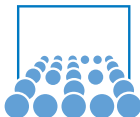


Scientific Computing I

Module 8: An Introduction to Finite Element Methods

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Part I: Introduction to Finite Element Methods

The Model Problem

FEM Main Ingredients

- Weak Forms and Weak Solutions
- FEM and the Residual Equation
- Test and Shape Functions

Assembling the System of Equations

- Example Problem: 1D Poisson
- Stiffness Matrix for Linear Nodal Basis Functions

A Road to Theory

Time-Dependent Problems

The Model Problem: Poisson Equation

- 2D Poisson Equation on unit square:

$$\frac{\partial^2}{\partial x^2} u(x, y) + \frac{\partial^2}{\partial y^2} u(x, y) = f(x, y) \quad \text{in } \Omega = (0, 1)^2$$

- Dirichlet boundary conditions:

$$u(x, y) = g(x, y) \quad \text{on } \partial\Omega$$

- **new for FEM**: compute a function to approximate $u(x, y)$
(instead of approximate values at certain grid points)

Finite Elements – Main Ingredients

1. solve *weak form* of PDE to reduce regularity properties

$$u'' = f \quad \longrightarrow \quad \int v' u' \, dx = \int v f \, dx$$

→ allows additional *weak* solutions

2. compute a *function* as numerical solution

→ search in a function space W_h :

$$u_h = \sum_j u_j \varphi_j(x), \quad \text{span}\{\varphi_1, \dots, \varphi_J\} = W_h$$

3. find weak solutions of simple form:
for example piecewise linear functions and choose basis functions with *local support* (“hat functions”)
→ leads to system of linear equations

Weak Forms and Weak Solutions

- consider a PDE $Lu = f$ (e.g. $Lu = \Delta u$ or $Lu = u''$)
- transformation to the *weak form*:

$$\langle Lu, v \rangle = \int vLu \, dx = \int vf \, dx = \langle f, v \rangle \quad \forall v \in V$$

V a certain class of functions

- “real solution” u also solves the weak form
however, *additional, weak solutions* are now allowed
- $\langle Lu, v \rangle$ a *bilinear form*; often written as:

$$a(u, v) = \langle f, v \rangle \quad \forall v \in V$$

Weak Form of the Poisson Equation

- Poisson equation with Dirichlet conditions:

$$-\Delta u = f \quad \text{in } \Omega, u = 0 \quad \text{on } \delta\Omega$$

- weak form:

$$-\int_{\Omega} v \Delta u \, d\Omega = \int_{\Omega} v f \, d\Omega \quad \forall v$$

- apply divergence theorem:

$$-\int_{\Omega} v \Delta u \, d\Omega = \int_{\Omega} \nabla v \cdot \nabla u \, d\Omega - \int_{\partial\Omega} v \cdot \nabla u \, ds$$

- choose functions v such that $v = 0$ on $\partial\Omega$:

$$\int_{\Omega} \nabla v \cdot \nabla u \, d\Omega = \int_{\Omega} v f \, d\Omega \quad \forall v$$

Weak Form of the Poisson Equation (2)

- Poisson equation with Dirichlet conditions:

$$-\Delta u = f \quad \text{in } \Omega, u = 0 \quad \text{on } \delta\Omega$$

- transformed into weak form:

$$\int_{\Omega} \nabla v \cdot \nabla u \, d\Omega = \int_{\Omega} v f \, d\Omega \quad \forall v$$

- weaker requirements for a solution u :
twice differentiable \rightarrow *first derivative integrable*

FEM and the Residual Equation

- for a general PDE $Lu = f$, the **residual** is defined as

$$r(x) := f(x) - Lu(x) \stackrel{!}{=} 0$$

- in the weak form (multiply with test function and integrate) we obtain

$$\int v(x) r(x) = \int v(x)(f(x) - Lu(x)) dx = 0 \quad \text{for all } v$$

- remember that $\int f(x)g(x) dx$ is the standard scalar product on functions
- hence: the residual of the weak solution has to be **orthogonal** to all test functions

Test and Shape Functions

- search for solution functions u_h of the form

$$u_h = \sum_j u_j \varphi_j(x)$$

the $\varphi_j(x)$ are typically called **shape** or **ansatz** functions

- the basis functions $\varphi_j(x)$ build a vector space (i.e., a **function space**) W_h

$$\text{span}\{\varphi_1, \dots, \varphi_J\} = W_h$$

- insert into weak formulation

$$\int vL\left(\sum_j u_j \varphi_j(x)\right) dx = \int vf dx \quad \forall v \in V$$

Test and Shape Functions (2)

- choose a basis $\{\psi_i\}$ of the *test* space V_h
- then: if all basis functions ψ_i satisfy

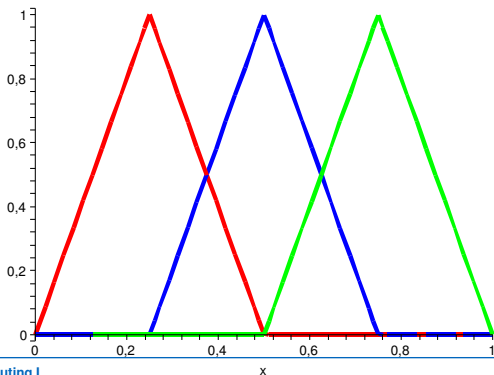
$$\int \psi_i L\left(\sum_j u_j \varphi_j(x)\right) dx = \int \psi_i f dx \quad \forall \psi_i$$

then all $v \in V_h$ satisfy the equation

- the $\{\psi_i\}$ are therefore often called **test functions**
- we obtain a system of equations for unknowns u_j :
one equation for each test function ψ_i
- V_h is often chosen to be identical to W_h (**Ritz-Galerkin method**)
→ we then have as many equations as unknowns

Example: Nodal Basis

$$\varphi_i(x) := \begin{cases} \frac{1}{h}(x - x_{i-1}) & x_{i-1} < x < x_i \\ \frac{1}{h}(x_{i+1} - x) & x_i < x < x_{i+1} \\ 0 & \text{otherwise} \end{cases}$$



Assembling the System of Equations

- L linear \Rightarrow system of linear equations

$$\sum_j \underbrace{\left(\int \psi_i L \varphi_j(x) \, dx \right)}_{=: A_{ij}} u_j = \int \psi_i f \, dx \quad \forall \psi_i$$

- aim: make matrix A *sparse* \rightarrow most $A_{ij} = 0$
- approach: local basis functions on a discretisation grid
- ψ_j, φ_j zero everywhere except in grid cells adjacent to grid point x_j
- $A_{ij} = 0$, if ψ_i and φ_j don't overlap

Example Problem: 1D Poisson

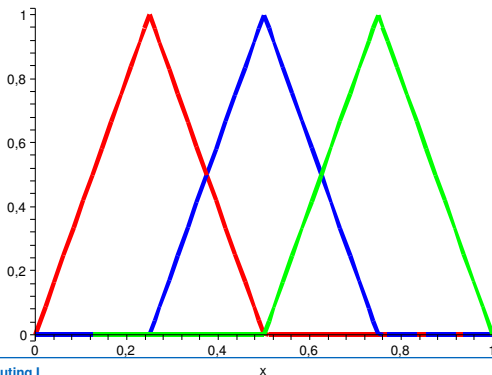
- in 1D: $-u''(x) = f(x)$ on $\Omega = (0, 1)$,
hom. Dirichlet boundary cond.: $u(0) = u(1) = 0$
- weak form:

$$\int_0^1 v'(x) \cdot u'(x) \, dx = \int_0^1 v(x) f(x) \, dx \quad \forall v$$

- computational grid:
 $x_i = ih$, (for $i = 1, \dots, n - 1$); mesh size $h = 1/n$
- $V_h = W_h$: piecewise linear functions
(on intervals $[x_i, x_{i+1}]$)

Nodal Basis

$$\varphi_i(x) := \begin{cases} \frac{1}{h}(x - x_{i-1}) & x_{i-1} < x < x_i \\ \frac{1}{h}(x_{i+1} - x) & x_i < x < x_{i+1} \\ 0 & \text{otherwise} \end{cases}$$



Nodal Basis – Derivatives and Integrals

Compute derivative of basis functions:

$$\varphi_i'(x) := \begin{cases} \frac{1}{h} & x_{i-1} < x < x_i \\ -\frac{1}{h} & x_i < x < x_{i+1} \\ 0 & \text{otherwise} \end{cases}$$

Compute integrals of weak form:

- $\int \varphi_i'(x) \varphi_i'(x) dx = \int_{x_{i-1}}^{x_i} \frac{1}{h} \cdot \frac{1}{h} dx + \int_{x_i}^{x_{i+1}} \left(-\frac{1}{h}\right) \left(-\frac{1}{h}\right) dx = \frac{2}{h}$
- $\int \varphi_i'(x) \varphi_{i+1}'(x) dx = \int_{x_i}^{x_{i+1}} \left(-\frac{1}{h}\right) \frac{1}{h} dx = -\frac{1}{h}$
- $\int \varphi_i'(x) \varphi_{i-1}'(x) dx = -\frac{1}{h}$ (same computation)
- $\int \varphi_i'(x) \varphi_j'(x) dx = 0$ for all $j \neq i, i \pm 1$
(supports of basis functions do not overlap!)

Nodal Basis – System of Equations

- stiffness matrix:

$$\frac{1}{h} \begin{pmatrix} 2 & -1 & & & \\ -1 & 2 & \ddots & & \\ & \ddots & \ddots & \ddots & \\ & & & -1 & 2 \\ & & & & -1 & 2 \end{pmatrix}$$

- right hand sides (assume $f(x) = \alpha \in \mathbb{R}$):

$$\int_0^1 \varphi_i(x) f(x) dx = \int_0^1 \varphi_i(x) \alpha dx = \alpha h$$

- system of equations very similar to finite differences
- exercise: compute right-hand-side vector, if $f(x) := \sum f_j \phi_j(x)$

Outlook: A Road to Theory

- weak formulation is equivalent to variational approach: solution u minimises an energy functional
- *best approximation* property:

$$\|u - u_h^{FE}\|_a \leq \inf_{u_h \in V} \|u - u_h\|_a$$

in terms of the norm induced by the bilinear form a (energy norm)

- thus: error bounded by interpolation error (in energy norm)

(details in lecture *Numerical Programming II* ...)

Time-Dependent Problems

Example: 1D Heat Equation

- $u_t = u_{xx} + f$ on domain $\Omega = [0, 1]$ for $t \in [0, t_{\text{end}}]$
- spatial discretisation: weak form

$$\int v u_t \, dx = \int v u_{xx} \, dx + \int v f \, dx$$
$$\frac{\partial}{\partial t} \left(\int v u \, dx \right) = \int v u_{xx} \, dx + \int v f \, dx$$

- spatial discretisation – finite elements:

$$\frac{\partial}{\partial t} (M_h u_h) = A_h u_h + f_h$$

M_h : mass matrix, A_h : stiffness matrix, $u_h = u_h(t)$

Time-Dependent Problems (2)

Solve a system of ordinary differential equations:

- after spatial discretisation (M_h constant):

$$\frac{\partial}{\partial t} M_h (u_h) = A_h u_h + f_h$$

- u_h a vector of time-dependent functions:

$$u_h = (u_1(t), \dots, u_i(t), \dots, u_n(t))^T$$

- usually: approximate M_h by a simpler matrix (diagonal matrix, e.g.) → **mass lumping**

Part II: Implementation of Finite Element Methods

Element Stiffness Matrices

Element-Oriented Computation of Stiffness Matrices

Example: 1D Poisson

Example: 2D Poisson

Typical Workflow

Reference Elements and Stiffness Matrices

Element-Oriented Computation on Unstructured Meshes

Accumulation of Global Stiffness Matrix

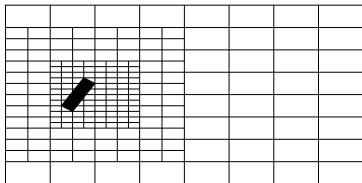
Simple Example: 1D Poisson

Outlook: Extension to 2D and 3D

Outlook: Further Components and Aspects of FEM

Element Stiffness Matrices

Finite Element methods are often used for complicated meshes:



Questions:

- how to set up the system of equations efficiently?
- is it possible to use stencil notation??

⇒ Switch to element stiffness matrices!

Element Stiffness Matrices (2)

- domain Ω subdivided into finite elements $\Omega^{(k)}$:

$$\Omega = \Omega^{(1)} \cup \Omega^{(2)} \cup \dots \cup \Omega^{(n)}$$

- observation: basis functions are defined element-wisely
- use: $\int_a^b f(x) dx = \int_a^c f(x) dx + \int_c^b f(x) dx$
- element-wise evaluation of the integrals:

$$\int_{\Omega} \nabla v \cdot \nabla u \, dx = \sum_k \int_{\Omega^{(k)}} \nabla v \cdot \nabla u \, dx$$
$$\int_{\Omega} v f \, dx = \sum_k \int_{\Omega^{(k)}} v f \, dx$$

Element Stiffness Matrices (3)

- leads to local stiffness matrices for each element:

$$\underbrace{\int_{\Omega^{(k)}} \nabla \phi_i \cdot \nabla \phi_j \, dx}_{=: A_{ij}^{(k)}}$$

- and respective element systems:

$$A^{(k)} x = b^{(k)}$$

- accumulate to obtain global system:

$$\underbrace{\sum_k A^{(k)}}_{=: A} x = \sum_k b^{(k)}$$

Element Stiffness Matrices (4)

Some comments on notation:

- assume: 1D problem, n elements (i.e. intervals)
- in each element only two basis functions are non-zero!
- hence, almost all $A_{ij}^{(k)}$ are zero:

$$A_{ij}^{(k)} = \int_{\Omega^{(k)}} \nabla \phi_i \cdot \nabla \phi_j \, dx$$

- only 2×2 elements of $A^{(k)}$ are non-zero
- therefore convention to omit zero columns/rows
⇒ leaves only unknowns that are in $\Omega^{(k)}$
⇒ notation: write this matrix as $\widehat{A}^{(k)}$

Example: 1D Poisson

- $\Omega = [0, 1]$ splitted into $\Omega^{(k)} = [x_{k-1}, x_k]$
- nodal basis; leads to element stiffness matrix:

$$\hat{A}^{(k)} = \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix}$$

- consider case with only three unknowns (i.e., 3 basis functions):

$$A^{(1)} + A^{(2)} = \begin{pmatrix} 1 & -1 & 0 \\ -1 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & -1 \\ 0 & -1 & 1 \end{pmatrix}$$

- in stencil notation:

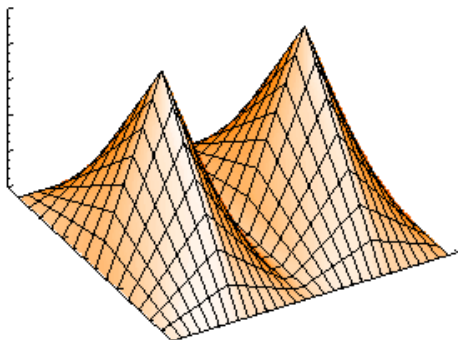
$$[-1 \quad 1^*] + [1^* \quad -1] \rightarrow [-1 \quad 2 \quad -1]$$

Example: 2D Poisson

- $-\Delta u = f$ on domain $\Omega = [0, 1]^2$
- splitted into $\Omega^{(i,j)} = [x_{i-1}, x_i] \times [x_{j-1}, x_j]$
- bilinear basis functions

$$\varphi_{ij}(x, y) = \varphi_i(x)\varphi_j(y)$$

- “pagoda” functions



Example: 2D Poisson (2)

- leads to element stiffness matrix:

$$\widehat{A}^{(k)} = \begin{pmatrix} 2 & -\frac{1}{2} & -\frac{1}{2} & -1 \\ -\frac{1}{2} & 2 & -1 & -\frac{1}{2} \\ -\frac{1}{2} & -1 & 2 & -\frac{1}{2} \\ -1 & -\frac{1}{2} & -\frac{1}{2} & 2 \end{pmatrix}$$

- accumulation leads to 9-point stencil

$$\begin{bmatrix} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{bmatrix}$$

- exercise at home: compute $\widehat{A}^{(k)}$ and assemble global matrix (and compare with stencil)

Typical Workflow

1. choose elements:
 - quadratic or cubic cells
 - triangles (structured, unstructured)
 - tetrahedra, etc.
2. set up basis functions for each element $\Omega^{(k)}$;
for example, at all nodes $x_j \in \Omega^{(k)}$

$$\begin{aligned}\varphi_i(x_i) &= 1 \\ \varphi_i(x_j) &= 0 \quad \text{for all } j \neq i\end{aligned}$$

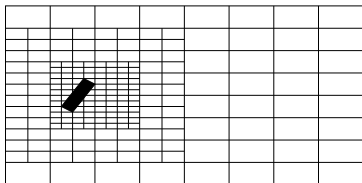
3. for element stiffness matrix, compute all

$$\widehat{A}_{ij}^{(k)} = \int_{\Omega^{(k)}} \varphi_i L \varphi_j \, d\Omega$$

4. accumulate global stiffness matrix A (and rhs)

Element-Oriented Computation on Unstructured Meshes

Recall: FEM often used for complicated meshes:



(Re-)computation of element matrices required for each element?

- left grid: no (up to scaling with mesh size)
- right grid: yes?

⇒ requires a closer look at the computation of element matrices

Element Stiffness Matrices – Notation Revisited

- recall notation for local stiffness matrices $A_{ij}^{(k)}$:

$$A_{ij}^{(k)} = \int_{\Omega^{(k)}} \nabla \phi_i(x) \cdot \nabla \phi_j(x) \, dx$$

⇒ which basis functions ϕ_i, ϕ_j belong to element k ?

- switch to element-local numbering of basis functions:

$$\widehat{A}_{\mu\nu}^{(k)} = \int_{\Omega^{(k)}} \nabla \phi_{\mu}^{(k)}(x) \cdot \nabla \phi_{\nu}^{(k)}(x) \, dx$$

where $\phi_{\mu}^{(k)}(x) = \phi_i(x)$ and $\phi_{\nu}^{(k)}(x) = \phi_j(x)$ in $\Omega^{(k)}$

- requires a mapping $\phi_{\mu}^{(k)} \rightarrow \phi_i$ (and $\phi_{\nu}^{(k)} \rightarrow \phi_j$),
i.e., a function $\iota^{(k)}$ with $i = \iota^{(k)}(\mu)$ and $j = \iota^{(k)}(\nu)$

Accumulation of Global Stiffness Matrix

- note the different dimensions of $A^{(k)}$ and $\widehat{A}^{(k)}$:
 $\widehat{A}^{(k)}$ omits zero rows and columns of $A^{(k)}$
- formulated via a projection matrix:

$$A^{(k)} = (P^{(k)})^T \widehat{A}^{(k)} P^{(k)} \quad \text{with } P_{\mu,i}^{(k)} := \begin{cases} 1 & \text{if } i = \iota^{(k)}(\mu) \\ 0 & \text{otherwise} \end{cases}$$

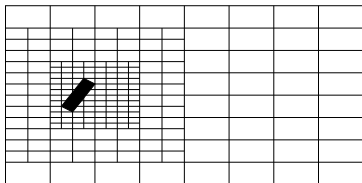
- recall computation of global stiffness matrix:

$$A := \sum_k A^{(k)} = \sum_k (P^{(k)})^T \widehat{A}^{(k)} P^{(k)}$$

- hence, for each element:
 - compute element stiffness matrix $\widehat{A}^{(k)}$
 - determine position of matrix elements $\widehat{A}^{(k)}$ in $A^{(k)}$
 \rightarrow based on mapping $\iota^{(k)}(\mu)$
 - add non-zero elements of $A^{(k)} = (P^{(k)})^T \widehat{A}^{(k)} P^{(k)}$ to global matrix A

Element Stiffness Matrices and Meshes

Recall our initial question:



(Re-)computation of $\hat{A}^{(k)}$ required for each element?

- left grid: no (up to scaling with mesh size)
- right grid: yes?

⇒ efficient computation of $\hat{A}^{(k)}$ via reference elements

Simple Example: 1D Poisson

Consider FEM for 1D Poisson on an adaptive grid:

- grid points given as x_i , not necessarily equidistant; define elements $\Omega^{(k)} = [x_k, x_{k+1}]$
- piecewise linear basis functions (“hat functions”) $\phi_i(x)$; $\phi_i(x)$ non-zero only on two elements: $\Omega^{(i-1)}$ and $\Omega^{(i)}$
- mapping local to global indices: $\iota^{(k)}(1) := k$ and $\iota^{(k)}(2) := k + 1$
- wanted: $\widehat{A}_{\mu,\nu}^{(k)} := \int_{\Omega^{(k)}} \frac{\partial}{\partial x} \phi_{\mu}^{(k)}(x) \frac{\partial}{\partial x} \phi_{\nu}^{(k)}(x) dx$ for every element k

Introduce **reference element** Ω_{ref} with linear basis functions Φ_{μ} :

$$\Phi_1(\xi) := \xi \quad \Phi_2(\xi) := 1 - \xi \quad \xi \in \Omega_{\text{ref}} := [0, 1]$$

and a mapping $x = \chi^{(k)}(\xi)$ for each $\Omega^{(k)}$ defined as

$$\chi^{(k)}(\xi) := x_k + \xi(x_{k+1} - x_k)$$

such that $\phi_{\mu}^{(k)}(x) = \phi_{\mu}^{(k)}(\chi^{(k)}(\xi)) := \Phi_{\mu}(\xi)$ for $x \in \Omega^{(k)}$.

Simple Example: 1D Poisson (2)

We need to compute

$$\widehat{A}_{\mu,\nu}^{(k)} := \int_{x_k}^{x_{k+1}} \frac{\partial}{\partial x} \phi_{\mu}^{(k)}(x) \frac{\partial}{\partial x} \phi_{\nu}^{(k)}(x) dx = \int_{\chi^{(k)}(0)}^{\chi^{(k)}(1)} \frac{\partial}{\partial x} \phi_{\mu}^{(k)}(x) \frac{\partial}{\partial x} \phi_{\nu}^{(k)}(x) dx$$

Compare integration by substitution: $\int_{g(a)}^{g(b)} f(x) dx = \int_a^b f(g(t))g'(t) dt$

$$\widehat{A}_{\mu,\nu}^{(k)} = \int_0^1 \frac{\partial}{\partial x} \phi_{\mu}^{(k)}(\chi^{(k)}(\xi)) \frac{\partial}{\partial x} \phi_{\nu}^{(k)}(\chi^{(k)}(\xi)) (x_{k+1} - x_k) d\xi.$$

Note that:

- $\frac{\partial}{\partial \xi} \chi_k(\xi) = (x_{k+1} - x_k)$ corresponds to the factor $g'(t)$ in the substitution rule
- we still have to deal with the partial derivatives in x

Simple Example: 1D Poisson (3)

We require the chain rule, $\frac{\partial f}{\partial x} = \frac{\partial f}{\partial g} \frac{\partial g}{\partial x}$, to obtain:

$$\frac{\partial}{\partial x} \phi_{\mu}^{(k)}(\chi^{(k)}(\xi)) = \frac{\partial}{\partial x} \Phi_{\mu}(\xi) = \frac{\partial}{\partial \xi} \Phi_{\mu}(\xi) \frac{\partial \xi}{\partial x}$$

As $x = \chi^{(k)}(\xi) := x_k + \xi(x_{k+1} - x_k)$, we have $\xi = \frac{x - x_k}{x_{k+1} - x_k}$ and thus:

$$\frac{\partial}{\partial \xi} \Phi_{\mu}(\xi) \frac{\partial \xi}{\partial x} = \frac{\partial}{\partial \xi} \Phi_{\mu}(\xi) \frac{1}{x_{k+1} - x_k}$$

Finally, we get:

$$\begin{aligned} \widehat{A}_{\mu,\nu}^{(k)} &= \int_0^1 \frac{\partial}{\partial x} \phi_{\mu}^{(k)}(\chi^{(k)}(\xi)) \frac{\partial}{\partial x} \phi_{\nu}^{(k)}(\chi^{(k)}(\xi)) (x_{k+1} - x_k) d\xi \\ &= \int_0^1 \frac{\partial}{\partial \xi} \Phi_{\mu}(\xi) \frac{\partial}{\partial \xi} \Phi_{\nu}(\xi) \frac{1}{(x_{k+1} - x_k)^2} (x_{k+1} - x_k) d\xi. \end{aligned}$$

Simple Example: 1D Poisson (4)

Altogether, element stiffness matrices are computed as:

$$\widehat{\mathbf{A}}_{\mu,\nu}^{(k)} = \frac{1}{x_{k+1} - x_k} \int_0^1 \frac{\partial}{\partial \xi} \Phi_\mu(\xi) \frac{\partial}{\partial \xi} \Phi_\nu(\xi) d\xi$$

With $\Phi_1(\xi) = \xi$ and $\Phi_2(\xi) = 1 - \xi$, we obtain that

$$\widehat{\mathbf{A}}^{(k)} = \frac{1}{x_{k+1} - x_k} \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix}$$

Observations:

- the integral values only depend on the reference element $\Omega_{\text{ref}} = [0, 1]$ and the reference basis functions Φ_μ, Φ_ν
- all other element matrices are obtained by simple scaling
- we did **not** use that Φ_μ, Φ_ν are linear functions;
same computation for more complicated basis functions!

Outlook: Extension to 2D and 3D

For 2D, 3D, etc., we require the multidimensional substitution rule:

$$\int_{\Omega^{(k)}} f(x, y, z) \, d\Omega = \int_{\Omega_{\text{ref}}} f(x(\xi, \eta, \zeta), y(\xi, \eta, \zeta), z(\xi, \eta, \zeta)) |\mathcal{J}| \, d\xi \, d\eta \, d\zeta$$

where $|\mathcal{J}|$ is the determinant of the Jacobian:

$$|\mathcal{J}| = \begin{vmatrix} \frac{\partial x}{\partial \xi} & \frac{\partial x}{\partial \eta} & \frac{\partial x}{\partial \zeta} \\ \frac{\partial y}{\partial \xi} & \frac{\partial y}{\partial \eta} & \frac{\partial y}{\partial \zeta} \\ \frac{\partial z}{\partial \xi} & \frac{\partial z}{\partial \eta} & \frac{\partial z}{\partial \zeta} \end{vmatrix}$$

and also the multidimensional chain rule.

Result:

- similar, element-wise computation of stiffness matrices via reference elements
- Jacobian instead of factor $\frac{1}{x_{k+1} - x_k}$; more complicated, in general

Outlook: Further Components and Aspects of FEM

Additional components and “features” of Finite Element Methods:

- **mesh generation:**
structured/unstructured meshes consisting of triangles, tetrahedra, rectangles, cuboids, quadrilaterals, hexahedrals, prisms, ...
- **higher-order basis functions:**
polynomials of higher degree in various dimensions; “nodal” vs. “spectral” elements, ...
- **quadrature rules for integration:**
Gaussian quadrature, e.g., to compute integrals of weak forms; resp. choice of quadrature points for certain elements?
- **solving the system of equations:**
e.g., set up a global system of equations explicitly, or work directly on element representation?

... and many more ...