

Study Guide: Solving differential equations with finite elements

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0.1 Differential equation models

Our aim is to extend the ideas for approximating f by u , or solving

$$u = f$$

to real differential equations like

$$-u'' + bu = f, \quad u(0) = 1, \quad u'(L) = D$$

Three methods are addressed:

1. least squares
2. Galerkin/projection

3. collocation (interpolation)

Method 2 will be totally dominating!

0.1.1 Abstract differential equation

$$\mathcal{L}(u) = 0, \quad x \in \Omega \quad (1)$$

Examples (1D problems):

$$\mathcal{L}(u) = \frac{d^2 u}{dx^2} - f(x), \quad (2)$$

$$\mathcal{L}(u) = \frac{d}{dx} \left(\alpha(x) \frac{du}{dx} \right) + f(x), \quad (3)$$

$$\mathcal{L}(u) = \frac{d}{dx} \left(\alpha(u) \frac{du}{dx} \right) - au + f(x), \quad (4)$$

$$\mathcal{L}(u) = \frac{d}{dx} \left(\alpha(u) \frac{du}{dx} \right) + f(u, x) \quad (5)$$

0.1.2 Abstract boundary conditions

$$\mathcal{B}_0(u) = 0, \quad x = 0, \quad \mathcal{B}_1(u) = 0, \quad x = L \quad (6)$$

Examples:

$$\mathcal{B}_i(u) = u - g, \quad \text{Dirichlet condition} \quad (7)$$

$$\mathcal{B}_i(u) = -\alpha \frac{du}{dx} - g, \quad \text{Neumann condition} \quad (8)$$

$$\mathcal{B}_i(u) = -\alpha \frac{du}{dx} - h(u - g), \quad \text{Robin condition} \quad (9)$$

0.1.3 Reminder about notation

- $u_e(x)$ is the symbol for the *exact* solution of $\mathcal{L}(u_e) = 0$
- $u(x)$ denotes an *approximate* solution
- We seek $u \in V$
- $V = \text{span}\{\psi_0(x), \dots, \psi_N(x)\}$, V has basis $\{\psi_i\}_{i \in I}$
- $I = \{0, \dots, N\}$ is an index set
- $u(x) = \sum_{j \in I} c_j \psi_j(x)$
- Inner product: $(u, v) = \int_{\Omega} uv \, dx$
- Norm: $\|u\| = \sqrt{(u, u)}$

0.1.4 Residual-minimizing principles

- When solving $u = f$ we knew the error $e = f - u$ and could use principles for minimizing the error
- When solving $\mathcal{L}(u_e) = 0$ we do not know u_e and cannot work with the error $e = u_e - u$
- We only have the *error in the equation*: the residual R

Inserting $u = \sum_j c_j \psi_j$ in $\mathcal{L} = 0$ gives a residual

$$R = \mathcal{L}(u) = \mathcal{L}\left(\sum_j c_j \psi_j\right) \neq 0 \quad (10)$$

Goal: minimize R wrt $\{c_i\}_{i \in I}$ (and hope it makes a small e too)

$$R = R(c_0, \dots, c_N; x)$$

0.1.5 The least squares method

Idea: minimize

$$E = \|R\|^2 = (R, R) = \int_{\Omega} R^2 dx \quad (11)$$

Minimization wrt $\{c_i\}_{i \in I}$ implies

$$\frac{\partial E}{\partial c_i} = \int_{\Omega} 2R \frac{\partial R}{\partial c_i} dx = 0 \quad \Leftrightarrow \quad (R, \frac{\partial R}{\partial c_i}) = 0, \quad i \in I \quad (12)$$

$N + 1$ equations for $N + 1$ unknowns $\{c_i\}_{i \in I}$

0.1.6 The Galerkin method

Idea: make R orthogonal to V ,

$$(R, v) = 0, \quad \forall v \in V \quad (13)$$

This implies

$$(R, \psi_i) = 0, \quad i \in I \quad (14)$$

$N + 1$ equations for $N + 1$ unknowns $\{c_i\}_{i \in I}$

0.1.7 The Method of Weighted Residuals

Generalization of the Galerkin method: demand R orthogonal to some space W , possibly $W \neq V$:

$$(R, v) = 0, \quad \forall v \in W \quad (15)$$

If $\{w_0, \dots, w_N\}$ is a basis for W :

$$(R, w_i) = 0, \quad i \in I \quad (16)$$

- $N + 1$ equations for $N + 1$ unknowns $\{c_i\}_{i \in I}$
- Weighted residual with $w_i = \partial R / \partial c_i$ gives least squares

0.1.8 Terminology: test and trial Functions

- ψ_j used in $\sum_j c_j \psi_j$ is called *trial function*
- ψ_i or w_i used as weight in Galerkin's method is called *test function*

0.1.9 The collocation method

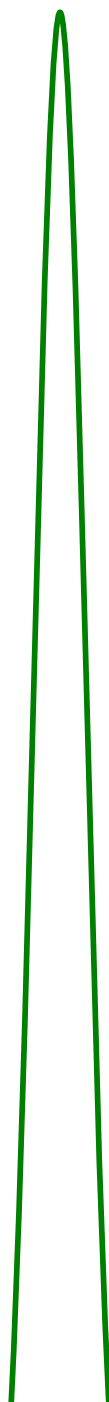
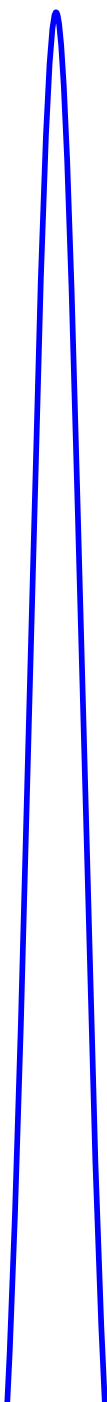
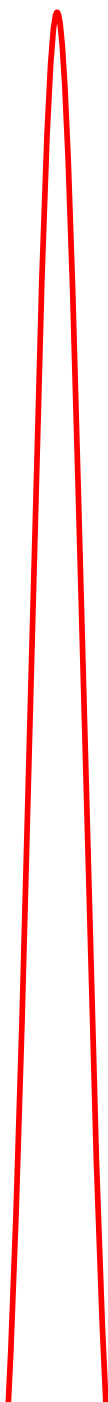
Idea: demand $R = 0$ at $N + 1$ points

$$R(x_i; c_0, \dots, c_N) = 0, \quad i \in I \quad (17)$$

Note: The collocation method is a weighted residual method with delta functions as weights

$$0 = \int_{\Omega} R(x; c_0, \dots, c_N) \delta(x - x_i) dx = R(x_i; c_0, \dots, c_N)$$

$$\text{property of } \delta(x): \quad \int_{\Omega} f(x) \delta(x - x_i) dx = f(x_i), \quad x_i \in \Omega \quad (18)$$



0.2 Examples on using the principles

Goal.

Exemplify the least squares, Galerkin, and collocation methods in a simple 1D problem with global basis functions.

0.2.1 The first model problem

$$-u''(x) = f(x), \quad x \in \Omega = [0, L], \quad u(0) = 0, \quad u(L) = 0 \quad (19)$$

Basis functions:

$$\psi_i(x) = \sin\left((i+1)\pi\frac{x}{L}\right), \quad i \in I \quad (20)$$

The residual:

$$\begin{aligned} R(x; c_0, \dots, c_N) &= u''(x) + f(x), \\ &= \frac{d^2}{dx^2} \left(\sum_{j \in I} c_j \psi_j(x) \right) + f(x), \\ &= - \sum_{j \in I} c_j \psi_j''(x) + f(x) \end{aligned} \quad (21)$$

0.2.2 Boundary conditions

Since $u(0) = u(L) = 0$ we must ensure that all $\psi_i(0) = \psi_i(L) = 0$. Then

$$u(0) = \sum_j c_j \psi_j(0) = 0, \quad u(L) = \sum_j c_j \psi_j(L)$$

- u known: Dirichlet boundary condition
- u' known: Neumann boundary condition
- Must have $\psi_i = 0$ where Dirichlet conditions apply

0.2.3 The least squares method; principle

$$\left(R, \frac{\partial R}{\partial c_i}\right) = 0, \quad i \in I$$

$$\frac{\partial R}{\partial c_i} = \frac{\partial}{\partial c_i} \left(\sum_{j \in I} c_j \psi_j''(x) + f(x) \right) = \psi_i''(x) \quad (22)$$

Because:

$$\frac{\partial}{\partial c_i} (c_0 \psi_0'' + c_1 \psi_1'' + \dots + c_{i-1} \psi_{i-1}'' + c_i \psi_i'' + c_{i+1} \psi_{i+1}'' + \dots + c_N \psi_N'') = \psi_i''$$

0.2.4 The least squares method; equation system

$$\left(\sum_j c_j \psi_j'' + f, \psi_i''\right) = 0, \quad i \in I \quad (23)$$

Rearrangement:

$$\sum_{j \in I} (\psi_i'', \psi_j'') c_j = -(f, \psi_i''), \quad i \in I \quad (24)$$

This is a linear system

$$\sum_{j \in I} A_{i,j} c_j = b_i, \quad i \in I$$

with

$$\begin{aligned} A_{i,j} &= (\psi_i'', \psi_j'') \\ &= \pi^4 (i+1)^2 (j+1)^2 L^{-4} \int_0^L \sin\left((i+1)\pi \frac{x}{L}\right) \sin\left((j+1)\pi \frac{x}{L}\right) dx \\ &= \begin{cases} \frac{1}{2} L^{-3} \pi^4 (i+1)^4 & i = j \\ 0, & i \neq j \end{cases} \end{aligned} \quad (25)$$

$$b_i = -(f, \psi_i'') = (i+1)^2 \pi^2 L^{-2} \int_0^L f(x) \sin\left((i+1)\pi \frac{x}{L}\right) dx \quad (26)$$

0.2.5 Orthogonality of the basis functions gives diagonal matrix

Useful property:

$$\int_0^L \sin\left((i+1)\pi \frac{x}{L}\right) \sin\left((j+1)\pi \frac{x}{L}\right) dx = \delta_{ij}, \quad \Rightarrow (\psi_i'', \psi_j'') = \delta_{ij}, \quad \delta_{ij} = \begin{cases} \frac{1}{2} L & i = j \\ 0, & i \neq j \end{cases} \quad (27)$$

With diagonal $A_{i,j}$ we can easily solve for c_i :

$$c_i = \frac{2L}{\pi^2 (i+1)^2} \int_0^L f(x) \sin\left((i+1)\pi \frac{x}{L}\right) dx \quad (28)$$

0.2.6 Least squares method; solution

Let's sympy do the work ($f(x) = 2$):

```
from sympy import *
import sys

i, j = symbols('i j', integer=True)
x, L = symbols('x L')
f = 2
a = 2*L/(pi**2*(i+1)**2)
c_i = a*integrate(f*sin((i+1)*pi*x/L), (x, 0, L))
c_i = simplify(c_i)
print c_i
```

$$c_i = 4 \frac{L^2 \left((-1)^i + 1 \right)}{\pi^3 (i^3 + 3i^2 + 3i + 1)}$$

$$u(x) = \sum_{k=0}^{N/2} \frac{8L^2}{\pi^3 (2k+1)^3} \sin \left((2k+1)\pi \frac{x}{L} \right). \quad (29)$$

- Fast decay: $c_2 = c_0/27$, $c_4 = c_0/125$
- Only one term might be good enough

$$u(x) \approx \frac{8L^2}{\pi^3} \sin \left(\pi \frac{x}{L} \right).$$

0.2.7 The Galerkin method; principle

$$(u'' + f, v) = 0, \quad \forall v \in V,$$

or

$$(u'', v) = -(f, v), \quad \forall v \in V \quad (30)$$

This is a *variational formulation* of the differential equation problem.
 $\forall v \in V$ means for all basis functions:

$$\left(\sum_{j \in I} c_j \psi_j'', \psi_i \right) = -(f, \psi_i), \quad i \in I \quad (31)$$

0.2.8 The Galerkin method; solution

Since $\psi_i'' \propto \psi_i$, Galerkin's method gives the same linear system and the same solution as the least squares method (in this particular example).

0.2.9 The collocation method

$R = 0$ or the differential equation must be satisfied at $N + 1$ points:

$$-\sum_{j \in I} c_j \psi_j''(x_i) = f(x_i), \quad i \in I \quad (32)$$

This is a linear system $\sum_j A_{i,j} = b_i$ with entries

$$A_{i,j} = -\psi_j''(x_i) = (j+1)^2 \pi^2 L^{-2} \sin \left((j+1)\pi \frac{x_i}{L} \right), \quad b_i = 2$$

Choose: $N = 0$, $x_0 = L/2$

$$c_0 = 2L^2/\pi^2$$

0.2.10 Comparison of the methods

- Exact solution: $u(x) = x(L - x)$
- Galerkin or least squares ($N = 0$): $u(x) = 8L^2\pi^{-3} \sin(\pi x/L)$
- Collocation method ($N = 0$): $u(x) = 2L^2\pi^{-2} \sin(\pi x/L)$.
- Max error in Galerkin/least sq.: $-0.008L^2$
- Max error in collocation: $0.047L^2$

0.3 Useful techniques

0.3.1 Integration by parts

Second-order derivatives will hereafter be integrated by parts

$$\begin{aligned}\int_0^L u''(x)v(x)dx &= -\int_0^L u'(x)v'(x)dx + [vu']_0^L \\ &= -\int_0^L u'(x)v'(x)dx + u'(L)v(L) - u'(0)v(0)\end{aligned}\quad (33)$$

Motivation:

- Lowers the order of derivatives
- Gives more symmetric forms (incl. matrices)
- Enables easy handling of Neumann boundary conditions
- Finite element basis functions φ_i have discontinuous derivatives (at cell boundaries) and are not suited for terms with φ_i''

0.3.2 Boundary function; principles

- What about nonzero Dirichlet conditions?
- E.g. $u(L) = D$
- Problem: $u(L) = \sum_j c_j \psi_j(L) = 0$ - always
- Remedy: $u(x) = B(x) + \sum_j c_j \psi_j(x)$
- Construct B such that $B(0) = u(0)$, $B(L) = u(L)$
- No restrictions of how $B(x)$ varies in the interior of Ω

0.3.3 Boundary function; example

$u(0) = C$ and $u(L) = D$. Choose

$$B(x) = L^{-1}(C(L-x) + Dx) : \quad B(0) = C, \quad B(L) = D$$

$$u(x) = L^{-1}(C(L-x) + Dx) + \sum_{j \in I} c_j \psi_j(x), \quad (34)$$

$$u(0) = C, \quad u(L) = 0$$

0.3.4 Abstract notation for variational formulations

The finite element literature (and much FEniCS documentation) applies an abstract notation for the variational formulation:

*Find $(u - B) \in V$ such that

$$a(u, v) = L(v) \quad \forall v \in V$$

0.3.5 Example on abstract notation

Given a variational formulation for $-u'' = f$:

$$\int_{\Omega} u'v' dx = \int_{\Omega} f v dx \quad \text{or} \quad (u', v') = (f, v) \quad \forall v \in V$$

Abstract formulation: find $(u - B) \in V$ such that

$$a(u, v) = L(v) \quad \forall v \in V$$

We identify

$$a(u, v) = (u', v'), \quad L(v) = (f, v)$$

0.3.6 Bilinear and linear forms

- $a(u, v)$ is a *bilinear form*
- $L(v)$ is a *linear form*

Linear form means

$$L(\alpha_1 v_1 + \alpha_2 v_2) = \alpha_1 L(v_1) + \alpha_2 L(v_2),$$

Bilinear form means

$$\begin{aligned} a(\alpha_1 u_1 + \alpha_2 u_2, v) &= \alpha_1 a(u_1, v) + \alpha_2 a(u_2, v), \\ a(u, \alpha_1 v_1 + \alpha_2 v_2) &= \alpha_1 a(u, v_1) + \alpha_2 a(u, v_2) \end{aligned}$$

In nonlinear problems: Find $(u - B) \in V$ such that $F(u; v) = 0 \quad \forall v \in V$

0.3.7 The linear system associated with abstract form

$$a(u, v) = L(v) \quad \forall v \in V$$

is equivalent to

$$a(u, \psi_i) = L(\psi_i) \quad i \in I$$

Insert $u = \sum_j c_j \psi_j$ and use linearity:

$$\sum_{j \in I} a(\psi_j, \psi_i) c_j = L(\psi_i) \quad i \in I$$

This is a linear system

$$\sum_{j \in I} A_{i,j} c_j = b_i, \quad i \in I$$

with

$$\begin{aligned} A_{i,j} &= a(\psi_j, \psi_i) \\ b_i &= L(\psi_i) \end{aligned}$$

0.3.8 Equivalence with minimization problem

If $a(u, v) = a(v, u)$,

$$a(u, v) = L(v) \quad \forall v \in V,$$

is equivalent to minimizing the functional

$$F(v) = \frac{1}{2}a(v, v) - L(v)$$

over all functions $v \in V$. That is,

$$F(u) \leq F(v) \quad \forall v \in V.$$

- Much used in the early days of finite elements
- Still much used in structural analysis and elasticity
- Not as general as Galerkin's method (since $a(u, v) = a(v, u)$)

0.4 Examples on variational formulations

Goal.

Derive variational formulations for many prototype differential equations in 1D that include

- variable coefficients
- mixed Dirichlet and Neumann conditions
- nonlinear coefficients

0.4.1 Variable coefficient; problem

$$-\frac{d}{dx} \left(\alpha(x) \frac{du}{dx} \right) = f(x), \quad x \in \Omega = [0, L], \quad u(0) = C, \quad u(L) = D. \quad (35)$$

- Variable coefficient $\alpha(x)$
- *Nonzero* Dirichlet conditions at $x = 0$ and $x = L$
- Must have $\psi_i(0) = \psi_i(L) = 0$
- $V = \text{span}\{\psi_0, \dots, \psi_N\}$
- $v \in V$: $v(0) = v(L) = 0$

$$u(x) = B(x) + \sum_{j \in I} c_j \psi_j(x)$$

$$B(x) = C + \frac{1}{L}(D - C)x$$

0.4.2 Variable coefficient; variational formulation (1)

$$R = -\frac{d}{dx} \left(\alpha \frac{du}{dx} \right) - f$$

Galerkin's method:

$$(R, v) = 0, \quad \forall v \in V,$$

or with integrals:

$$\int_{\Omega} \left(\frac{d}{dx} \left(\alpha \frac{du}{dx} \right) - f \right) v \, dx = 0, \quad \forall v \in V.$$

0.4.3 Variable coefficient; variational formulation (2)

Integration by parts:

$$-\int_{\Omega} \frac{d}{dx} \left(\alpha(x) \frac{du}{dx} \right) v \, dx = \int_{\Omega} \alpha(x) \frac{du}{dx} \frac{dv}{dx} \, dx - \left[\alpha \frac{du}{dx} v \right]_0^L.$$

Boundary terms vanish since $v(0) = v(L) = 0$

Variational formulation.

Find $(u - B) \in V$ such that

$$\int_{\Omega} \alpha(x) \frac{du}{dx} \frac{dv}{dx} \, dx = \int_{\Omega} f(x) v \, dx, \quad \forall v \in V,$$

Compact notation:

$$(\alpha u', v') = (f, v), \quad \forall v \in V$$

0.4.4 Variable coefficient; abstract notation

$$a(u, v) = L(v) \quad \forall v \in V,$$

$$a(u, v) = (\alpha u', v'), \quad L(v) = (f, v)$$

0.4.5 Variable coefficient; linear system

$v = \psi_i$ and $u = B + \sum_j c_j \psi_j$:

$$(\alpha B' + \alpha \sum_{j \in I} c_j \psi_j', \psi_i') = (f, \psi_i), \quad i \in I.$$

Reorder to form linear system:

$$\sum_{j \in I} (\alpha \psi_j', \psi_i') c_j = (f, \psi_i) + (a(D - C)L^{-1}, \psi_i'), \quad i \in I.$$

This is $\sum_j A_{i,j} c_j = b_i$ with

$$A_{i,j} = (\alpha \psi_j', \psi_i') = \int_{\Omega} \alpha(x) \psi_j'(x) \psi_i'(x) \, dx,$$

$$b_i = (f, \psi_i) + (a(D - C)L^{-1}, \psi_i') = \int_{\Omega} \left(f(x) \psi_i(x) + \alpha(x) \frac{D - C}{L} \psi_i'(x) \right) \, dx.$$

0.4.6 First-order derivative in the equation and boundary condition; problem

$$-u''(x) + bu'(x) = f(x), \quad x \in \Omega = [0, L], \quad u(0) = C, \quad u'(L) = E \quad (36)$$

New features:

- first-order derivative u' in the equation
- boundary condition with u' : $u'(L) = E$

Initial steps:

- Must force $\psi_i(0) = 0$ because of Dirichlet condition at $x = 0$
- Boundary function: $B(x) = C(L - x)/L$
- No requirements on $\psi_i(L)$ (no Dirichlet condition at $x = L$)

0.4.7 First-order derivative in the equation and boundary condition; details

$$u = \frac{C}{L}(L - x) + \sum_{j \in I} c_j \psi_j(x)$$

Galerkin's method: multiply by v , integrate over Ω , integrate by parts.

$$(-u'' + bu' - f, v) = 0, \quad \forall v \in V,$$

$$(u', v') + (bu', v) = (f, v) + [u'v]_0^L, \quad \forall v \in V,$$

$$(u'v') + (bu', v) = (f, v) + Ev(L), \quad \forall v \in V,$$

0.4.8 First-order derivative in the equation and boundary condition; observations

$$(u'v') + (bu', v) = (f, v) + Ev(L), \quad \forall v \in V,$$

Important:

- $[u'v]_0^L = u'(L)v(L) = Ev(L)$ because $v(0) = 0$ and $u'(L) = E$
- The boundary term can be used to implement Neumann conditions
- Forgetting the boundary term implies the condition $u' = 0$ (!)
- Such conditions are called *natural boundary conditions*

0.4.9 First-order derivative in the equation and boundary condition; abstract notation

Abstract notation:

$$a(u, v) = L(v) \quad \forall v \in V,$$

where

$$a(u, v) = (u', v') + (bu', v), \quad L(v) = (f + C, v) + Ev(L)$$

0.4.10 First-order derivative in the equation and boundary condition; linear system

Insert $u = B + \sum_j c_j \psi_j$ and $v = \psi_i$:

$$\sum_{j \in I} \underbrace{((\psi_j', \psi_i') + (b\psi_j', \psi_i))}_{A_{i,j}} c_j = \underbrace{(f, \psi_i) + (bCL^{-1}, \psi_i') + E\psi_i(L)}_{b_i}$$

Observation: $A_{i,j}$ is not symmetric because of the term

$$(b\psi_j', \psi_i) = \int_{\Omega} b\psi_j' \psi_i dx \neq \int_{\Omega} b\psi_i' \psi_j dx = (\psi_i', b\psi_j)$$

0.4.11 Terminology: natural and essential boundary conditions

$$(u', v') + (bu', v) = (f, v) + u'(L)v(L) - u'(0)v(0)$$

- Note: forgetting the boundary terms implies $u'(L) = u'(0) = 0$ (unless prescribe a Dirichlet condition)
- Conditions on u' are simply inserted in the variational form and called *natural conditions*
- Conditions on u at $x = 0$ requires modifying V (through $\psi_i(0) = 0$) and are known as *essential conditions*

Lesson learned.

It is easy to forget the boundary term when integrating by parts. That mistake may prescribe a condition on u' !

0.4.12 Nonlinear coefficient; problem

$$-(\alpha(u)u')' = f(u), \quad x \in [0, L], \quad u(0) = 0, \quad u'(L) = E. \quad (37)$$

- V : basis $\{\psi_i\}_{i \in I}$ with $\psi_i(0) = 0$ because of $u(0) = 0$
- How does the nonlinear coefficient $\alpha(u)$ impact the variational formulation?

0.4.13 Nonlinear coefficient; variational formulation

Galerkin: multiply by v , integrate, integrate by parts

$$\int_0^L \alpha(u) \frac{du}{dx} \frac{dv}{dx} dx = \int_0^L f(u)v dx + [\alpha(u)vu']_0^L \quad \forall v \in V$$

- $\alpha(u(0))v(0)u'(0) = 0$ since $v(0) = 0$
- $\alpha(u(L))v(L)u'(L) = \alpha(u(L))v(L)E$ since $u'(L) = E$

$$\int_0^L \alpha(u) \frac{du}{dx} \frac{dv}{dx} v dx = \int_0^L f(u)v dx + \alpha(u(L))v(L)E \quad \forall v \in V$$

or

$$(\alpha(u)u', v') = (f(u), v) + \alpha(L)v(L)E \quad \forall v \in V$$

0.4.14 Nonlinear coefficient; where does the nonlinearity cause challenges?

- Abstract notation: no $a(u, v)$ and $L(v)$ because a and L are nonlinear
- Abstract notation: $F(u; v) = 0 \quad \forall v \in V$
- What about forming a linear system? We get a *nonlinear* system of algebraic equations
- Must use methods like Picard iteration or Newton's method to solve nonlinear algebraic equations
- But: the variational formulation was not much affected by nonlinearities

0.4.15 Computing with Dirichlet and Neumann conditions; problem

$$-u''(x) = f(x), \quad x \in \Omega = [0, 1], \quad u'(0) = C, \quad u(1) = D$$

- Use a *global* polynomial basis $\psi_i \sim x^i$ on $[0, 1]$
- Because of $u(1) = D$: $\psi_i(1) = 0$
- Basis: $\psi_i(x) = (1 - x)^{i+1}$, $i \in I$
- $B(x) = Dx$

0.4.16 Computing with Dirichlet and Neumann conditions; details

$$A_{i,j} = (\psi'_j, \psi'_i) = \int_0^1 \psi'_i(x) \psi'_j(x) dx = \int_0^1 (i+1)(j+1)(1-x)^{i+j} dx,$$

$$\begin{aligned} b_i &= (2, \psi_i) - (D, \psi'_i) - C\psi_i(0) \\ &= \int_0^1 (2(1-x)^{i+1} - D(i+1)(1-x)^i) dx - C\psi_i(0) \end{aligned}$$

Can easily do the integrals with `sympy`. $N = 1$:

$$\begin{pmatrix} 1 & 1 \\ 1 & 4/3 \end{pmatrix} \begin{pmatrix} c_0 \\ c_1 \end{pmatrix} = \begin{pmatrix} -C + D + 1 \\ 2/3 - C + D \end{pmatrix}$$

$$c_0 = -C + D + 2, \quad c_1 = -1,$$

$$u(x) = 1 - x^2 + D + C(x - 1) \quad (\text{exact solution})$$

0.4.17 When the numerical method is exact

Let

$$u = B + F, \quad F \in Va(B + F, v) = L(v) \quad \forall v \in V, \quad u_e = B + E, \quad E \in Va(B + E, v) = L(v) \quad \forall v \in V$$

Subtract: $a(F - E, v) = 0$ and $E = F$.

Apart from boundary conditions, u_e lies in the same as we seek u . Then $u = u_e$.

!split ===== Computing with finite elements =====

Tasks:

* Address the model problem $-u''(x) = 2$, $u(0) = u(L) = 0$ * Uniform finite element mesh with P1 elements * Show all finite element computations in detail

!split ===== Variational formulation, finite element mesh, and basis =====

$$-u''(x) = 2, \quad x \in (0, L), \quad u(0) = u(L) = 0,$$

Variational formulation:

$$(u', v') = (2, v) \quad \forall v \in V$$

Since $u(0) = 0$ and $u(L) = 0$, we must force

$$v(0) = v(L) = 0, \quad \psi_i(0) = \psi_i(L) = 0$$

Use finite element basis, but exclude φ_0 and φ_{N_n} since these are not 0 on the boundary:

$$\psi_i = \varphi_{i+1}, \quad i = 0, \dots, N = N_n - 2$$

$$u = \sum_{j \in I} c_j \varphi_{\nu(j)}, \quad i = 0, \dots, N, \quad \nu(j) = j + 1$$

Irregular numbering: more complicated $\nu(j)$ mapping

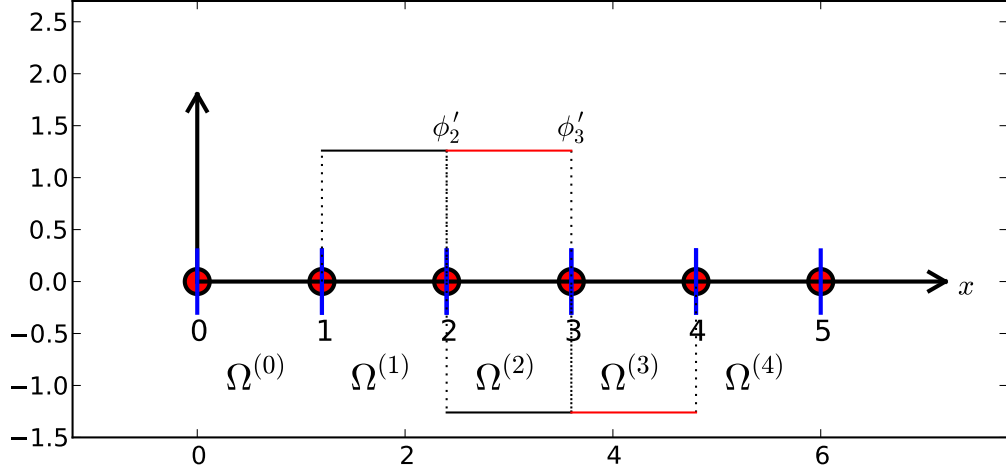
0.4.18 Computation in the global physical domain; formulas

$$A_{i,j} = \int_0^L \varphi'_{i+1}(x) \varphi'_{j+1}(x) dx, \quad b_i = \int_0^L 2\varphi_{i+1}(x) dx$$

$$i + 1 \rightarrow i, \quad j + 1 \rightarrow j$$

$$A_{i-1,j-1} = \int_0^L \varphi'_i(x) \varphi'_j(x) dx, \quad b_{i-1} = \int_0^L 2\varphi_i(x) dx$$

0.4.19 Computation in the global physical domain; details



$$\varphi_i = \pm h^{-1}$$

$$A_{i-1,i-1} = h^{-2}2h = 2h^{-1}, \quad A_{i-1,i-2} = h^{-1}(-h^{-1})h = -h^{-1}, \quad A_{i-1,i} = A_{i-1,i-2}$$

$$b_{i-1} = 2\left(\frac{1}{2}h + \frac{1}{2}h\right) = 2h$$

0.4.20 Computation in the global physical domain; linear system

$$\frac{1}{h} \begin{pmatrix} 2 & -1 & 0 & \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\ -1 & 2 & -1 & \ddots & & & & & \vdots \\ 0 & -1 & 2 & -1 & \ddots & & & & \vdots \\ \vdots & \ddots & & \ddots & \ddots & 0 & & & \vdots \\ \vdots & & \ddots & \ddots & \ddots & \ddots & \ddots & & \vdots \\ \vdots & & & 0 & -1 & 2 & -1 & \ddots & \vdots \\ \vdots & & & & \ddots & \ddots & \ddots & \ddots & 0 \\ \vdots & & & & & \ddots & \ddots & \ddots & -1 \\ 0 & \cdots & \cdots & \cdots & \cdots & \cdots & 0 & -1 & 2 \end{pmatrix} \begin{pmatrix} c_0 \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ c_N \end{pmatrix} = \begin{pmatrix} 2h \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ 2h \end{pmatrix} \quad (38)$$

0.4.21 Comparison with a finite difference discretization

- Recall: $c_i = u(x_{i+1}) \equiv u_{i+1}$
- Write out a general equation at node $i - 1$, expressed by u_i

$$-\frac{1}{h}u_{i-1} + \frac{2}{h}u_i - \frac{1}{h}u_{i+1} = 2h \quad (39)$$

The standard finite difference method for $-u'' = 2$ is

$$-\frac{1}{h^2}u_{i-1} + \frac{2}{h^2}u_i - \frac{1}{h^2}u_{i+1} = 2$$

The finite element method and the finite difference method are identical *in this example*.

(Remains to study the equations involving boundary values)

0.4.22 Cellwise computations; formulas

- Repeat the previous example, but apply the cellwise algorithm
- Work with one cell at a time
- Transform physical cell to reference cell $X \in [-1, 1]$

$$A_{i-1,j-1}^{(e)} = \int_{\Omega^{(e)}} \varphi'_i(x) \varphi'_j(x) dx = \int_{-1}^1 \frac{d}{dx} \tilde{\varphi}_r(X) \frac{d}{dx} \tilde{\varphi}_s(X) \frac{h}{2} dX,$$

$$\tilde{\varphi}_0(X) = \frac{1}{2}(1 - X), \quad \tilde{\varphi}_1(X) = \frac{1}{2}(1 + X)$$

$$\frac{d\tilde{\varphi}_0}{dX} = -\frac{1}{2}, \quad \frac{d\tilde{\varphi}_1}{dX} = \frac{1}{2}$$

From the chain rule

$$\frac{d\tilde{\varphi}_r}{dx} = \frac{d\tilde{\varphi}_r}{dX} \frac{dX}{dx} = \frac{2}{h} \frac{d\tilde{\varphi}_r}{dX}$$

0.4.23 Cellwise computations; details

$$A_{i-1,j-1}^{(e)} = \int_{\Omega^{(e)}} \varphi'_i(x) \varphi'_j(x) dx = \int_{-1}^1 \frac{2}{h} \frac{d\tilde{\varphi}_r}{dX} \frac{2}{h} \frac{d\tilde{\varphi}_s}{dX} \frac{h}{2} dX$$

$$b_{i-1}^{(e)} = \int_{\Omega^{(e)}} 2\varphi_i(x) dx = \int_{-1}^1 2\tilde{\varphi}_r(X) \frac{h}{2} dX, \quad i = q(e, r), \quad r = 0, 1$$

Must run through all $r, s = 0, 1$ and $r = 0, 1$ and compute each entry in the element matrix and vector:

$$\tilde{A}^{(e)} = \frac{1}{h} \begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix}, \quad \tilde{b}^{(e)} = h \begin{pmatrix} 1 \\ 1 \end{pmatrix}. \quad (40)$$

0.4.24 Cellwise computations; details of boundary cells

- The boundary cells involve only one unknown
- $\Omega^{(0)}$: left node value known, only a contribution from right node
- $\Omega^{(N_e)}$: right node value known, only a contribution from left node

$$\tilde{A}^{(e)} = \frac{1}{h} \begin{pmatrix} 1 \\ 1 \end{pmatrix}, \quad \tilde{b}^{(e)} = h \begin{pmatrix} 1 \\ 1 \end{pmatrix}, \quad e = 0, \quad e = N_e$$

Only one degree of freedom ("node") in these cells ($r = 0$)

0.4.25 Cellwise computations; assembly

4 P1 elements:

```
vertices = [0, 0.5, 1, 1.5, 2]
cells = [[0, 1], [1, 2], [2, 3], [3, 4]]
dof_map = [[0], [0, 1], [1, 2], [2]]
```

Python code for the assembly algorithm:

```
# Ae[e][r,s]: element matrix, be[e][r]: element vector
# A[i,j]: coefficient matrix, b[i]: right-hand side

for e in range(len(Ae)):
    for r in range(Ae[e].shape[0]):
        for s in range(Ae[e].shape[1]):
            A[dof_map[e,r],dof_map[e,s]] += Ae[e][i,j]
            b[dof_map[e,r]] += be[e][i,j]
```

Result: same linear system

0.5 Boundary conditions: specified nonzero value

0.5.1 General construction of a boundary function

- $B(x)$ is not always easy to construct (extend to the interior of Ω), at least not in 2D and 3D
- With finite element φ_i , $B(x)$ can be constructed in a completely general way
- I_b : set of indices with nodes where u is known
- U_i : Dirichlet value of u at node i , $i \in I_b$

$$B(x) = \sum_{j \in I_b} U_j \varphi_j(x), \quad (41)$$

1D: $I_b = \{1, N_n\}$

$$u(x) = U_0 \varphi_0(x) + U_{N_n} \varphi_{N_n}(x) + \sum_{j \in I_c} c_j \varphi_{\nu(j)}, \quad \nu(j) = j + 1, \quad N = N_n - 2 \quad (42)$$

0.5.2 Example with two Dirichlet values; variational formulation

$$-u'' = 2, \quad u(0) = C, \quad u(L) = D$$

$$(u', v') = (2, v) \quad \forall v \in V$$

Insert $u = B + \sum_j c_j \psi_j$ in variational formulation:

$$A_{i,j} = \int_0^L \psi'_i(x) \psi'_j(x) dx, \quad b_i = \int_0^L (f(x) - B'(x)) \psi_i(x) dx$$

0.5.7 Modification of the linear system; modifications

- Dirichlet condition $u(x_i) = U_i$ means $c_i = U_i$ (since $c_i = u(x_i)$)
- Replace first row by $c_0 = 0$
- Replace last row by $c_N = D$

$$\frac{1}{h} \begin{pmatrix} 1 & 0 & 0 & \cdots & \cdots & \cdots & \cdots & 0 \\ -1 & 2 & -1 & \ddots & & & & \vdots \\ 0 & -1 & 2 & -1 & \ddots & & & \vdots \\ \vdots & \ddots & & \ddots & \ddots & 0 & & \vdots \\ \vdots & & \ddots & \ddots & \ddots & \ddots & \ddots & \vdots \\ \vdots & & & 0 & -1 & 2 & -1 & \ddots \\ \vdots & & & & \ddots & \ddots & \ddots & 0 \\ \vdots & & & & & \ddots & \ddots & -1 \\ 0 & \cdots & \cdots & \cdots & \cdots & \cdots & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_0 \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ c_N \end{pmatrix} = \begin{pmatrix} 0 \\ 2h \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ 2h \\ D \end{pmatrix} \quad (45)$$

0.5.8 Modification of the linear system; element matrix/vector

In cell 0 we know u for local node (degree of freedom) $r = 0$ and replace the first cell equation by $\tilde{c}_0 = 0$:

$$\tilde{A}^{(0)} = A = \frac{1}{h} \begin{pmatrix} 1 & 0 \\ -1 & 1 \end{pmatrix}, \quad \tilde{b}^{(0)} = \begin{pmatrix} 0 \\ h \end{pmatrix} \quad (46)$$

In cell N_e we know u for local node $r = 1$ and replace the last equation in the cell system by $\tilde{c}_1 = D$:

$$\tilde{A}^{(N_e)} = A = \frac{1}{h} \begin{pmatrix} 1 & -1 \\ 0 & 1 \end{pmatrix}, \quad \tilde{b}^{(N_e)} = \begin{pmatrix} h \\ D \end{pmatrix} \quad (47)$$

0.5.9 Symmetric modification of the linear system; algorithm

- The modification above destroys symmetry of the matrix: $A_{0,1} \neq A_{1,0}$
- Symmetry is often important in 2D and 3D (faster computations)
- A more complex modification preserves symmetry

Algorithm for incorporating $c_i = U_i$:

1. Subtract column i times U_i from the right-hand side
2. Zero out column and row no i
3. Place 1 on the diagonal
4. Set $b_i = U_i$

0.5.10 Symmetric modification of the linear system; example

$$\frac{1}{h} \begin{pmatrix} 1 & 0 & 0 & \cdots & \cdots & \cdots & \cdots & \cdots & 0 \\ 0 & 2 & -1 & \ddots & & & & & \vdots \\ 0 & -1 & 2 & -1 & \ddots & & & & \vdots \\ \vdots & \ddots & & \ddots & \ddots & 0 & & & \vdots \\ \vdots & & \ddots & \ddots & \ddots & \ddots & \ddots & & \vdots \\ \vdots & & & 0 & -1 & 2 & -1 & \ddots & \vdots \\ \vdots & & & & \ddots & \ddots & \ddots & \ddots & 0 \\ \vdots & & & & & \ddots & \ddots & \ddots & 0 \\ 0 & \cdots & \cdots & \cdots & \cdots & \cdots & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} c_0 \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ c_N \end{pmatrix} = \begin{pmatrix} 0 \\ 2h \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ \vdots \\ 2h + D/h \\ D \end{pmatrix} \quad (48)$$

0.5.11 Modification of the element matrix and vector

- Modification of the linear system can be done in the the element matrix and vector instead
- Exactly the same procedure

Last degree of freedom in the last element is prescribed:

$$\tilde{A}^{(N-1)} = A = \frac{1}{h} \begin{pmatrix} 1 & -1 \\ 0 & 1 \end{pmatrix}, \quad \tilde{b}^{(N-1)} = \begin{pmatrix} h \\ D \end{pmatrix} \quad (49)$$

Or symmetric modification:

$$\tilde{A}^{(N-1)} = A = \frac{1}{h} \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}, \quad \tilde{b}^{(N-1)} = \begin{pmatrix} h + D/h \\ D \end{pmatrix} \quad (50)$$

0.6 Boundary conditions: specified derivative

Focus: how to incorporate $u'(0) = C$ with finite elements.

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