\|Ax\|_2}{\|x\|_2} \right) = m$$



$$K = \underbrace{\|A\|_2}_{M} \cdot \underbrace{\|A^{-1}\|_2}_{1/m} = \frac{M}{m}$$

M ← maximum stretching of x induced by $[A]$

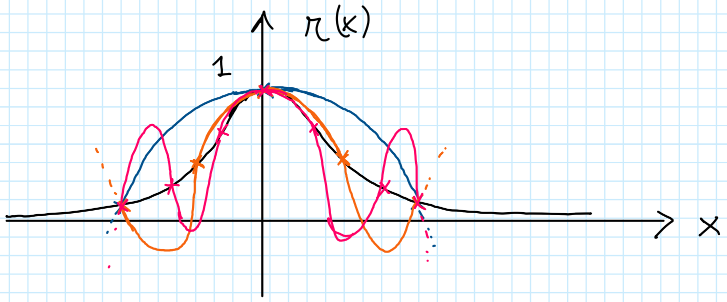
m ← MINIMUM " " " " "

if $K \sim 1$ ⇒ System is STABLE with respect to perturbations ⇒ WELL-COND.

$K \gg 1$ ⇒ " " UNSTABLE " " " " ⇒ ILL-COND

Polynomial interpolation is OSCILLATORY

Ex. RUNGE function $r(x) = \dfrac{1}{1+\alpha x^2}$, $\alpha = 25$



Polynomial interp

# points	Degree
$m = 3$	2
$m = 5$	4
$m = 7$	6

if we increase the polynomial order ⇒ larger oscillations near the boundaries of the sampling interval

PIECEWISE LINEAR INTERPOLATION (1D)

IDEA: construct an interpolating function $\tilde{f}(x)$ in $[a,b]$ from a SET of PIECEWISE-LINEAR POLYNOMIALS

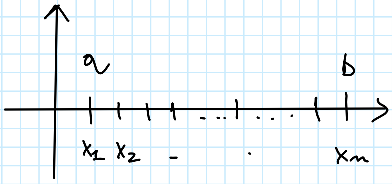
"HAT" FUNCTIONS (BASIS FUNCTIONS)

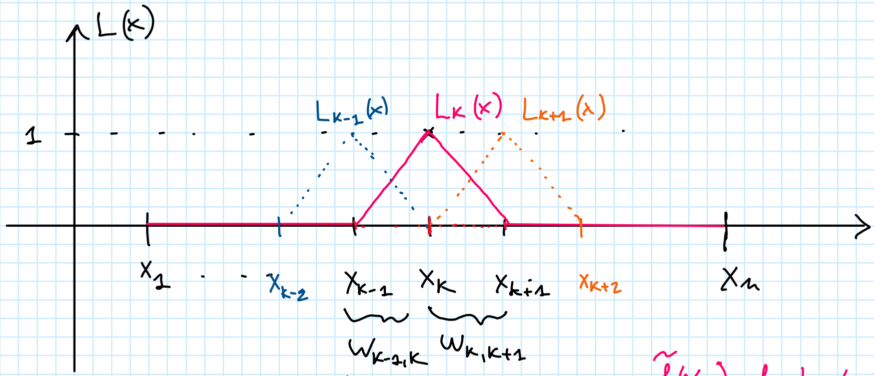
$$\tilde{f}(x) = L_1(x) f_1 + L_2(x) f_2 + \dots + L_K(x) f_K + \dots L_n(x) f_n$$

each polynomial is $\neq 0$ only on a

each polynomial is $\neq 0$ only on a SUBSET of $[a,b]$

STRATEGY: introduce set of n-points (nodes) to subdivide $[a,b]$ $n-1$ ELEMENTS (INTERVALS)





$W_{k-1,k}$ $W_{k,k+1}$

SUPPORT DOMAIN of node k Ω_k

$$\tilde{f}(x_k) = f_k \underbrace{L_k(x_k)}_{=1} + \underbrace{\cancel{f_{k+1} L_{k+1}(x_k)}}_{\text{must be } = 0 \text{ to have } \tilde{f}(x_k) = f_k}$$

$W_{k,k+1} = [x_k, x_{k+1}]$

$W_{k-1,k} = [x_{k-1}, x_k]$

$\Omega_k = W_{k-1,k} \cup W_{k,k+1}$

REQUIREMENTS:

$$\begin{cases} L_k(x_k) = 1 \\ L_k(x) = 0, \ \forall x \notin \Omega_k \\ L_k(x) \ \text{lineare} \end{cases}$$