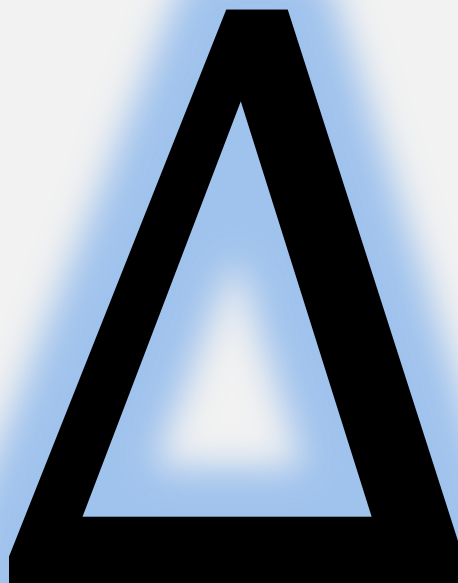


IFT 6113

CONTINUOUS LAPLACIAN

<http://tiny.cc/ift6113>



Mikhail Bessmeltsev

Some slides by Justin Solomon

Famous Motivation

CAN ONE HEAR THE SHAPE OF A DRUM?

MARK KAC, The Rockefeller University, New York

To George Eugene Uhlenbeck on the occasion of his sixty-fifth birthday

“La Physique ne nous donne pas seulement l'occasion de résoudre des problèmes . . . , elle nous fait sentir la solution.” H. POINCARÉ.

Before I explain the title and introduce the theme of the lecture I should like to state that my presentation will be more in the nature of a leisurely excursion than of an organized tour. It will not be my purpose to reach a specified destination at a scheduled time. Rather I should like to allow myself on many occasions the luxury of stopping and looking around. So much effort is being spent on streamlining mathematics and in rendering it more efficient, that a solitary transgression against the trend could perhaps be forgiven.

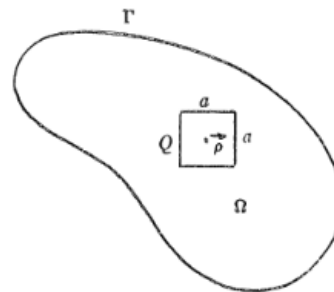


FIG. 1

1. And now to the theme and the title.

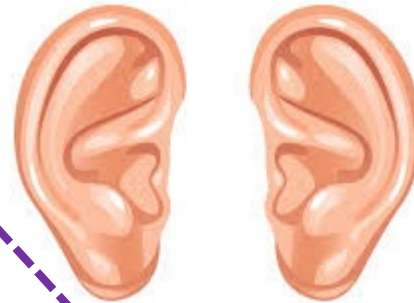
It has been known for well over a century that if a membrane Ω , held fixed along its boundary Γ (see Fig. 1), is set in motion its displacement (in the direction perpendicular to its original plane)

$$F(x, y; t) \equiv F(\vec{\rho}; t)$$

obeys the wave equation

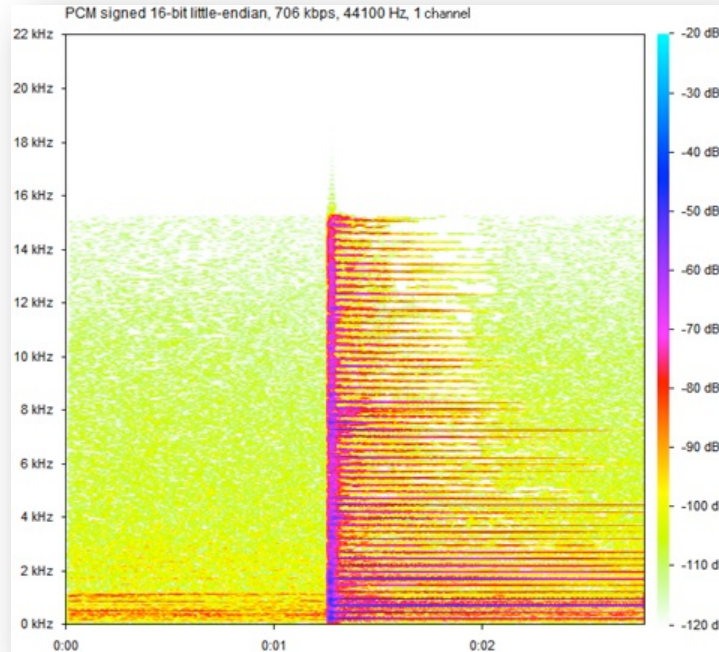
$$\partial^2 F$$

An Experiment



**Is this
possible?**

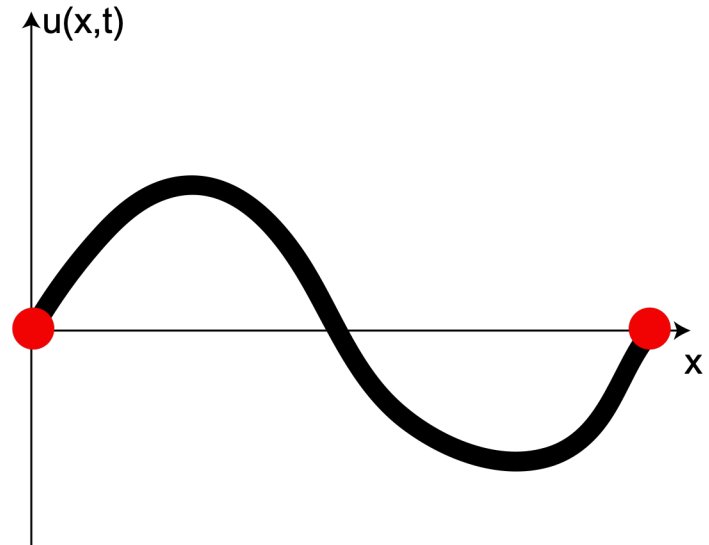
Unreasonable to Ask?



*Length
of string*

1D: length of a string

$u(x, t)$ - string height

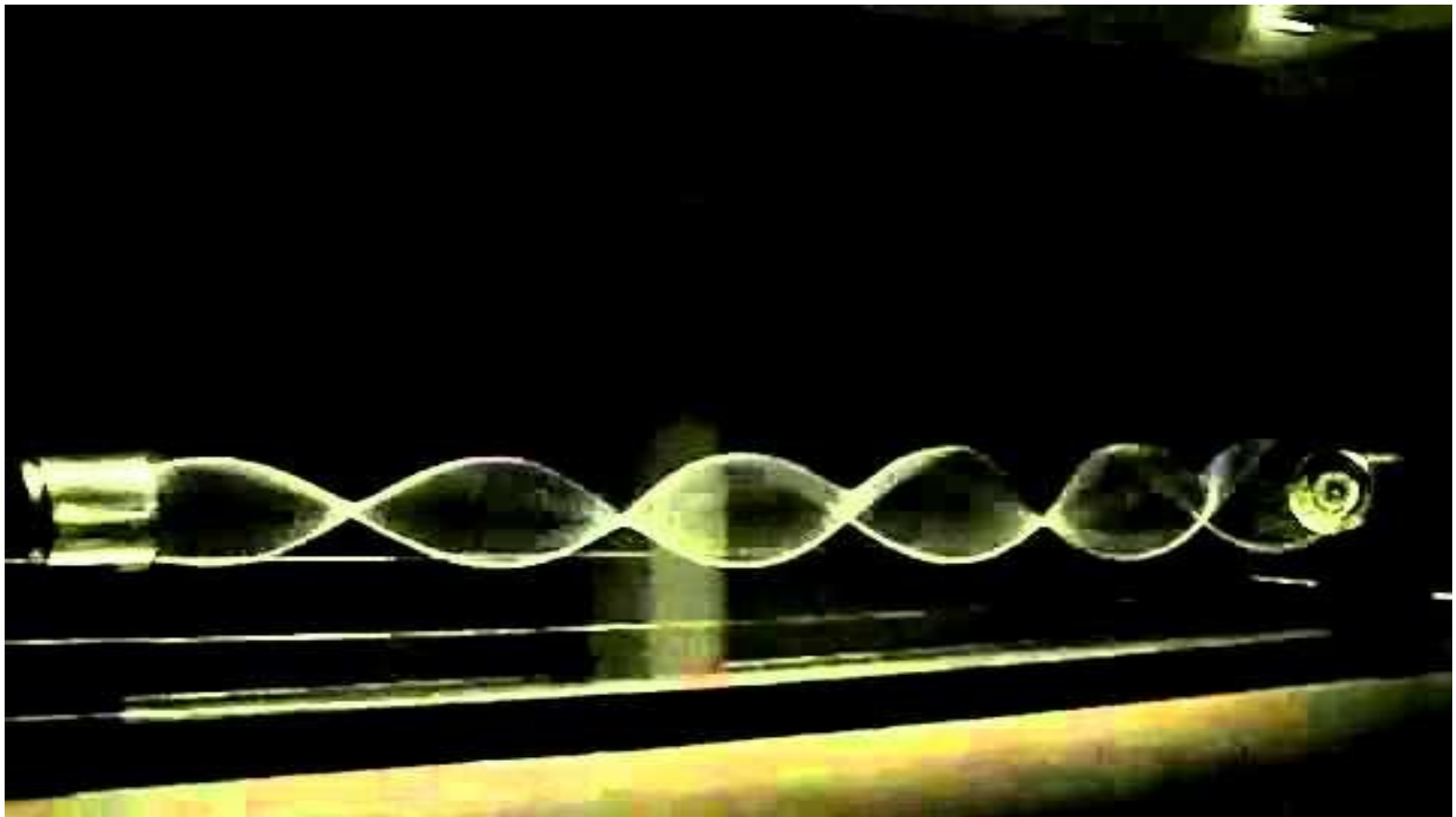


Boundary conditions: $u(0, t) = 0 = u(l, t)$

$$\text{PDE: } \frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2}$$

Standing waves?

(on the board)

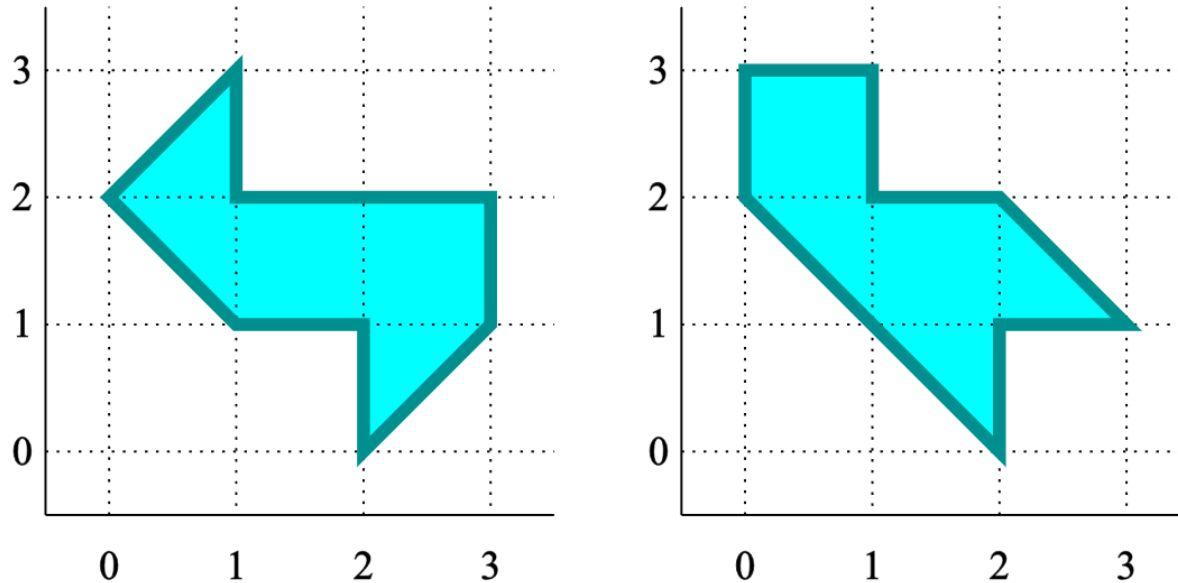


Can you hear the length of an interval?

$$\lambda_k = \left(\frac{\pi k}{\ell} \right)^2$$

Yes!

Spoiler Alert

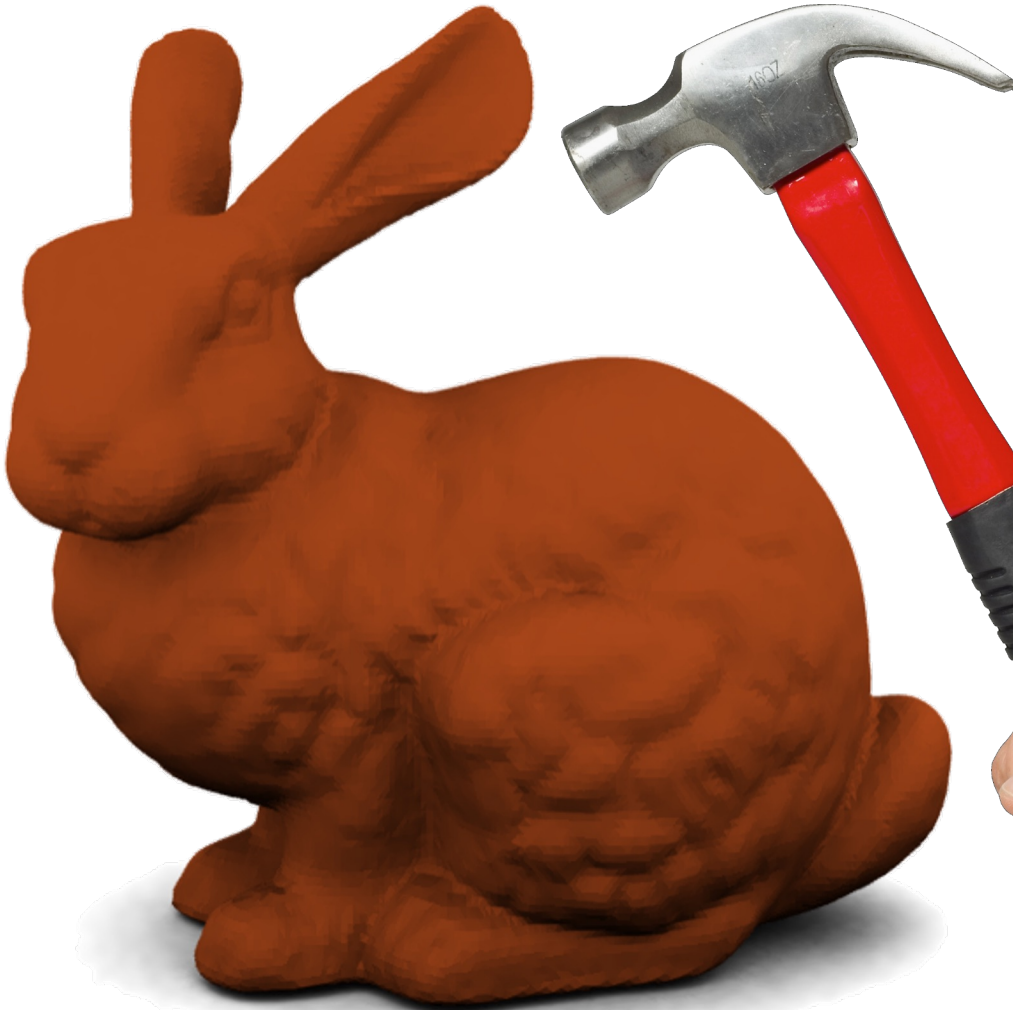


“No, but...”

- ***Has to be a weird drum***
- ***Spectrum tells you **a lot!*****

Rough Intuition

http://pngimg.com/upload/hammer_PNG3886.png



**You can learn a lot
about a shape by
hitting it (lightly)
with a hammer!**

Spectral Geometry

What can you learn about its shape
from

vibration frequencies and
oscillation patterns?

$$\Delta f = \lambda f$$

Objectives

- Make “vibration modes” more precise
- Progressively more complicated domains
 - Line segments
 - Regions in \mathbb{R}^2
 - Graphs
 - Surfaces/manifolds
- Next time: Discretization, applications

Review:

Vector Spaces and Linear Operators

$$\mathcal{L}[\vec{x} + \vec{y}] = \mathcal{L}[\vec{x}] + \mathcal{L}[\vec{y}]$$

$$\mathcal{L}[c\vec{x}] = c\mathcal{L}[\vec{x}]$$

Review:

In Finite Dimensions

A \vec{x}
matrix vector

$\vec{x} \mapsto A\vec{x}$
linear operator

Recall: Spectral Theorems in \mathbb{C}^n

Theorem. Suppose $A \in \mathbb{C}^{n \times n}$ is Hermitian. Then, A has an orthogonal basis of n eigenvectors. If A is positive semidefinite, the corresponding eigenvalues are nonnegative.

Our Progression

- *Line segments*
- *Regions in \mathbb{R}^2*
- *Graphs*
- *Surfaces/manifolds*

Minus Second Derivative Operator

“Dirichlet boundary conditions”

$$\{f(\cdot) \in C^\infty([a, b]) : f(0) = f(\ell) = 0\}$$

$$\mathcal{L}[f(\cdot)] := -f''(\cdot)$$

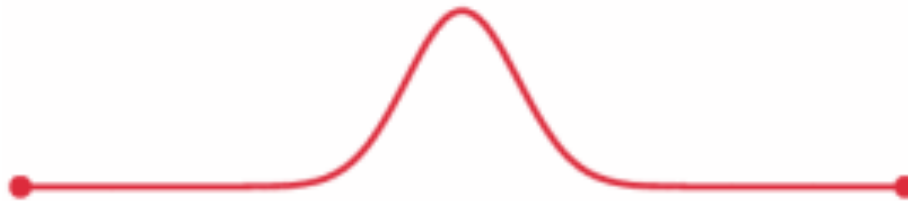
Eigenfunctions:

$$f_k(x) = \sin\left(\frac{\pi k x}{\ell}\right), \quad \lambda_k = \left(\frac{\pi k}{\ell}\right)^2$$

Physical Intuition: Wave Equation

Minus second derivative operator!

$$\frac{\partial^2 u}{\partial t^2} - \frac{\partial^2 u}{\partial x^2} = 0$$



Observation

$$\{f(\cdot) \in C^\infty([a, b]) : f(0) = f(\ell) = 0\}$$

$$\begin{aligned}\langle f, \mathcal{L}[f] \rangle &= - \int_0^\ell f(x) f''(x) dx \\ &= -[f(x) f'(x)]_0^\ell + \underbrace{\int_0^\ell f'(x)^2 dx}_{\geq 0} \\ &\geq 0\end{aligned}$$

Hilbert-Schmidt Theorem

Theorem. Let $H \neq 0$ be an infinite-dimensional, separable Hilbert space and let $K \in L(H)$ be compact and self-adjoint. Then, there exists a countable orthonormal basis of H consisting of eigenvectors of K .



Hilbert space: Space with inner product

Separable: Admits countable, dense subset

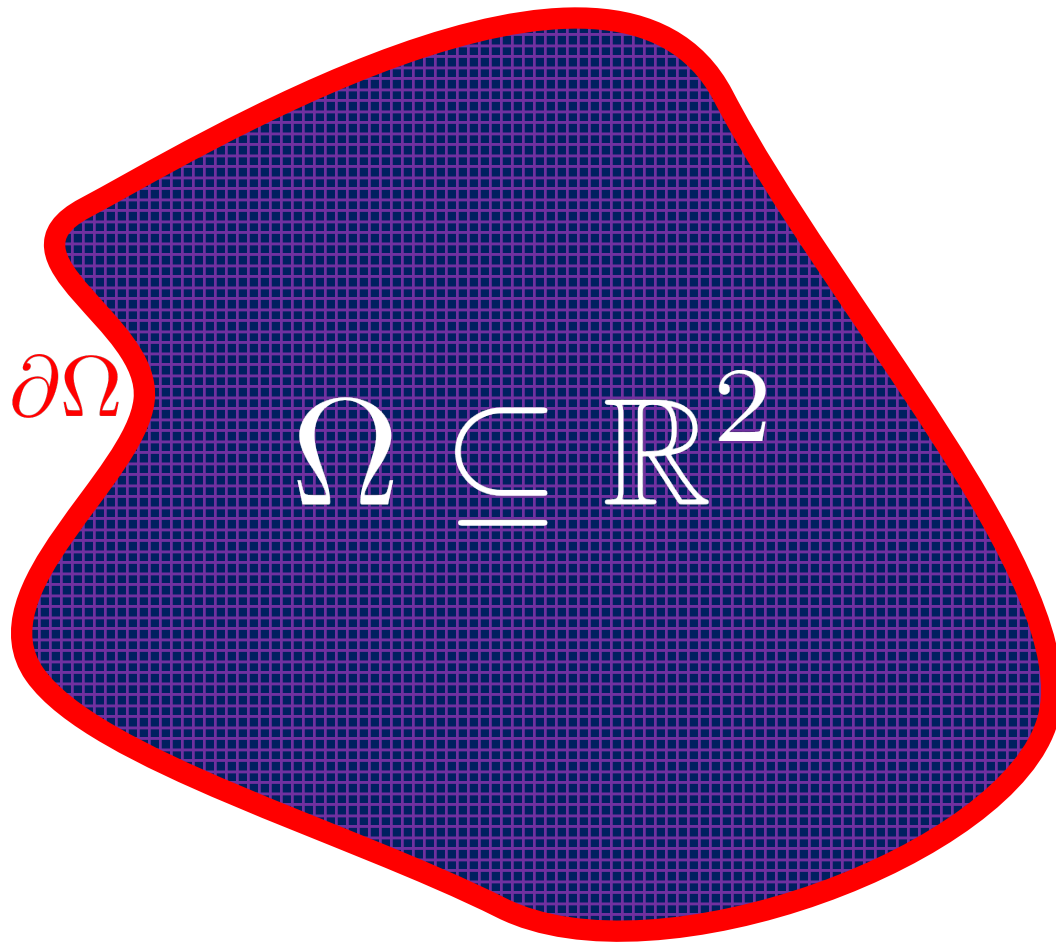
Compact operator: Bounded sets to relatively compact sets

Self-adjoint: $\langle Kv, w \rangle = \langle v, Kw \rangle$

Our Progression

- *Line segments*
- *Regions in \mathbb{R}^2*
- *Graphs*
- *Surfaces/manifolds*

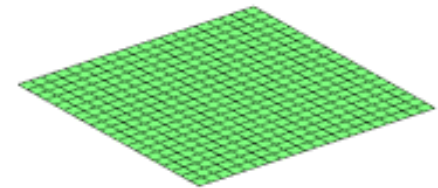
Planar Region



Wave equation:

$$\frac{\partial^2 u}{\partial t^2} = \Delta u$$

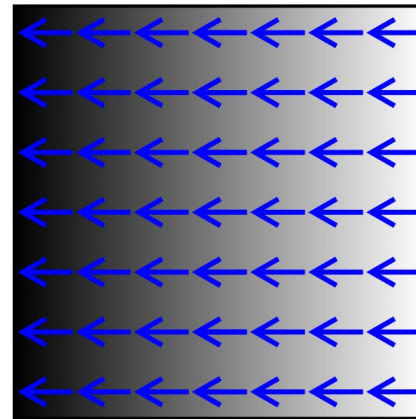
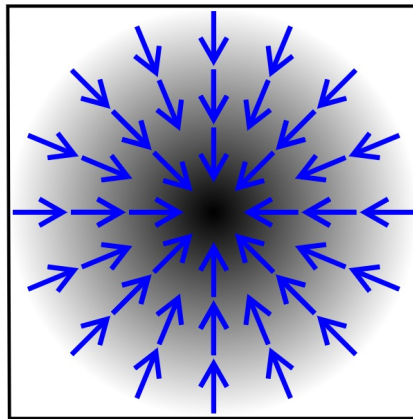
$$\Delta := \sum_i \frac{\partial^2}{\partial x_i^2}$$



Typical Notation

“ $\Delta = \underbrace{\nabla}_{\text{divergence}} \cdot \underbrace{\nabla}_{\text{gradient}}$ ”

More later...



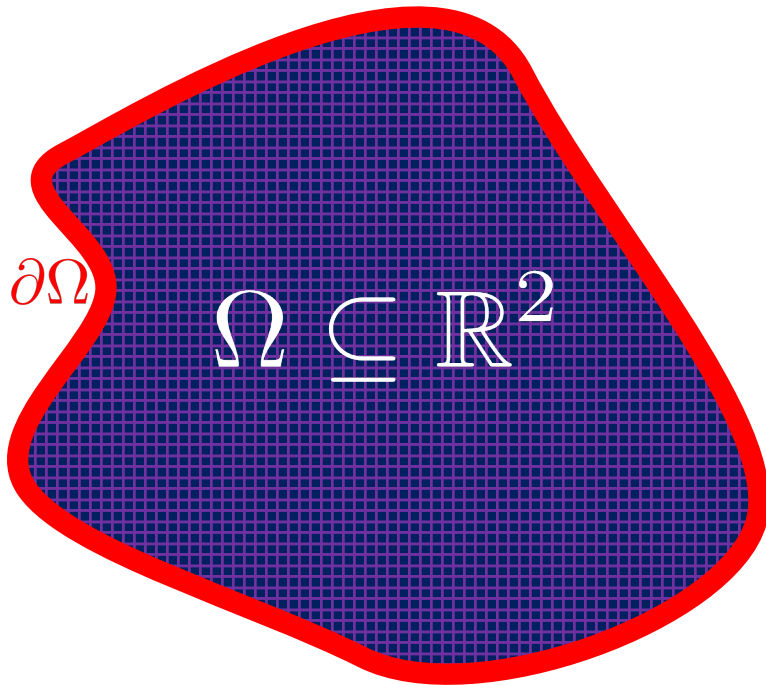
Gradient operator:

$$\nabla := \left(\frac{\partial}{\partial x_1}, \frac{\partial}{\partial x_2}, \dots, \frac{\partial}{\partial x_n} \right)$$

Positivity, Self-Adjointness

$$\{f(\cdot) \in C^\infty(\Omega) : f|_{\partial\Omega} \equiv 0\}$$

“Dirichlet boundary conditions”



$$\mathcal{L}[f] := -\Delta f$$

$$\langle f, g \rangle := \int_{\Omega} f(x)g(x) dx$$

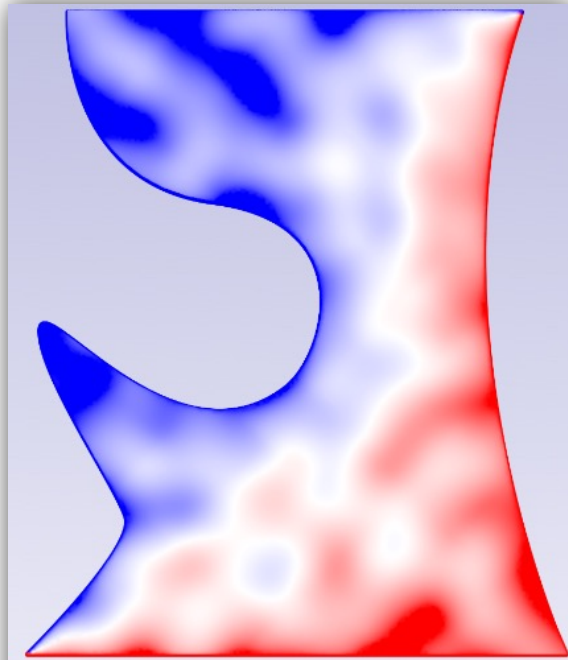
On board:

1. **Positive:** $\langle f, \mathcal{L}[f] \rangle \geq 0$
2. **Self-adjoint:** $\langle f, \mathcal{L}[g] \rangle = \langle \mathcal{L}[f], g \rangle$

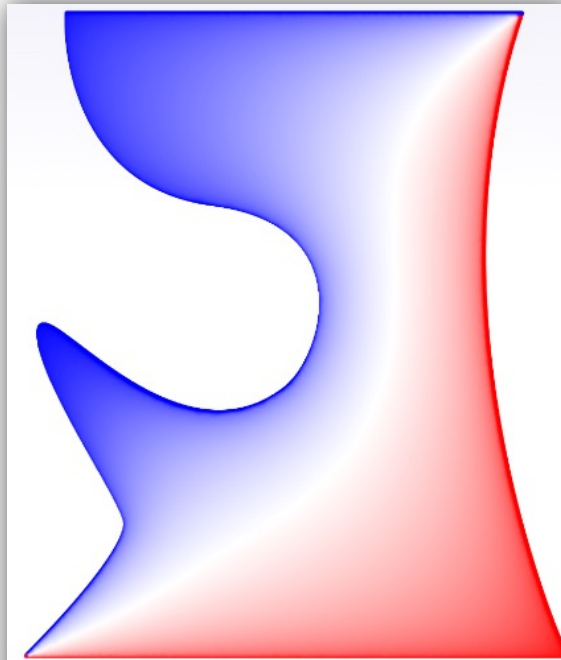
Dirichlet Energy

German: [dɪʁi'kleː]

$$E[f] := \int_{\Omega} \langle \nabla f, \nabla f \rangle dA$$



non-smooth $f(x)$



solution $\Delta f = 0$

On board:

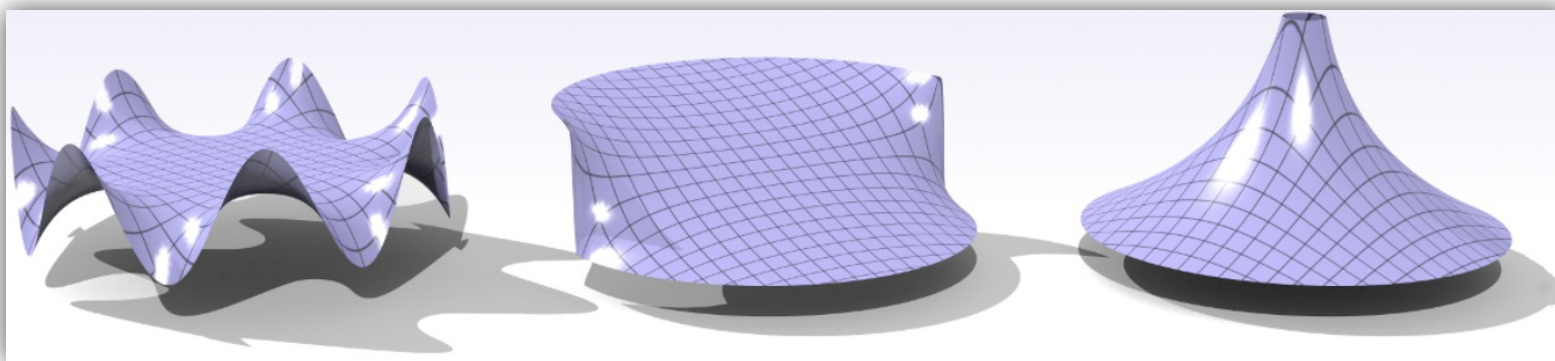
$$\begin{aligned} \min_f E[f] \\ \text{s.t. } f|_{\partial\Omega} = g \end{aligned}$$

$$\Delta f \equiv 0$$

“Laplace equation”
“Harmonic function”

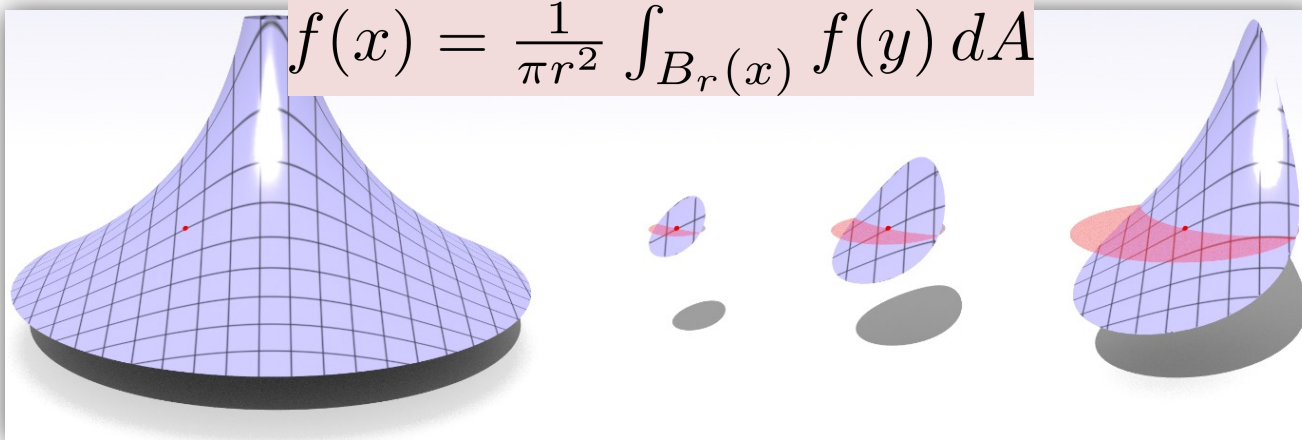
Harmonic Functions

$$\Delta f \equiv 0$$

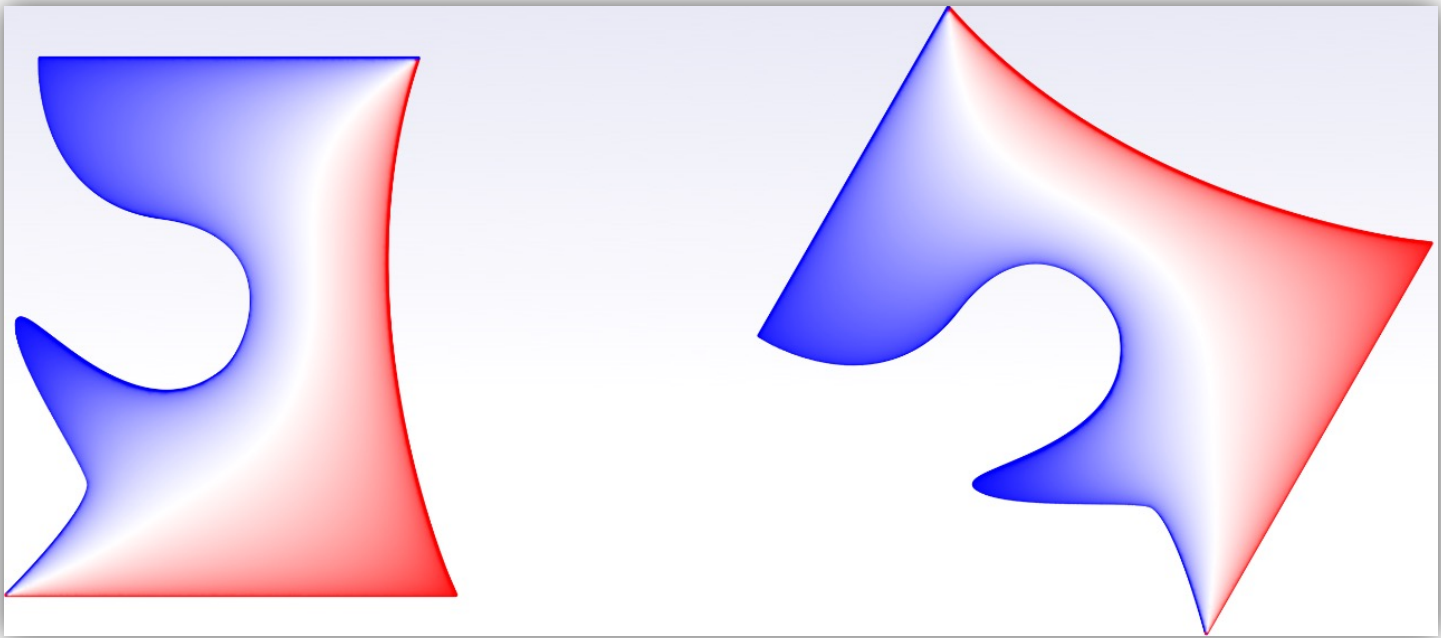


Mean value property:

$$f(x) = \frac{1}{\pi r^2} \int_{B_r(x)} f(y) dA$$



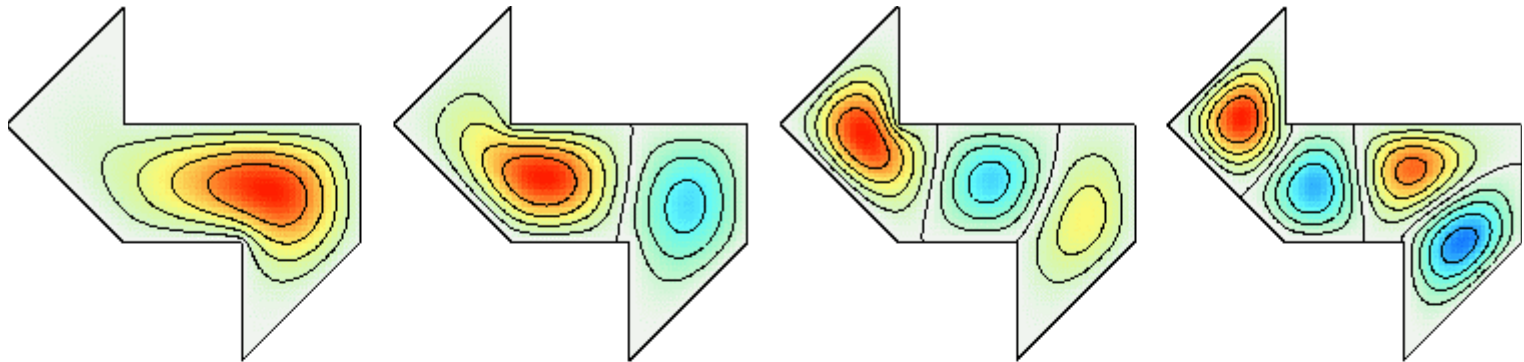
Intrinsic Operator



Images made by E. Vouga

Coordinate-independent

Another Interpretation of Eigenfunctions



Find critical points of $E[f]$

$$\text{s.t. } \int_{\Omega} f^2 = 1$$

<http://www.math.udel.edu/~driscoll/research/gww1-4.gif>

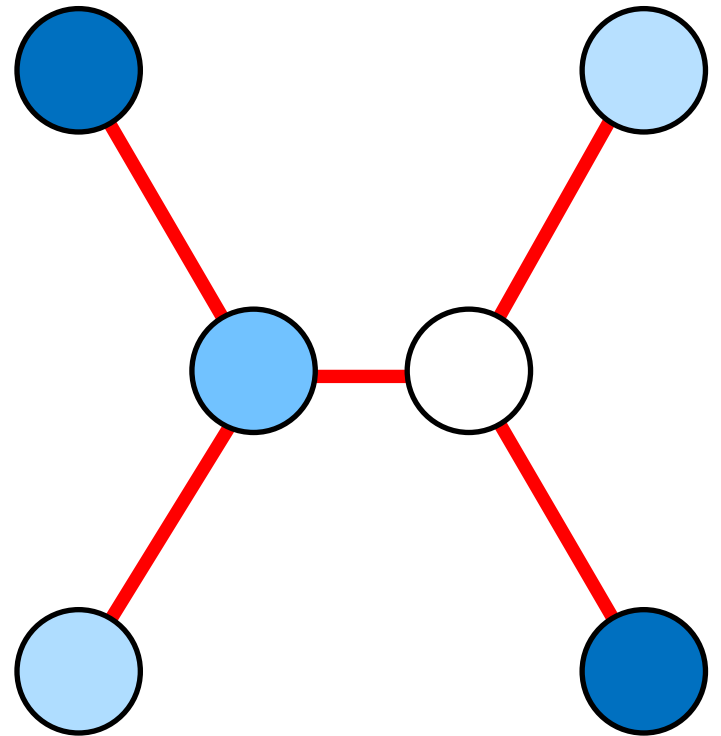
Small eigenvalue: smooth function

Our Progression

- *Line segments*
- *Regions in \mathbb{R}^2*
- *Graphs*
- *Surfaces/manifolds*

Basic Setup

- ***Function:***
One value per vertex

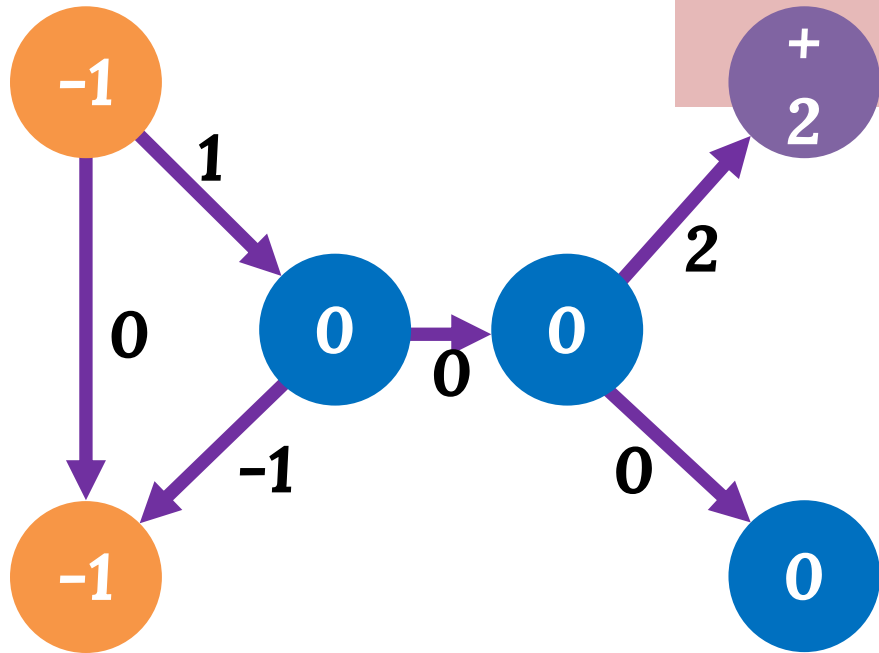


***Dirichlet energy of a
function on a graph?***

Differencing Operator

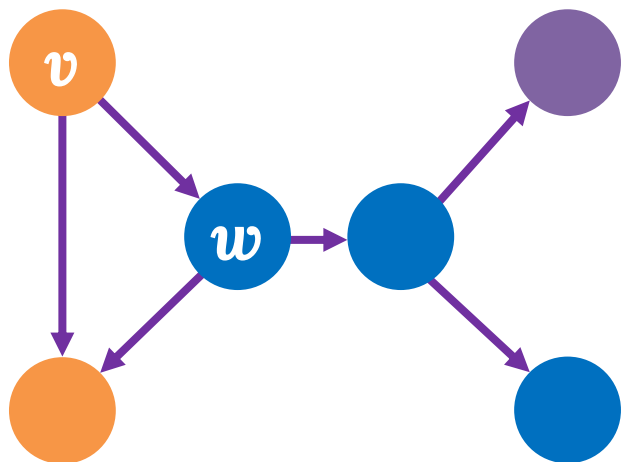
$$D_{ev} := \begin{cases} -1 & \text{if } E_{e1} = v \\ 1 & \text{if } E_{e2} = v \\ 0 & \text{otherwise} \end{cases}$$

$D \in \{-1, 0, 1\}^{|E| \times |V|}$



Orient edges arbitrarily

Dirichlet Energy on a Graph



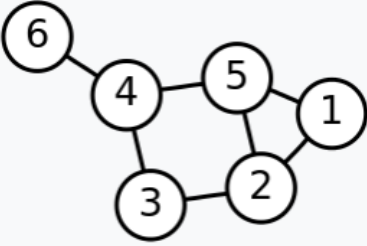
$$D_{ev} := \begin{cases} -1 & \text{if } E_{e1} = v \\ 1 & \text{if } E_{e2} = v \\ 0 & \text{otherwise} \end{cases}$$

$$E[f] := \|Df\|_2^2 = \sum_{(v,w) \in E} (f_v - f_w)^2$$

(Unweighted) Graph Laplacian

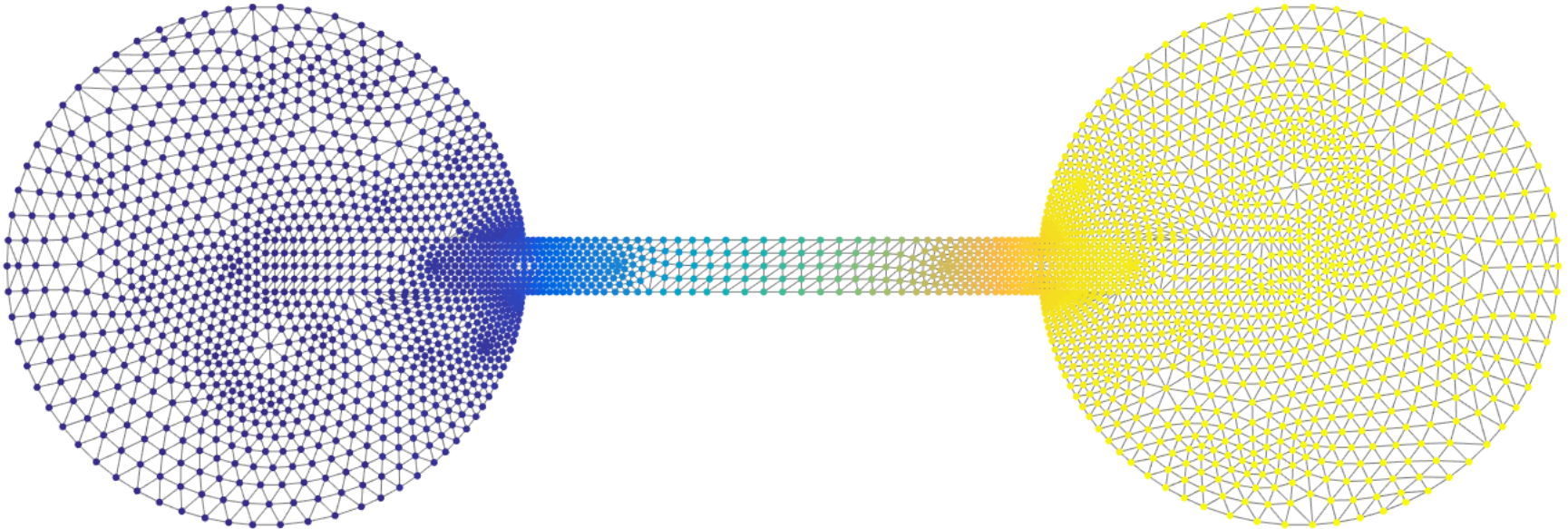
$$E[f] = \|Df\|_2^2 = f^\top (D^\top D) f := f^\top L f$$

$$L_{vw} = Deg - A = \begin{cases} -1, & \text{if } v \sim w \\ \text{degree}(v), & \text{if } v = w \\ 0, & \text{otherwise} \end{cases}$$

| Labeled graph | Degree matrix | Adjacency matrix | Laplacian matrix |
|---|--|--|--|
|  | $\begin{pmatrix} 2 & 0 & 0 & 0 & 0 & 0 \\ 0 & 3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{pmatrix}$ | $\begin{pmatrix} 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix}$ | $\begin{pmatrix} 2 & -1 & 0 & 0 & -1 & 0 \\ -1 & 3 & -1 & 0 & -1 & 0 \\ 0 & -1 & 2 & -1 & 0 & 0 \\ 0 & 0 & -1 & 3 & -1 & -1 \\ -1 & -1 & 0 & -1 & 3 & 0 \\ 0 & 0 & 0 & -1 & 0 & 1 \end{pmatrix}$ |

- **Symmetric**
- **Positive definite**

Second-Smallest Eigenvector



$$Lx = \lambda x$$

Used for
graph
partitioning

Fiedler vector (“algebraic connectivity”)

Mean Value Property

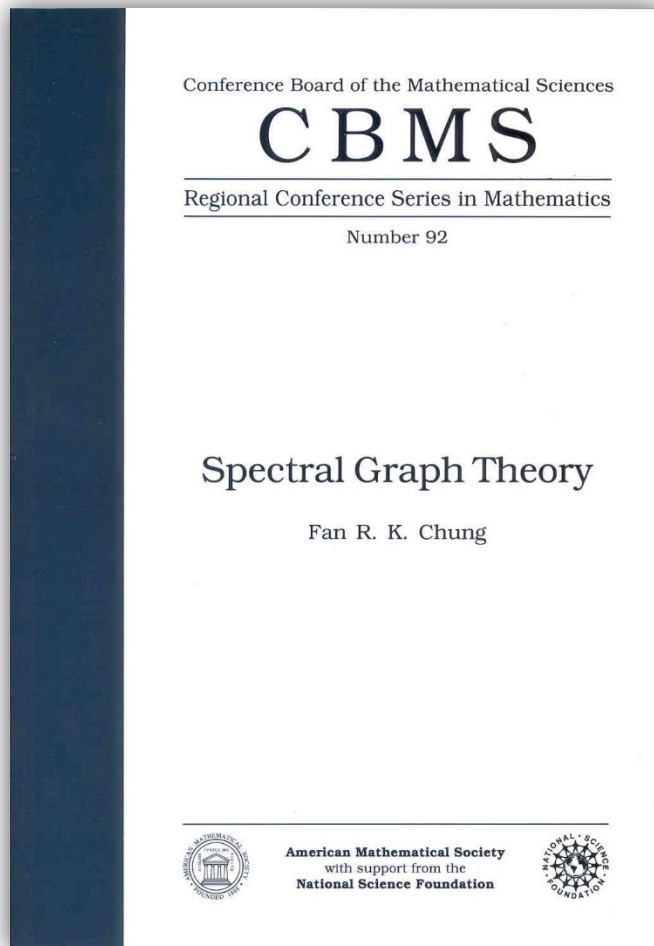
$$L_{vw} = A - D = \begin{cases} 1 & \text{if } v \sim w \\ -\text{degree}(v) & \text{if } v = w \\ 0 & \text{otherwise} \end{cases}$$

$$(Lx)_v = 0$$



Value at v is average of neighboring values

For More Information...

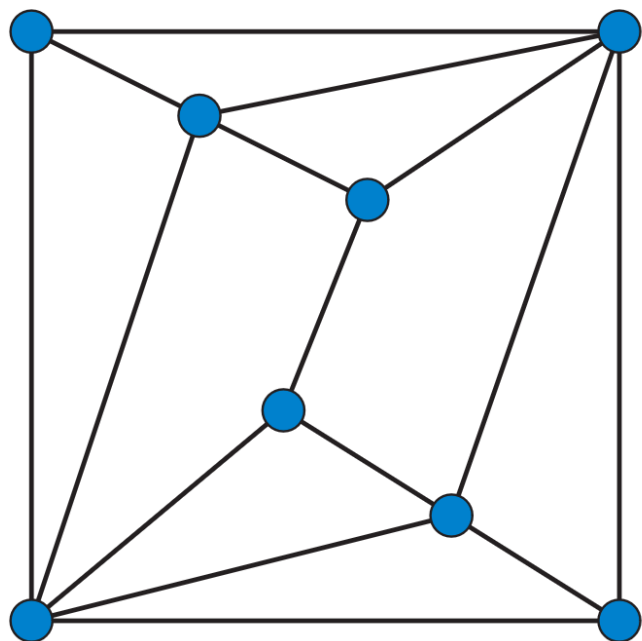


Graph Laplacian encodes lots of information!

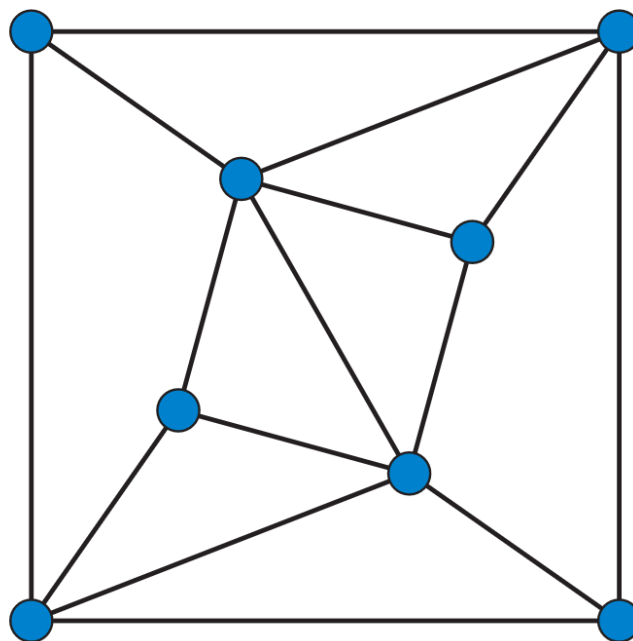
Example: Kirchoff's Theorem
Number of spanning trees equals

$$\frac{1}{n} \lambda_2 \lambda_3 \cdots \lambda_n$$

Hear the Shape of a Graph?



No!



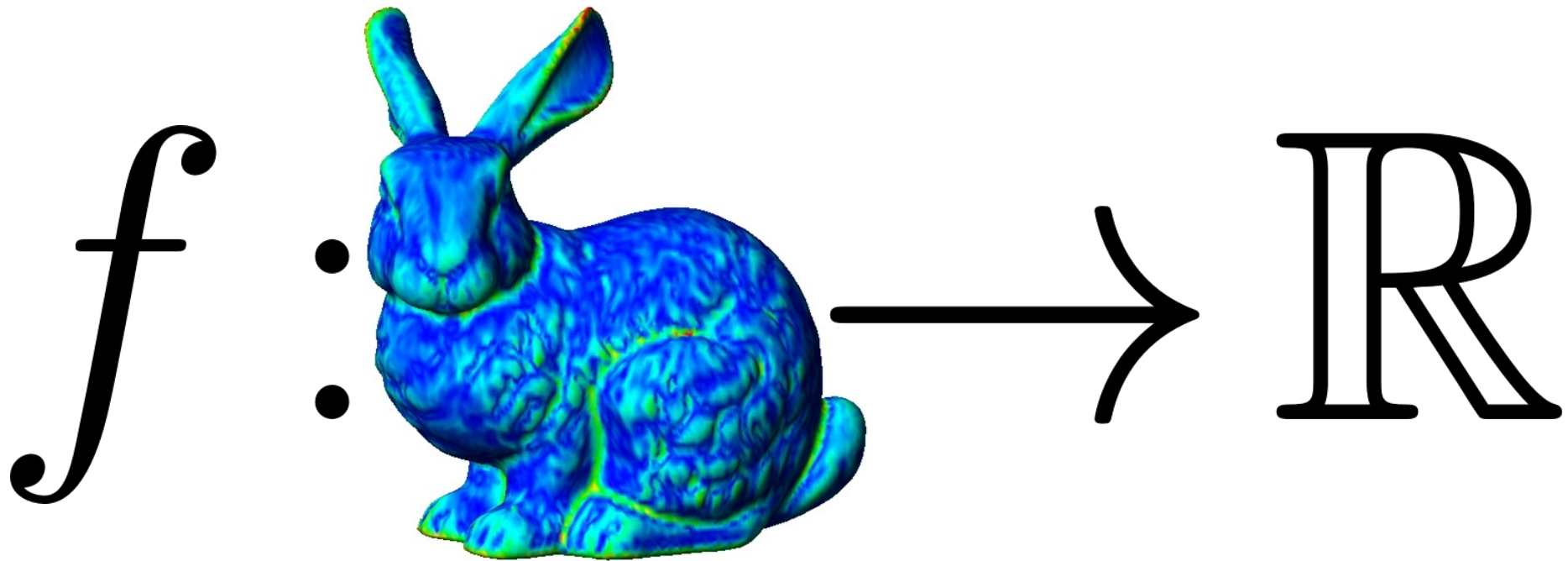
“Enneahedra”

Our Progression

- *Line segments*
- *Regions in \mathbb{R}^2*
- *Graphs*
- *Surfaces/manifolds*

Recall:

Scalar Functions



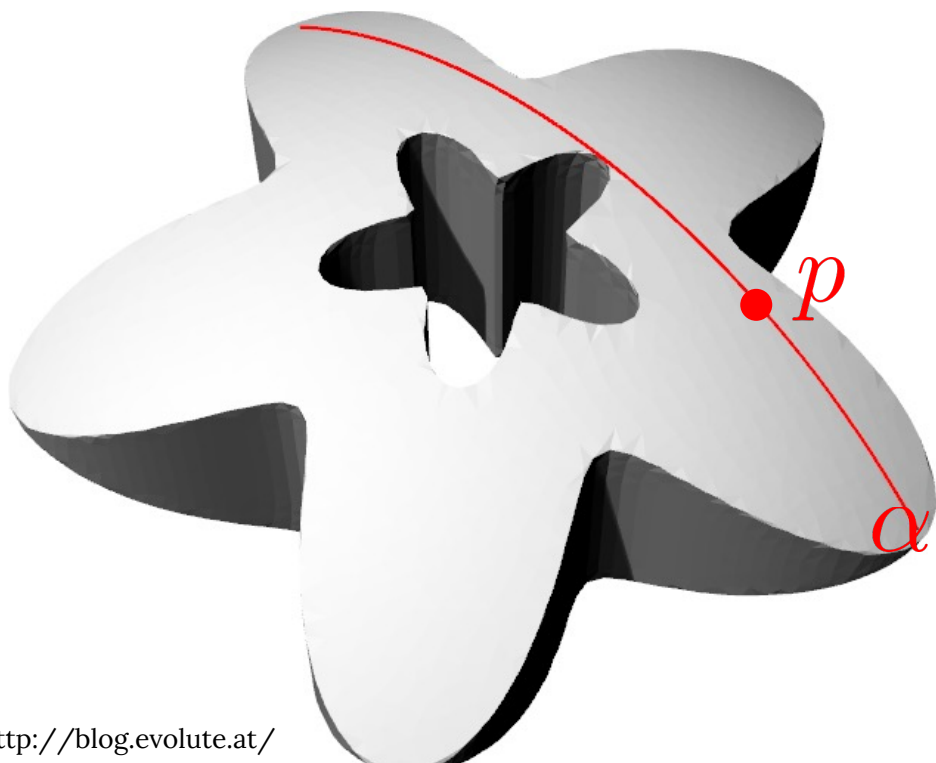
http://www.ieeta.pt/polymeco/Screenshots/PolyMeCo_OneView.jpg

Map points to real numbers

Differential of a Map

Suppose $f: S \rightarrow \mathbb{R}$ and take $p \in S$. For $v \in T_p S$, choose a **curve** $\alpha: (-\varepsilon, \varepsilon) \rightarrow S$ with $\alpha(0) = p$ and $\alpha'(0) = v$. Then the differential of f is $df: T_p S \rightarrow \mathbb{R}$ with

$$(df)_p(v) := \left. \frac{d}{dt} \right|_{t=0} (f \circ \alpha)(t) = (f \circ \alpha)'(0).$$



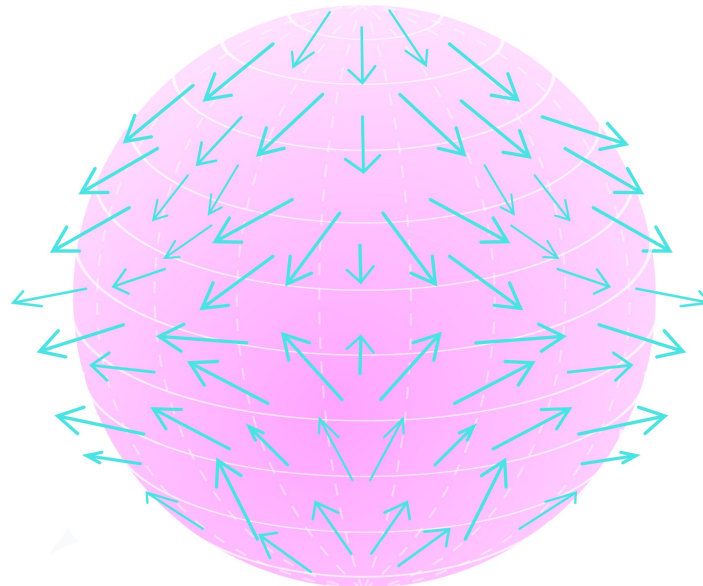
On the board (time-permitting):

- Does not depend on choice of α
- Linear map

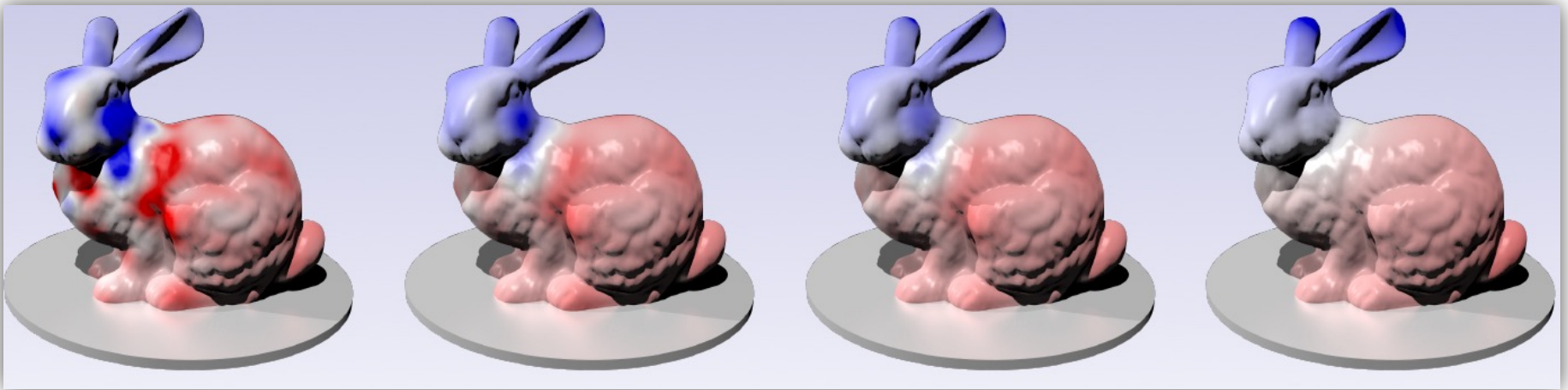
Gradient Vector Field

$\nabla f : S \rightarrow \mathbb{R}^3$ with

$$\begin{cases} \langle (\nabla f)(p), v \rangle = (df)_p(v), v \in T_p S \\ \langle (\nabla f)(p), N(p) \rangle = 0 \end{cases}$$



Dirichlet Energy



Decreasing E

$$E[f] := \int_S \|\nabla f\|_2^2 dA$$

From Inner Product to Operator

$$\begin{aligned}\langle f, g \rangle_{\Delta} &:= \int_S \nabla f(x) \cdot \nabla g(x) dA \\ &:= \langle f, \Delta g \rangle\end{aligned}$$

Implies
 $\langle f, f \rangle \geq 0$

On the board:

“Motivation” from finite-dimensional linear algebra.

Laplace–Beltrami operator

What is Divergence?

$V : S \rightarrow \mathbb{R}^3$ where $V(p) \in T_p S$

$dV_p : T_p S \rightarrow \mathbb{R}^3$

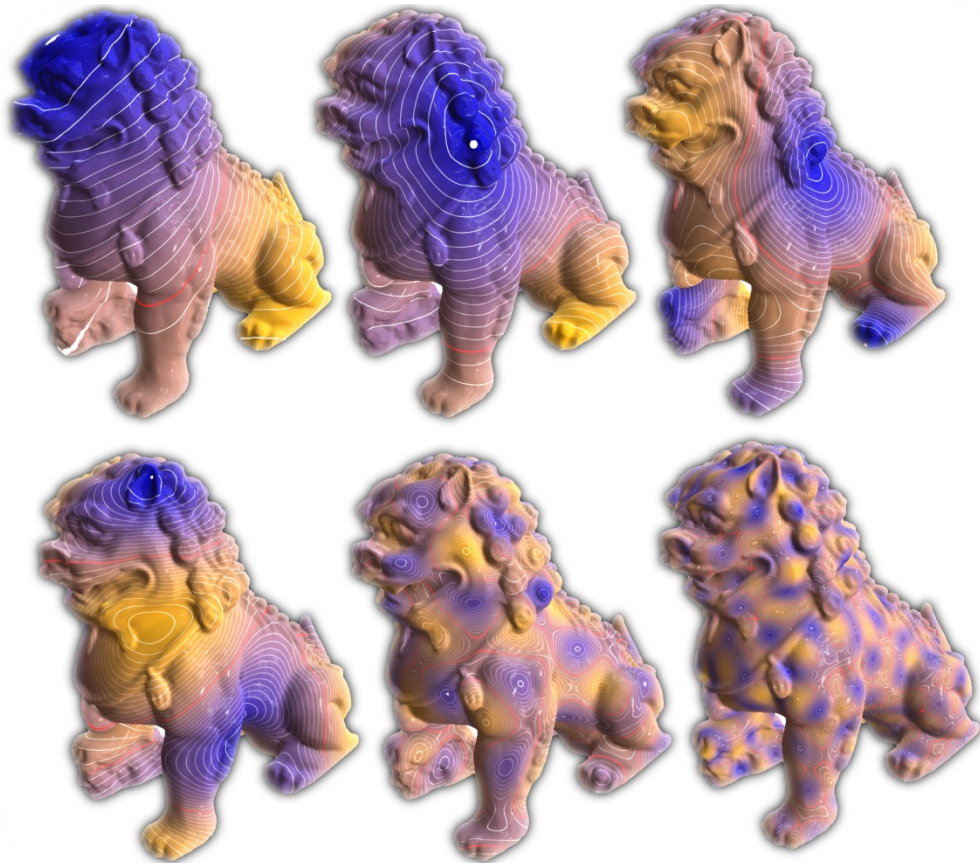
$\{e_1, e_2\} \subset T_p S$ orthonormal basis

$$(\nabla \cdot V)_p := \sum_{i=1}^2 \langle e_i, dV(e_i) \rangle_p$$

Things we **should check** (but probably won't):

- Independent of choice of basis
 - $\Delta = \nabla \cdot \nabla$

Eigenfunctions



$$\Delta \psi_i = \lambda_i \psi_i$$

**Vibration modes of
surface (not
volume!)**

Chladni Plates



<https://www.youtube.com/watch?v=CGiISlMFFlI>

Performance Art?



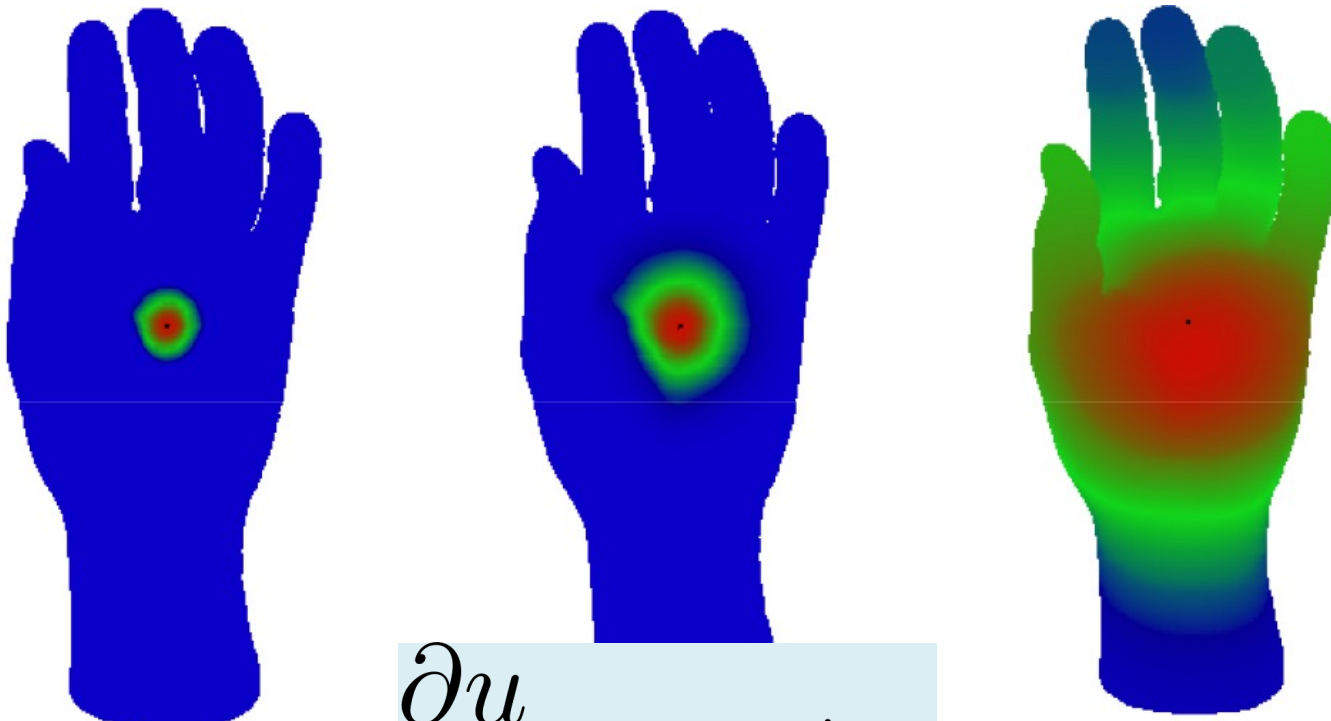
<https://www.youtube.com/watch?v=2awbKQ2DLRE>

Practical Application



<https://www.youtube.com/watch?v=3uMZzVvnSiU>

Additional Connection to Physics

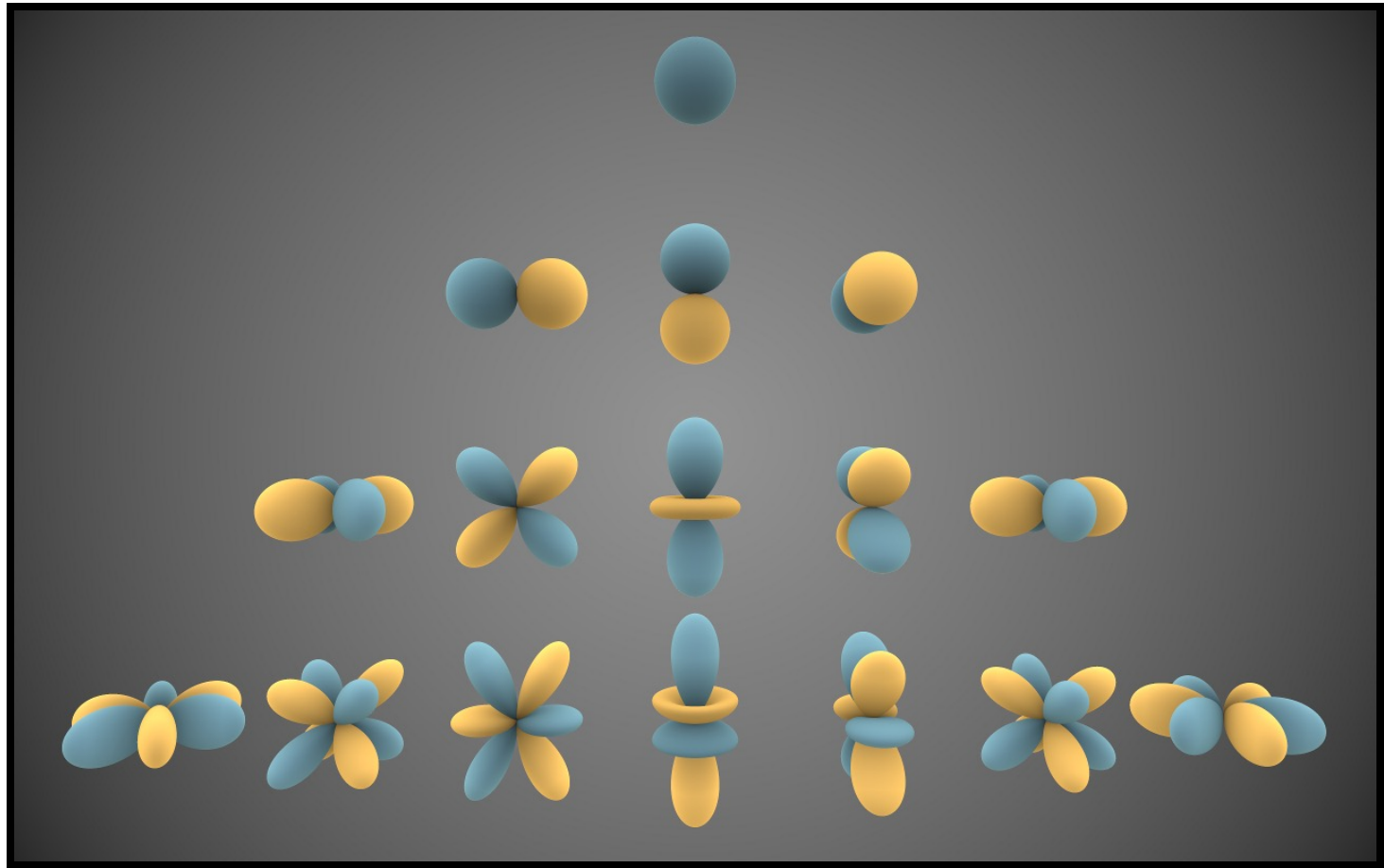


$$\frac{\partial u}{\partial t} = -\Delta u$$

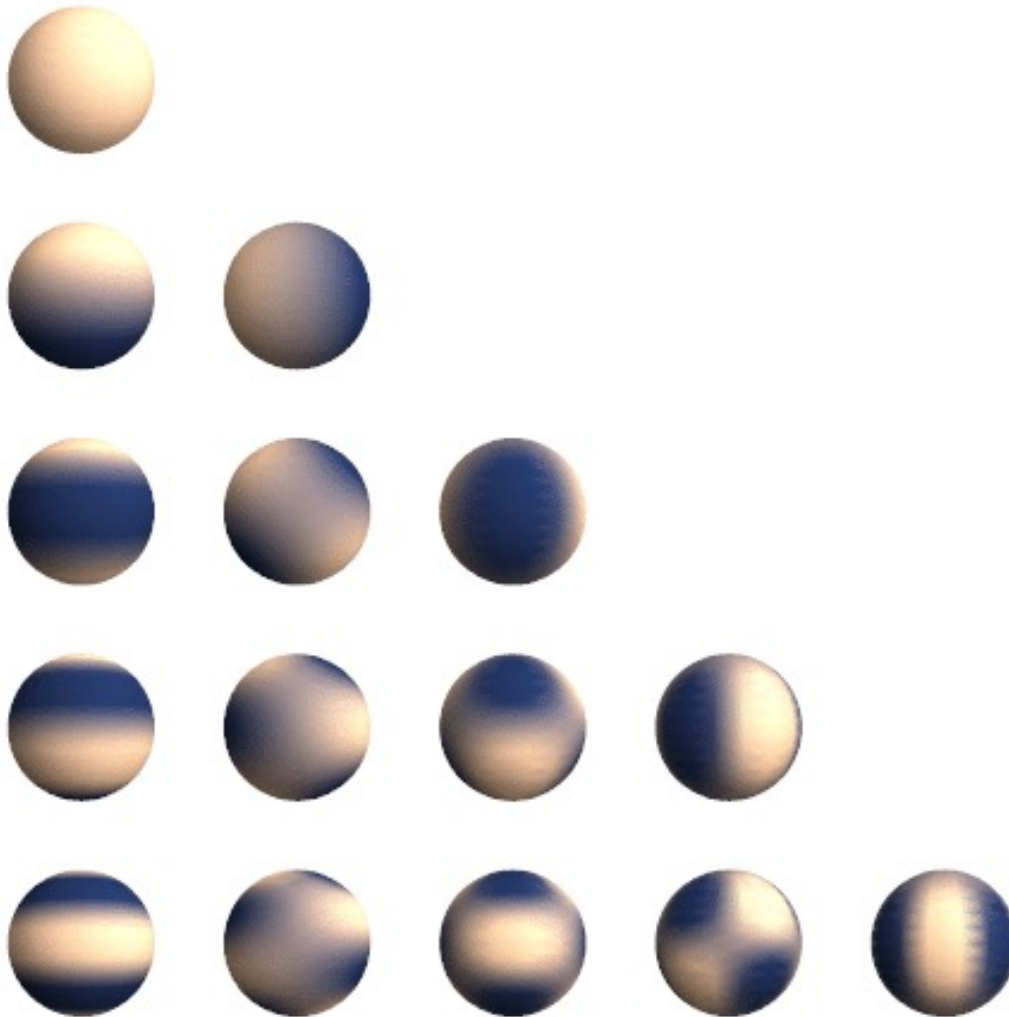
http://graphics.stanford.edu/courses/cs468-10-fall/LectureSlides/11_shape_matching.pdf

Heat equation

Spherical Harmonics



Spherical Harmonics



Weyl's Law

$$N(\lambda) := \# \text{ eigenfunctions } \leq \lambda$$

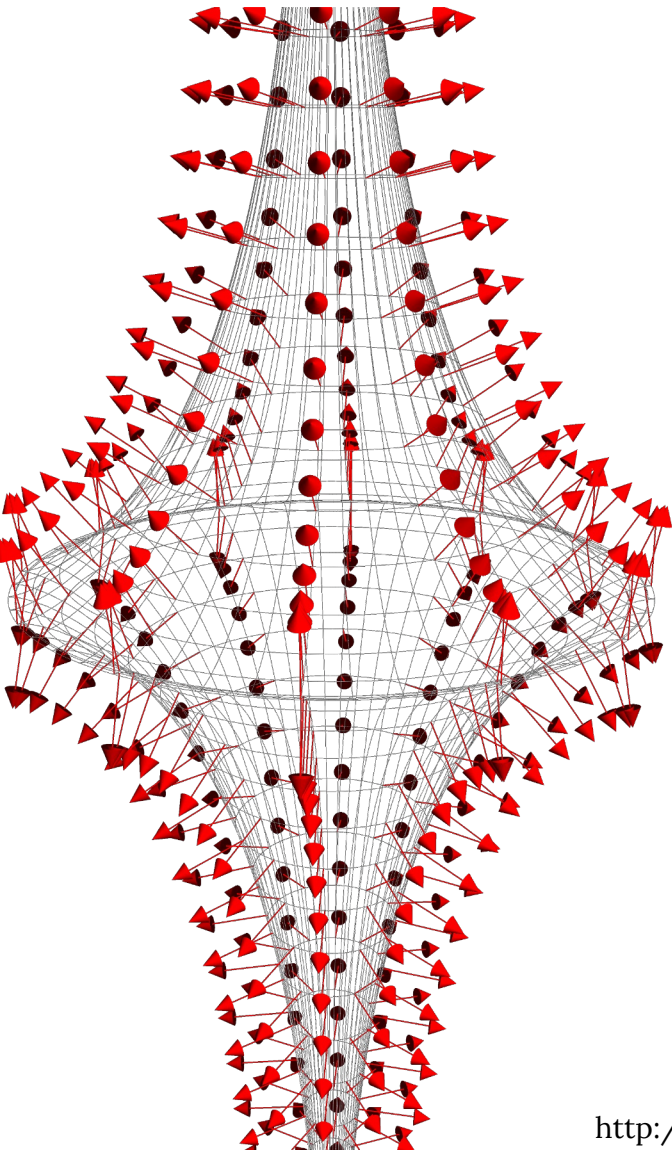
$$\omega_d := \text{volume of unit ball in } \mathbb{R}^d$$

$$\lim_{\lambda \rightarrow \infty} \frac{N(\lambda)}{\lambda^{d/2}} = (2\pi)^{-d} \omega_d \text{vol}(\Omega)$$

$$\text{Corollary: } \text{vol}(\Omega) = (2\pi)^d \lim_{R \rightarrow \infty} \frac{N(R)}{R^{d/2}}$$

$$\text{For surfaces: } \lambda_n \sim \frac{4\pi}{\text{vol}(\Omega)} n$$

Laplacian of xyz function



$$\Delta \vec{x} = \frac{1}{2} (\kappa_1 + \kappa_2) N$$

Intuition:
Laplacian measures difference with neighbors.