# Sampling and approximation theory

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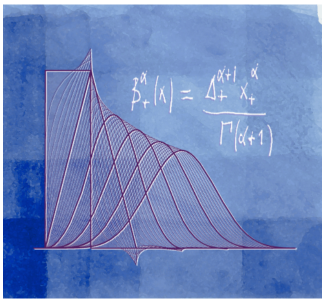
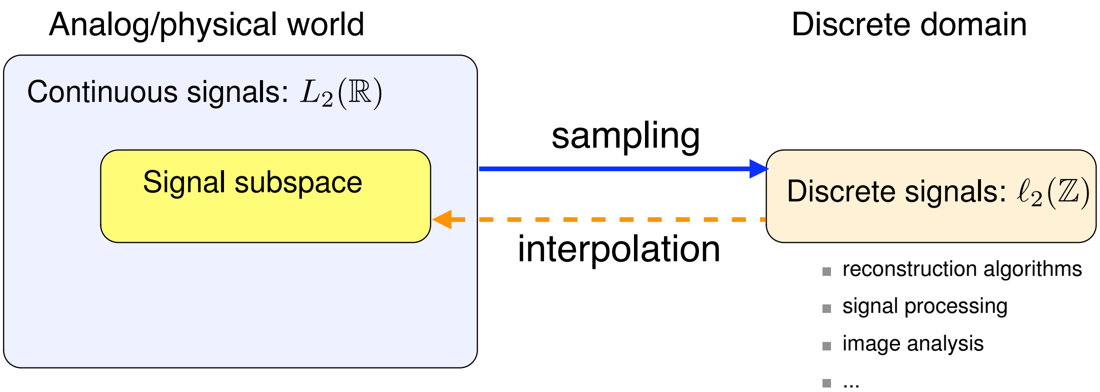



Tutorial, Inzell Summer School, September 2007

## SAMPLING: 50+ years after Shannon

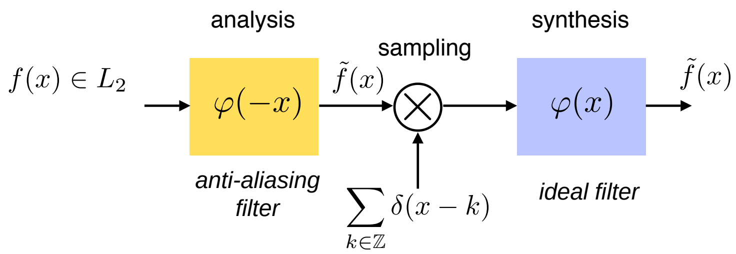



- Introduction: Shannon revisited
- Sampling preliminaries
- Sampling revisited
- Quantitative approximation theory

Review paper on sampling

# Shannon's sampling reinterpreted

- Generating function: $\varphi(x) = \mathrm{sinc}(x)$
- Subspace of bandlimited functions: $V(\varphi) = \mathrm{span}\{\varphi(x-k)\}_{k\in\mathbb{Z}}$



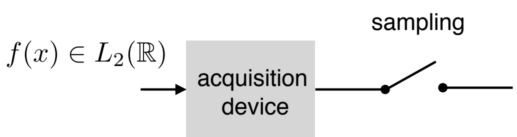

- Analysis: $\tilde{f}(k) = \langle \mathrm{sinc}(x-k), f(x)\rangle$
- Synthesis: $\tilde{f}(x) = \sum_{k\in Z} \tilde{f}(k)\,\mathrm{sinc}(x-k)$
- Orthogonal basis: $\langle \mathrm{sinc}(x-k), \mathrm{sinc}(x-l)\rangle = \delta_{k-l}$ [Hardy, 1941]

⇨ Orthogonal projection operator !



# Generalized sampling: roadmap

- Nonideal acquisition system




Measurements:

$$g[k] = (h * f)(x)|_{x=k}$$

⇩

Reconstruction algorithm

⇩

signal coefficients

$\{c[k]\}_{k\in\mathbb{Z}}$

**Goal**: Specify $\varphi$ and the reconstruction algorithm so that $\tilde{f}(x)$ is a good approximation of $f(x)$

Continuous-domain model

$$\tilde{f}(x) = \sum_{k\in\mathbb{Z}} c[k]\varphi(x-k)$$

⟺ *Riesz-basis property*

⇕ *Interpolation problem*

Discrete signal

$\{f[k]\}_{k\in\mathbb{Z}}$

## SAMPLING PRELIMINARIES

- Function and sequence spaces
- Smoothness conditions and sampling
- Shift-invariant subspaces
- Equivalent basis functions



## Continuous-domain signals

Mathematical representation: a function of the continuous variable $x \in \mathbb{R}$

- Lebesgue's space of finite-energy functions
  - $L_2(\mathbb{R}) = \left\{ f(x), x \in \mathbb{R} : \int_{x\in\mathbb{R}} |f(x)|^2 \mathrm{d}x < +\infty \right\}$
  - $L_2$-inner product: $\langle f, g \rangle = \int_{x\in\mathbb{R}} f(x) g^*(x) \mathrm{d}x$
  - $L_2$-norm: $\|f\|_{L_2} = \left( \int_{x\in\mathbb{R}} |f(x)|^2 \mathrm{d}x \right)^{1/2} = \sqrt{\langle f, f \rangle}$
- Fourier transform
  - Integral definition: $\hat{f}(\omega) = \int_{x\in\mathbb{R}} f(x) e^{-j\omega x} \mathrm{d}x$
  - Parseval relation: $\|f\|_{L_2}^2 = \frac{1}{2\pi} \int_{\omega\in\mathbb{R}} |\hat{f}(\omega)|^2 \mathrm{d}\omega$

# Discrete-domain signals

Mathematical representation: a sequence indexed by the discrete variable $k \in \mathbb{Z}$

- Space of finite-energy sequences
  - $\ell_2(\mathbb{Z}) = \left\{ a[k], k \in \mathbb{Z} : \sum_{k\in\mathbb{Z}} |a[k]|^2 < +\infty \right\}$
  - $\ell_2$-norm: $\|a\|_{\ell_2} = \left( \sum_{k\in\mathbb{Z}} |a[k]|^2 \right)^{1/2}$

- Discrete-time Fourier transform
  - $z$-transform: $A(z) = \sum_{k\in\mathbb{Z}} a[k] z^{-k}$
  - Fourier transform: $A(e^{j\omega}) = \sum_{k\in\mathbb{Z}} a[k] e^{-j\omega k}$



# Smoothness conditions and sampling

- Sobolev's space of order $s \in \mathbb{R}^+$

  $$W_2^s(\mathbb{R}) = \left\{ f(x), x \in \mathbb{R} : \int_{\omega\in\mathbb{R}} (1 + |\omega|^{2s}) |\hat{f}(\omega)|^2 \mathrm{d}\omega < +\infty \right\}$$

  $f$ and all its derivatives up to (fractional) order $s$ are in $L_2$

- Mathematical requirements for ideal sampling
  - The input signal $f(x)$ should be continuous
  - The samples $f[k] = f(x)|_{x=k}$ should be in $\ell_2$

**Theorem**
Let $f(x) \in W_2^s$ with $s > \frac{1}{2}$. Then, the samples of $f$ at the integers, $f[k] = f(x)|_{x=k}$, are in $\ell_2$ and

$$F(e^{j\omega}) = \sum_{k\in\mathbb{Z}} f[k] e^{-j\omega k} = \sum_{n\in\mathbb{Z}} \hat{f}(\omega + 2\pi n) \qquad \text{a.e.}$$

Generalized (*almost everywhere*) version of Poisson's formula [Blu-U., 1999]

# Shift-invariant spaces

Integer-shift-invariant subspace associated with a generating function $\varphi$ (e.g., B-spline):

$$V(\varphi) = \left\{ f(x) = \sum_{k\in\mathbb{Z}} c[k]\varphi(x-k) : c \in \ell_2(\mathbb{Z}) \right\}$$

Generating function: $\varphi(x) \quad \stackrel{\mathcal{F}}{\longleftrightarrow} \quad \hat{\varphi}(\omega) = \int_{x\in\mathbb{R}} \varphi(x) e^{-j\omega x} \mathrm{d}x$

- Autocorrelation (or Gram) sequence

$$a_\varphi[k] \triangleq \langle \varphi(\cdot), \varphi(\cdot - k)\rangle \quad \stackrel{\mathcal{F}}{\longleftrightarrow} \quad A_\varphi(e^{j\omega}) = \sum_{n\in\mathbb{Z}} |\hat{\varphi}(\omega + 2\pi n)|^2$$

- Riesz-basis condition

Positive-definite Gram sequence: $0 < A^2 \leq A_\varphi(e^{j\omega}) \leq B^2 < +\infty$

$$\Updownarrow$$

$$A \cdot \|c\|_{\ell_2} \leq \underbrace{\left\| \textstyle\sum_{k\in\mathbb{Z}} c[k]\varphi(x-k) \right\|_{L_2}}_{\|f\|_{L_2}} \leq B \cdot \|c\|_{\ell_2}$$

Orthonormal basis $\Leftrightarrow$ $a_\varphi[k] = \delta_k$ $\Leftrightarrow$ $A_\varphi(e^{j\omega}) = 1$ $\Leftrightarrow$ $\|c\|_{\ell_2} = \|f\|_{L_2}$ (Parseval)



# Example of sampling spaces

- Piecewise-constant functions

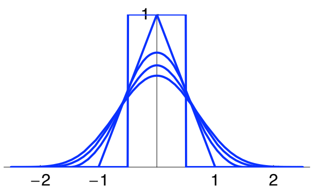
$\varphi(x) = \mathrm{rect}(x) = \beta^0(x)$ $\qquad a_\varphi[k] = \delta_k \quad \Leftrightarrow$ the basis is orthonormal

- bandlimited functions

$\varphi(x) = \mathrm{sinc}(x)$ $\qquad \sum_{n\in\mathbb{Z}} |\hat{\varphi}(\omega + 2\pi n)|^2 = 1 \quad \Leftrightarrow$ the basis is orthonormal

- Polynomial splines of degree $n$

$$\varphi(x) = \beta^n(x) = (\underbrace{\beta^0 * \beta^0 \cdots * \beta^0}_{(n+1)\text{ times}})(x)$$




Autocorrelation sequence: $a_{\beta^n}[k] = (\beta^n * \beta^n)(x)|_{x=k} = \beta^{2n+1}(k)$

**Proposition**. The B-spline of degree $n$, $\beta^n(x)$, generates a Riesz basis with lower and upper Riesz bounds $A = \inf_\omega\{A_{\beta^n}(e^{j\omega})\} \geq \left(\frac{2}{\pi}\right)^{n+1}$ and $B = \sup_\omega\{A_{\beta^n}(e^{j\omega})\} = 1$.

# Equivalent and dual basis functions

- Equivalent basis functions: $\varphi_{\mathrm{eq}}(x) = \sum_{k \in \mathbb{Z}} p[k]\varphi(x-k)$

**Proposition.** Let $\varphi$ be a valid (Riesz) generator of $V(\varphi) = \mathrm{span}\{\varphi(x-k)\}_{k\in\mathbb{Z}}$.
Then, $\varphi_{\mathrm{eq}}$ also generates a Riesz basis of $V(\varphi)$ iff.

$$0 < C_1 \leq |P(e^{j\omega})|^2 \leq C_2 < +\infty \qquad \text{(almost everywhere)}$$

- Dual basis function

Unique function $\mathring{\varphi} \in V(\varphi)$ such that $\langle \varphi(x), \mathring{\varphi}(x-k)\rangle = \delta_k$ (biorthogonality)

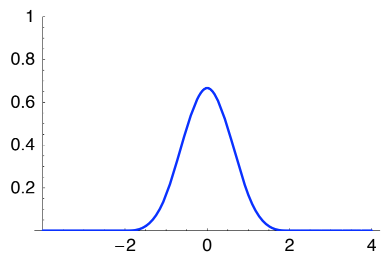
Together, $\varphi$ and $\mathring{\varphi}$ operate as if they were an orthogonal basis; i.e., the orthogonal projector of any function $f \in L_2$ onto $V(\varphi)$ is given by

$$\mathrm{P}_{V(\varphi)} f(x) = \sum_{k\in\mathbb{Z}} \underbrace{\langle f, \mathring{\varphi}(\cdot - k)\rangle}_{c[k]} \varphi(x-k)$$



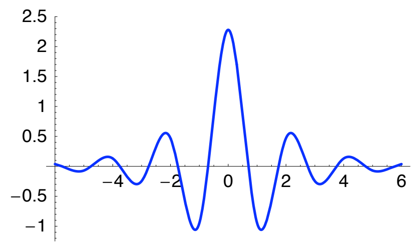
# Example: four equivalent cubic-spline bases

- Cubic B-spline: $\varphi(x) = \beta^3(x)$



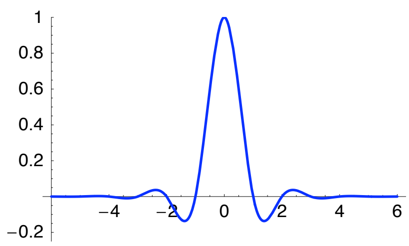

Compact support

- Dual spline: $\mathring{\varphi}(x)$



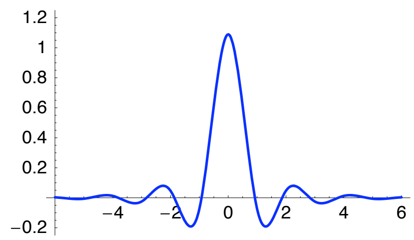

Biorthogonality: $\langle \varphi(x), \mathring{\varphi}(x-k)\rangle = \delta_k$

- Interpolating spline: $\varphi_{\mathrm{int}}(x)$




Interpolation: $\langle \varphi_{\mathrm{int}}(x), \delta(x-k)\rangle = \delta_k$

- Orthogonal spline: $\varphi_{\mathrm{ortho}}(x)$



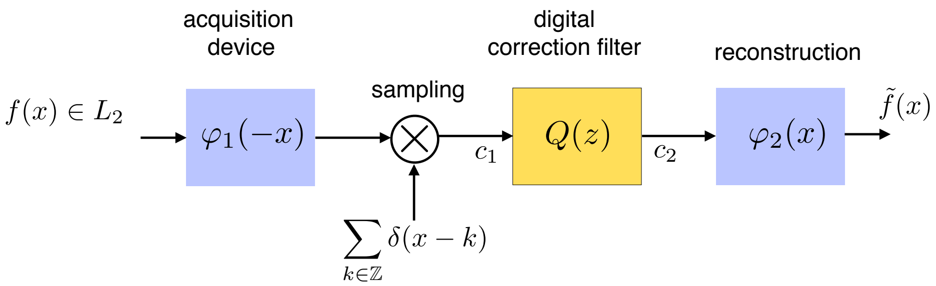

Orthogonality: $\langle \varphi_{\mathrm{ortho}}(x), \varphi_{\mathrm{ortho}}(x-k)\rangle = \delta_k$

# SAMPLING REVISITED

- Generalized sampling system
- Generalized sampling theorem
- Consistent sampling: properties
- Performance analysis
- Applications



# Generalized sampling system




- $\varphi_1(-x)$: prefilter (acquisition system)
- $\varphi_2(x)$: generating function (reconstruction subspace)

- Constraints
  - Consistent measurements: $\langle \tilde{f}, \varphi_1(\cdot - k)\rangle = c_1[k] = \langle f, \varphi_1(\cdot - k)\rangle, \ \ \forall k \in \mathbb{Z}$
  - Linearity and integer-shift invariance

⇒ Digital filtering solution: $\tilde{f}(x) = \sum_{n\in\mathbb{Z}} \underbrace{(q * c_1)[k]}_{c_2[k]} \varphi_2(x-k)$

# Generalized sampling theorem

Cross-correlation sequence: $a_{12}[k] = \langle \varphi_1(\cdot - k), \varphi_2(\cdot) \rangle \quad \stackrel{\mathcal{F}}{\longleftrightarrow} \quad A_{12}(e^{j\omega})$

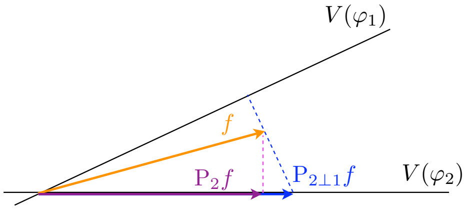
- **Consistent sampling theorem**

  Let $A_{12}(e^{j\omega}) \geq m > 0$. Then, there exists a unique solution $\tilde{f} \in V(\varphi_2)$ that is consistent with $f$ in the sense that $c_1[k] = \langle f, \varphi_1(\cdot - k) \rangle = \langle \tilde{f}, \varphi_1(\cdot - k) \rangle$

$$\tilde{f}(x) = \mathrm{P}_{2\perp 1} f(x) = \sum_{n \in \mathbb{Z}} (q * c_1)[k] \varphi_2(x - k) \quad \text{with} \quad Q(z) = \frac{1}{\sum_{k \in \mathbb{Z}} a_{12}[k] z^{-k}}$$

- Geometric interpretation

  $\tilde{f} = \mathrm{P}_{2\perp 1} f$ is the projection of $f$ onto $V(\varphi_2)$ perpendicular to $V(\varphi_1)$.




Orthogonality of error:

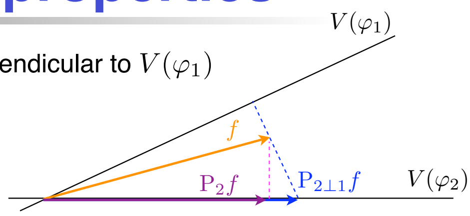
$$\langle f - \tilde{f}, \varphi_1(\cdot - k) \rangle = \underbrace{\langle f, \varphi_1(\cdot - k) \rangle}_{c_1[k]} - \underbrace{\langle \tilde{f}, \varphi_1(\cdot - k) \rangle}_{c_1[k]} = 0$$

(consistency)



# Consistent sampling: properties

$\tilde{f} = \mathrm{P}_{2\perp 1} f$: oblique projection onto $V(\varphi_2)$ perpendicular to $V(\varphi_1)$




- Generalization of Shannon's theorem

  Every signal $f \in V(\varphi_2)$ can be reconstructed exactly

  - Flexibility and realism
    - $\varphi_1$ and $\varphi_2$ can be selected freely
    - They need not be biorthogonal (unlike wavelet pairs)

- Special case: least-squares approximation

  $\varphi_1 \in V(\varphi_2) \quad \Rightarrow \quad V(\varphi_1) = V(\varphi_2) \quad \Rightarrow \quad \mathrm{P}_{2\perp 1} = \mathrm{P}_2$ (orthogonal projection)

  Minimun-error approximation: $\tilde{f}(x) = \mathrm{P}_2 f(x) = \sum_{k \in \mathbb{Z}} \underbrace{\langle f, \mathring{\varphi}_2(\cdot - k) \rangle}_{(c_1 * q)[k]} \varphi_2(x - k)$

# Application 1: interpolation revisited

- Interpolation constraint

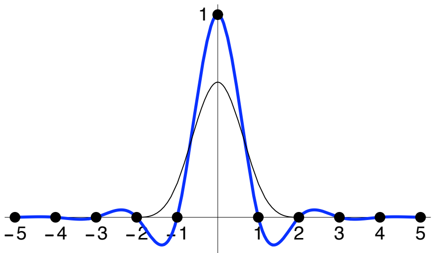
$$c_1[k] = f(x)|_{x=k} = \langle \delta(\cdot - k), f \rangle$$

- Interpolator = consistent ideal sampling system
  - Ideal sampler: $\varphi_1(x) = \delta(x)$
  - Reconstruction function: $\varphi_2(x) = \varphi(x)$
  - Cross-correlation: $a_{12}[k] = \langle \delta(\cdot - k), \varphi(\cdot) \rangle = \varphi(k)$

- Reconstruction/interpolation formula

$$Q_{\text{int}}(z) = \frac{1}{\sum_{k \in \mathbb{Z}} \varphi(k) z^{-k}}$$

$$f(x) = \sum_{k \in \mathbb{Z}} \overbrace{(f * q_{\text{int}})[k]}^{c[k]} \, \varphi(x-k) = \sum_{k \in \mathbb{Z}} f[k] \, \varphi_{\text{int}}(x-k)$$




Example: cubic-spline interpolant

$$\varphi_{\text{int}}(x) = \sum_{k \in \mathbb{Z}} q_{\text{int}}[k] \, \varphi(x-k)$$

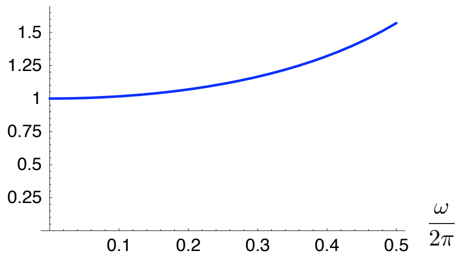


# Application 2: consistent image display

- Problem specification
  - Ideal acquisition device: $\varphi_1(x,y) = \text{sinc}(x) \cdot \text{sinc}(y)$
  - LCD display: $\varphi_2(x,y) = \text{rect}(x) \cdot \text{rect}(y)$

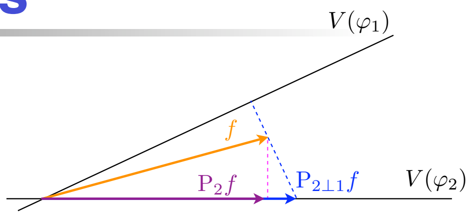
- Separable image-enhancement filter

$$A_{12}(e^{j\omega}) = \sum_{n \in \mathbb{Z}} \hat{\varphi}_1^*(\omega + 2\pi n) \hat{\varphi}_2(\omega + 2\pi n) \quad \Rightarrow \quad Q(e^{j\omega}) = \frac{1}{\text{sinc}\left(\frac{\omega}{2\pi}\right)}$$



# Performance analysis

General case: $f(x) \in L_2$ $\quad L_2 >> V(\varphi_2)$




- $\tilde{f} = \mathrm{P}_{2\perp 1} f$ is an approximation of $f$
- Reference solution: $\mathrm{P}_2 f$ (orthogonal projection)
- Performance depends on the "angle" between $V(\varphi_1)$ and $V(\varphi_2)$

**Theorem** (approximation equivalence)

$$\forall f \in L_2, \|f - \mathrm{P}_2 f\| \leq \|f - \mathrm{P}_{2\perp 1} f\| \leq \frac{1}{\cos\theta_{12}} \|f - \mathrm{P}_2 f\|$$

where $$\cos\theta_{12} = \inf_{\omega\in[-\pi,\pi]} \frac{\left|\sum_{n\in\mathbb{Z}} \hat{\varphi}_1^*(\omega+2\pi n)\hat{\varphi}_2(\omega+2\pi n)\right|}{\sqrt{\sum_{n\in\mathbb{Z}} |\hat{\varphi}_1(\omega+2\pi n)|^2}\sqrt{\sum_{n\in\mathbb{Z}} |\hat{\varphi}_2(\omega+2\pi n)|^2}}$$

[Unser-Aldroubi, 1994]



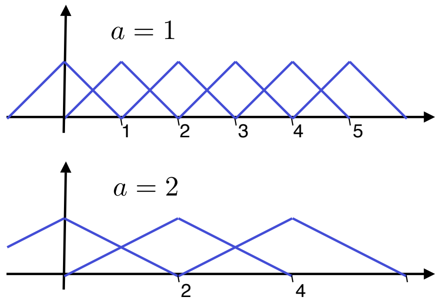
# QUANTITATIVE APPROXIMATION THEORY

- Order of approximation
- Fourier-domain prediction of the $L_2$-error
- Strang-Fix conditions
- Spline case
- Asymptotic form of the error
- Optimized basis functions (MOMS)
- Comparison of interpolators

# Order of approximation

- General "shift-invariant" space at scale $a$

$$V_a(\varphi) = \left\{ s_a(x) = \sum_{k\in\mathbb{Z}} c[k]\varphi\left(\frac{x}{a} - k\right) : c \in \ell_2 \right\}$$




- Projection operator

$$\forall f \in L_2, \qquad \mathrm{P}_a f = \arg \min_{s_a \in V_a} \|f - s_a\|_{L_2}$$

- Order of approximation

**Definition**

A scaling/generating function $\varphi$ has order of approximation $L$ iff.

$$\forall f \in W_2^L, \qquad \|f - \mathrm{P}_a f\|_{L_2} \le C \cdot a^L \cdot \|f^{(L)}\|_{L_2}$$



# Fourier-domain prediction of the $L_2$-error

**Theorem** [Blu-U., 1999]
Let $\mathrm{P}_a f$ denote the orthogonal projection of $f$ onto $V_a(\varphi)$ (at scale $a$).
Then,

$$\forall f \in W_2^s, \qquad \|f - \mathrm{P}_a f\|_{L_2} = \left( \int_{-\infty}^{+\infty} |\hat{f}(\omega)|^2 E_\varphi(a\omega) \frac{d\omega}{2\pi} \right)^{1/2} + o(a^s)$$

where

$$E_\varphi(\omega) = 1 - \frac{|\hat{\varphi}(\omega)|^2}{\sum_{k\in\mathbb{Z}} |\hat{\varphi}(\omega + 2\pi k)|^2}$$

Fourier-transform notation: $\hat{f}(\omega) = \int_{-\infty}^{+\infty} f(x) e^{-j\omega x} \mathrm{d}x$

# Strang-Fix conditions of order $L$

Let $\varphi(x)$ satisfy the Riesz-basis condition. Then, the following Strang-Fix conditions of order $L$ are equivalent:

(1) $\hat{\varphi}(0) = 1$, and $\hat{\varphi}^{(n)}(2\pi k) = 0$ for $\begin{cases} k \neq 0 \\ n = 0 \ldots L-1 \end{cases}$

(2) $\varphi(x)$ reproduces the polynomials of degree $L-1$; i.e., there exist weights $p_n[k]$ such that

$x^n = \sum_{k\in\mathbb{Z}} p_n[k]\varphi(x-k)$, for $n = 0 \ldots L-1$

(3) $E_\varphi(\omega) = \frac{C_L^2}{(2L)!} \cdot \omega^{2L} + O(\omega^{2L+2})$

(4) $\forall f \in W_2^L, \quad \|f - \mathrm{P}_a f\|_{L_2} = O(a^L)$

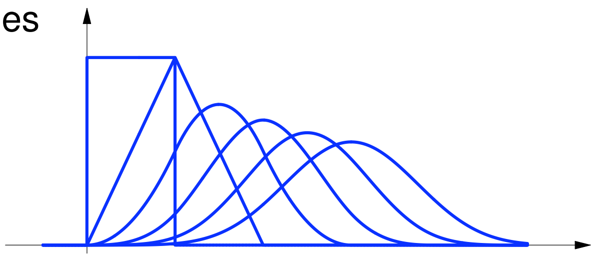


# Polynomial splines

- Basis functions: causal B-splines

$\beta_+^n(x) = \left(\beta_+^{n-1} * \beta_+^0\right)(x)$

$\beta_+^0(x) = \begin{cases} 1, & \text{for } 0 \leq x < 1 \\ 0, & \text{otherwise.} \end{cases}$



- Fourier-domain formula

$\hat{\beta}_+^n(\omega) = \left(\frac{1-e^{-j\omega}}{j\omega}\right)^{n+1}$

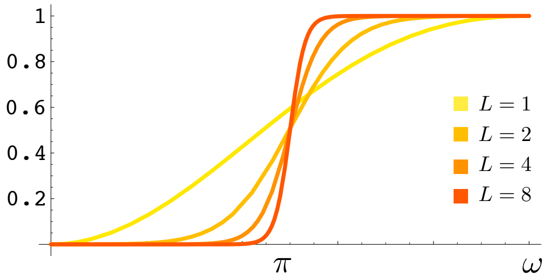
- Order of approximation

$\hat{\beta}_+^n(2\pi k + \Delta\omega) = O(|\Delta\omega|^{n+1})$ for $k \neq 0$

$\Longrightarrow \quad \beta_+^n$ has order of approximation $L = n+1$

# Spline approximation

- Fourier approximation kernel




$$E_{\beta^n}(\omega) = \frac{\sum_{k\neq 0} |\hat{\beta}^n(\omega+2\pi k)|^2}{\sum_{k\in\mathbb{Z}} |\hat{\beta}^n(\omega+2\pi k)|^2}$$

Order: $L = n+1$

- Link with Riemann's zeta function

$$\zeta(z) = \sum_{n=1}^{+\infty} n^{-z}$$

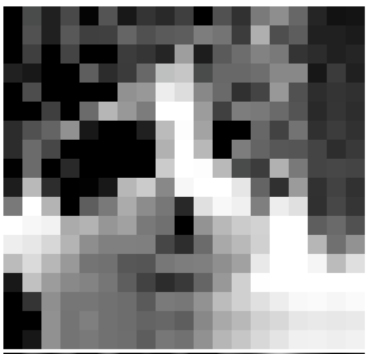
$$E_{\beta^n}(\omega) = |2\sin(\omega/2)|^{2n+2} \frac{\sum_{k\neq 0} \frac{1}{|\omega+2\pi k)|^{2n+2}}}{\sum_{k\in\mathbb{Z}} |\hat{\beta}^n(\omega+2\pi k)|^2}$$

$$= \frac{2\zeta(2n+2))}{(2\pi)^{2n+2}} \cdot \omega^{2n+2} + O(|\omega|^{2n+4})$$



# Spline reconstruction of a PET-scan

Piecewise constant
$L = 1$



Cubic spline
$L = 4$

# Asymptotic form of the error

**Theorem** [U.-Daubechies, 1997]
Let $\varphi$ be an $L$th order function. Then, asymptotically, as $a \to 0$,

$$\forall f \in W_2^L, \qquad \|f - \mathrm{P}_a f\|_{L_2} = C_L \cdot a^L \cdot \|f^{(L)}\|_{L_2}$$

where

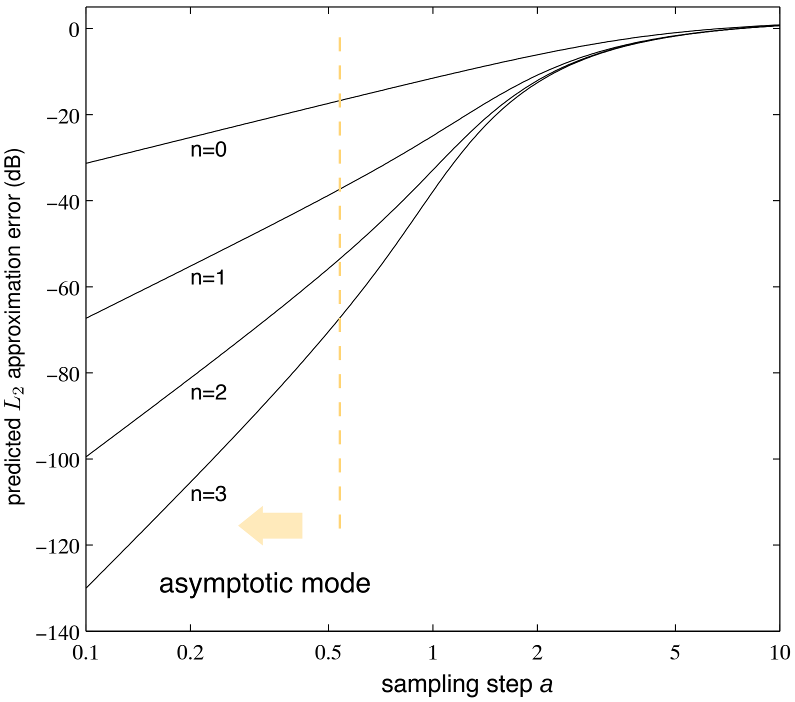
$$C_L = \frac{1}{L!}\sqrt{2\sum_{n=1}^{+\infty}\left|\hat{\varphi}^{(L)}(2\pi n)\right|^2} \qquad \left(= \sqrt{\frac{E_\varphi^{(2L)}(0)}{(2L)!}}\right)$$

- Special case: splines of order $L = n + 1$

$$C_{L,\text{splines}} = \frac{\sqrt{2\zeta(2L)}}{(2\pi)^L} = \sqrt{\frac{B_{2L}}{(2L)!}}$$ (Bernoulli number of order $2L$)



# Characteristic decay of the error for splines




Least squares approximation of the function $f(x) = e^{-x^2/2}$

# Optimized basis functions (MOMS)

- Motivation
  - Cost of prefiltering is negligible (in 2D and 3D)
  - Computational cost depends on kernel size $W$
  - Order of approximation is a strong determinant of quality

QUESTION: What are the basis functions with maximum order of approximation and minimum support ?

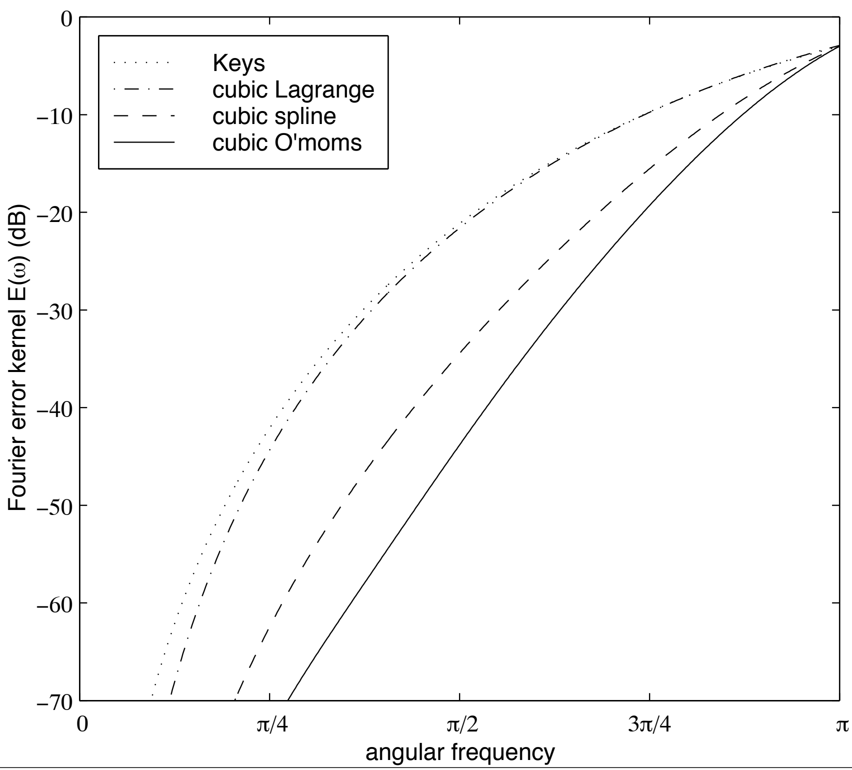
ANSWER: Shortest functions of order $L$ (MOMS) $\varphi_{\mathrm{moms}}(x) = \sum_{k=0}^{L-1} a_k \mathrm{D}^k \beta^{L-1}(x)$

- Most interesting MOMS
  - B-splines: smoothest ($\beta^{L-1} \in \dot{C}^{L-1}$) and only refinable MOMS
  - Shaum's piecewise-polynomial interpolants (no prefilter)
  - OMOMS: smallest approximation constant $C_L$

$$\varphi^3_{\mathrm{opt}}(x) = \beta^3(x) + \frac{1}{42}\frac{\mathrm{d}^2\beta^3(x)}{\mathrm{d}x^2}$$



# Comparisons of cubic interpolators of size *W*=4



# CONCLUSION

- Generalized sampling
  - Unifying Hilbert-space formulation: Riesz basis, etc.
  - Approximation point of view:
    projection operators (oblique vs. orthogonal)
  - Increased flexibility; closer to real-world systems
  - Generality: nonideal sampling, interpolation, etc...
- Quest for the "optimal" representation space
  - Not bandlimited ! (prohibitive cost, ringing, etc.)
  - Quantitative approximation theory: $L_2$-estimates, asymptotics
  - Optimized functions: MOMS
  - Signal-adapted design ?
- Interpolation/approximation in the presence of noise
  - Regularization theory: smoothing splines
  - Stochastic formulation: hybrid form of Wiener filter



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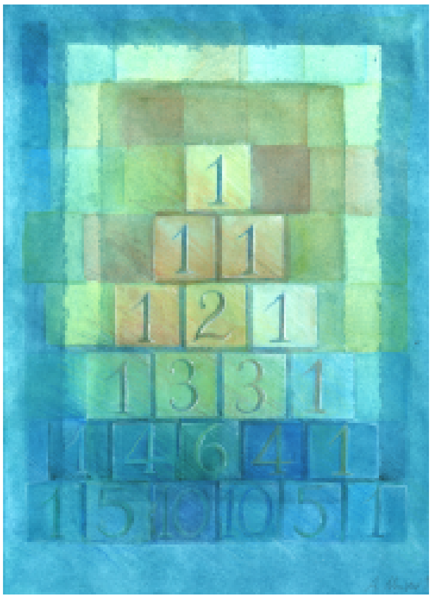


- Software and demos at: http://bigwww.epfl.ch/

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- Preprints and demos: **http://bigwww.epfl.ch/**