

FINITE ELEMENTS

This definitive introduction to finite element methods has been thoroughly updated for this third edition, which features important new material for both research and application of the finite element method.

The discussion of saddle point problems is a highlight of the book and has been elaborated to include many more nonstandard applications. The chapter on applications in elasticity now contains a complete discussion of locking phenomena.

The numerical solution of elliptic partial differential equations is an important application of finite elements and the author discusses this subject comprehensively. These equations are treated as variational problems for which the Sobolev spaces are the right framework. Graduate students who do not necessarily have any particular background in differential equations but require an introduction to finite element methods will find this text invaluable. Specifically, the chapter on finite elements in solid mechanics provides a bridge between mathematics and engineering.

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Dietrich Braess

Frontmatter

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Theory, Fast Solvers, and Applications in Elasticity Theory

DIETRICH BRAESS

Translated from the German by Larry L. Schumaker



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Preface to the Third English Edition

The theory of finite elements and their applications is such a lively area that a third edition has become necessary to cover new material that is of interest for actual applications. At the same time we have taken the opportunity to correct some misprints.

The greatest changes are found in Chapter III. Saddle point problems and mixed methods are used now not only for variational problems with given constraints, but there is also an increasing interest in nonstandard saddle point methods. Their flexibility enables the construction of finite elements with special properties, e.g. they can soften specific terms of the energy functional in order to eliminate locking phenomena. The treatment of the Poisson equation in the setting of saddle point formulations can be regarded as a template for other examples and some of these are covered in the present edition.

Another nonstandard application is the construction of a new type of a posteriori error estimate for conforming elements. This has the advantage that there is no generic constant in the main term. Moreover, in this framework it is possible to shed light on other relations between conforming elements and mixed methods.

In Chapter VI the treatment of locking has been reworked. Such phenomena are well known to engineers, but the mathematical proof of locking is often more cumbersome than the remedy. In most cases we focus therefore on the use of appropriate finite elements and describe the negative results more briefly within the context of the general theory of locking. In order to illustrate the full theory and how it is implemented we also verify the locking effect for the Timoshenko beam with all details and analyze all the standard remedies for this beam.

We have added many comments in all chapters in order to make a stronger connection with current research. We have done this by adding new problems whenever a comment in the text would have interrupted the thread. In addition, we intend to put updates and additional material on our web pages (<http://homepage.rub.de/Dietrich.Braess/ftp.html>) in the same way as we have done for the previous editions.

The author again wishes to thank numerous friends who have given valuable hints for improvements of the text. Finally, thanks go again to Cambridge University Press for cooperating on this Third Edition.

Autumn, 2006

Dietrich Braess

Preface to the First English Edition

This book is based on lectures regularly presented to students in the third and fourth year at the Ruhr-University, Bochum. It was also used by the translator, Larry Schumaker, in a graduate course at Vanderbilt University in Nashville. I would like to thank him for agreeing to undertake the translation, and for the close cooperation in carrying it out. My thanks are also due to Larry and his students for raising a number of questions which led to improvements in the material itself.

Chapters I and II and selected sections of Chapters III and V provide material for a typical course. I have especially emphasized the differences with the numerical treatment of ordinary differential equations (for more details, see the preface to the German edition).

One may ask why I was not content with presenting only simple finite elements based on complete polynomials. My motivation for doing more was provided by problems in fluid mechanics and solid mechanics, which are treated to some extent in Chapter III and VI. I am not aware of other textbooks for mathematicians which give a mathematical treatment of finite elements in solid mechanics in this generality.

The English translation contains some additions as compared to the German edition from 1992. For example, I have added the theory for basic a posteriori error estimates since a posteriori estimates are often used in connection with local mesh refinements. This required a more general interpolation process which also applies to non-uniform grids. In addition, I have also included an analysis of locking phenomena in solid mechanics.

Finally, I would like to thank Cambridge University Press for their friendly cooperation, and also Springer-Verlag for agreeing to the publication of this English version.

Autumn, 1996

Dietrich Braess

Preface to the German Edition

The method of finite elements is one of the main tools for the numerical treatment of elliptic and parabolic partial differential equations. Because it is based on the variational formulation of the differential equation, it is much more flexible than finite difference methods and finite volume methods, and can thus be applied to more complicated problems. For a long time, the development of finite elements was carried out in parallel by both mathematicians and engineers, without either group acknowledging the other. By the end of the 60's and the beginning of the 70's, the material became sufficiently standardized to allow its presentation to students. This book is the result of a series of such lectures.

In contrast to the situation for ordinary differential equations, for elliptic partial differential equations, frequently no classical solution exists, and we often have to work with a so-called weak solution. This has consequences for both the theory and the numerical treatment. While it is true that classical solutions do exist under appropriate regularity hypotheses, for numerical calculations we usually cannot set up our analysis in a framework in which the existence of classical solutions is guaranteed.

One way to get a suitable framework for solving elliptic boundary-value problems using finite elements is to pose them as variational problems. It is our goal in Chapter II to present the simplest possible introduction to this approach. In Sections 1 – 3 we discuss the existence of weak solutions in Sobolev spaces, and explain how the boundary conditions are incorporated into the variational calculation. To give the reader a feeling for the theory, we derive a number of properties of Sobolev spaces, or at least illustrate them. Sections 4 – 8 are devoted to the foundations of finite elements. The most difficult part of this chapter is §6 where approximation theorems are presented. To simplify matters, we first treat the special case of regular grids, which the reader may want to focus on in a first reading.

In Chapter III we come to the part of the theory of finite elements which requires deeper results from functional analysis. These are presented in §3. Among other things, the reader will learn about the famous Ladyshenskaja–Babuška–Brezzi condition, which is of great importance for the proper treatment of problems in fluid mechanics and for mixed methods in structural mechanics. In fact, without this knowledge and relying only on *common sense*, we would very likely find ourselves trying to solve problems in fluid mechanics using elements with an unstable behavior.

It was my aim to present this material with as little reliance on results from real analysis and functional analysis as possible. On the other hand, a certain basic

knowledge is extremely useful. In Chapter I we briefly discuss the difference between the different types of partial differential equations. Students confronting the numerical solution of elliptic differential equations for the first time often find the finite difference method more accessible. However, the limits of the method usually become apparent only later. For completeness we present an elementary introduction to finite difference methods in Chapter I.

For fine discretizations, the finite element method leads to very large systems of equations. The operation count for solving them by direct methods grows like n^2 . In the last two decades, very efficient solvers have been developed based on multigrid methods and on the method of conjugate gradients. We treat these subjects in detail in Chapters IV and V.

Structural mechanics provides a very important application area for finite elements. Since these kinds of problems usually involve systems of partial differential equations, often the elementary methods of Ch. II do not suffice, and we have to use the extra flexibility which the deeper results of Ch. III allow. I found it necessary to assemble a surprisingly wide set of building blocks in order to present a mathematically rigorous theory for the numerical treatment by finite elements of problems in linear elasticity theory.

Almost every section of the book includes a set of Problems, which are not only exercises in the strict sense, but also serve to further develop various formulae or results from a different viewpoint, or to follow a topic which would have disturbed the flow had it been included in the text itself. It is well-known that in the numerical treatment of partial differential equations, there are many opportunities to go down a false path, even if unintended, particularly if one is thinking in terms of classical solutions. Learning to avoid such pitfalls is one of the goals of this book.

This book is based on lectures regularly presented to students in the fifth through eighth semester at the Ruhr University, Bochum. Chapters I and II and parts of Chapters III and V were presented in one semester, while the method of conjugate gradients was left to another course. Chapter VI is the result of my collaboration with both mathematicians and engineers at the Ruhr University.

A text like this can only be written with the help of many others. I would like to thank F.-J. Barthold, C. Blömer, H. Blum, H. Cramer, W. Hackbusch, A. Kirmse, U. Langer, P. Peisker, E. Stein, R. Verfürth, G. Wittum and B. Worat for their corrections and suggestions for improvements. My thanks are also due to Frau L. Mischke, who typeset the text using $\text{\TeX}$, and to Herr Schwarz for his help with technical problems relating to $\text{\TeX}$. Finally, I would like to express my appreciation to Springer-Verlag for the publication of the German edition of this book, and for the always pleasant collaboration on its production.

Bochum, Autumn, 1991

Dietrich Braess

Notation

Notation for Differential Equations and Finite Elements

Ω	open set in $\mathbb{R}^n$
Γ	$=\partial\Omega$
Γ_D	part of the boundary on which Dirichlet conditions are prescribed
Γ_N	part of the boundary on which Neumann conditions are prescribed
Δ	Laplace operator
L	differential operator
a_{ik}, a_0	coefficient functions of the differential equation
$[\cdot]_*$	difference star, stencil
$L^2(\Omega)$	space of square-integrable functions over Ω
$H^m(\Omega)$	Sobolev space of L_2 functions with square-integrable derivatives up to order m
$H_0^m(\Omega)$	subspace of $H^m(\Omega)$ of functions with generalized zero boundary conditions
$C^k(\Omega)$	set of functions with continuous derivatives up to order k
$C_0^k(\Omega)$	subspace of $C^k(\Omega)$ of functions with compact support
γ	trace operator
$\ \cdot\ _m$	Sobolev norm of order m
$ \cdot _m$	Sobolev semi-norm of order m
$\ \cdot\ _\infty$	supremum norm
ℓ_2	space of square-summable sequences
H'	dual space of H
$\langle\cdot,\cdot\rangle$	dual pairing
$ \alpha $	$=\sum\alpha_i$, order of multiindex α
∂_i	partial derivative $\frac{\partial}{\partial x_i}$
∂^α	partial derivative of order α
D	(Fréchet) derivative
α	ellipticity constant
ν, n	exterior normal
$\partial_\nu, \partial/\partial\nu, \partial/\partial n$	derivative in the direction of the exterior normal
∇f	$(\partial f/\partial x_1, \partial f/\partial x_2, \dots, \partial f/\partial x_n)$
$\operatorname{div} f$	$\sum_{i=1}^n(\partial f/\partial x_i)$
S_h	finite element space
ψ_h	basis function in S_h
$\mathcal{T}_h$	partition of Ω
T	(triangular or quadrilateral) element in $\mathcal{T}_h$
T_{ref}	reference element

h_T, ρ_T	radii of circumscribed circle and incircle of T , respectively
κ	shape parameter of a partition
$\mu(T)$	area (volume) of T
$\mathcal{P}_t$	set of polynomials of degree $\leq t$
$\mathcal{Q}_t$	polynomial set (II.5.4) w.r.t. quadrilateral elements
$\mathcal{P}_{3,\text{red}}$	cubic polynomial without bubble function term
Π_{ref}	set of polynomials which are formed by the restriction of S_h to a (reference) element
s	$= \dim \Pi_{\text{ref}}$
Σ	set of linear functionals in the definition of affine families
$\mathcal{M}^k, \mathcal{M}_s^k, \mathcal{M}_{s,0}^k$	polynomial finite element spaces in L_2, H^{s+1} and H_0^{s+1}
$\mathcal{M}_{*,0}^1$	set of functions in $\mathcal{M}^1$ which are continuous at the midpoints of the sides and which satisfy zero boundary conditions in the same sense
RT_k	Raviart–Thomas element of degree k
I, I_h	interpolation operators on Π_{ref} and on S_h , respectively
A	stiffness or system matrix
$\delta_{..}$	Kronecker symbol
e	edge of an element
$\ \cdot\ _{m,h}$	mesh-dependent norm
$\ker L$	kernel of the linear mapping L
$V^\perp$	orthogonal complement of V
V^0	polar of V
$\mathcal{L}$	Lagrange function
M	space of restrictions (for saddle point problems)
β	constant in the Brezzi condition
$H(\text{div}, \Omega)$	$:= \{v \in L_2(\Omega)^d; \text{div } v \in L_2(\Omega)\}, \Omega \in \mathbb{R}^d$
$L_{2,0}(\Omega)$	set of functions in $L_2(\Omega)$ with integral mean 0
B_3	cubic bubble functions
$\eta_{\dots}$	error estimator

Notation for the Method of Conjugate Gradients

∇f	gradient of f (column vector)
$\kappa(A)$	spectral condition number of the matrix A
$\sigma(A)$	spectrum of the matrix A
$\rho(A)$	spectral radius of the matrix A
$\lambda_{\min}(A)$	smallest eigenvalue of the matrix A
$\lambda_{\max}(A)$	largest eigenvalue of the matrix A
A^t	transpose of the matrix A
I	unit matrix
C	preconditioning matrix
g_k	gradient at the actual approximation x_k

d_k	direction of the correction in step k
V_k	$= \text{span}[g_0, \dots, g_{k-1}]$
$x'y$	Euclidean scalar product of the vectors x and y
$\ x\ _A$	$= \sqrt{x'Ax}$ (energy norm)
$\ x\ _\infty$	$= \max_i x_i $ (maximum norm)
T_k	k -th Chebyshev polynomial
ω	relaxation parameter

Notation for the Multigrid Method

$\mathcal{T}_\ell$	triangulation on the level ℓ
$S_\ell = S_{h_\ell}$	finite element space on the level ℓ
A_ℓ	system matrix on the level ℓ
N_ℓ	$= \dim S_\ell$
$\mathcal{S}$	smoothing operator
$r, \tilde{r}$	restrictions
p	prolongation
$x^{\ell,k,m}, u^{\ell,k,m}$	variable on the level ℓ in the k -th iteration step and in the m -th substep
v_1, v_2	number of presmoothings or postsmoothings, respectively
v	$= v_1 + v_2$
μ	$= 1$ for V-cycle, $= 2$ for W-cycle
q	$= \ell_{\max}$
ψ_ℓ^j	j -th basis function on the level ℓ
ρ_ℓ	convergence rate of MGM $_\ell$
ρ	$= \sup_\ell \rho_\ell$
$ \cdot _s$	discrete norm of order s
β	measure of the smoothness of a function in S_h
$\mathcal{L}$	nonlinear operator
$\mathcal{L}_\ell$	nonlinear mapping on the level ℓ
$D\mathcal{L}$	derivative of $\mathcal{L}$
λ	homotopy parameter for incremental methods

Notation for Solid Mechanics

u	displacement
ϕ	deformation
id	identity mapping
C	$= \nabla \phi^T \nabla \phi$ Cauchy–Green strain tensor
E	strain
ε	strain in a linear approximation
t	Cauchy stress vector
T	Cauchy stress tensor
T_R	first Piola–Kirchhoff stress tensor
Σ_R	second Piola–Kirchhoff stress tensor

$\hat{T}$	$= \hat{T}(F)$ response function for the Cauchy stress tensor
$\hat{\Sigma}$	$= \hat{\Sigma}(F)$ response function for the Piola–Kirchhoff stress tensor
$\tilde{\Sigma}$	$\tilde{\Sigma}(F^T F) = \hat{\Sigma}(F)$
$\bar{T}$	$\bar{T}(F F^T) = \hat{T}(F)$
σ	stress in linear approximation
S^2	unit sphere in $\mathbb{R}^3$
$\mathbb{M}^3$	set of 3×3 matrices
$\mathbb{M}_+^3$	set of matrices in $\mathbb{M}^3$ with positive determinants
$\mathbb{O}^3$	set of orthogonal 3×3 matrices
$\mathbb{O}_+^3$	$= \mathbb{O}^3 \cap \mathbb{M}_+^3$
$\mathbb{S}^3$	set of symmetric 3×3 matrices
$\mathbb{S}_>^3$	set of positive definite matrices in $\mathbb{S}^3$
ι_A	$= (\iota_1(A), \iota_2(A), \iota_3(A))$, invariants of A
$\wedge$	vector product in $\mathbb{R}^3$
$\text{diag}(d_1, \dots, d_n)$	diagonal matrix with elements $d_1, \dots, d_n$
λ, μ	Lamé constants
E	modulus of elasticity
ν	Poisson ratio
n	normal vector (different from Chs. II and III)
$\mathcal{C}$	$\sigma = \mathcal{C} \varepsilon$
$\hat{W}$	energy functional of hyperelastic materials
$\tilde{W}$	$\tilde{W}(F^T F) = \hat{W}(F)$
$\varepsilon : \sigma$	$= \sum_{ij} \varepsilon_{ij} \sigma_{ij}$
Γ_0, Γ_1	parts of the boundary on which u and $\sigma \cdot n$ are prescribed, respectively
Π	energy functional in the linear theory
$\nabla^{(s)}$	symmetric gradient
$as(\tau)$	skew-symmetric part of τ
$H^s(\Omega)^d$	$= [H^s(\Omega)]^d$
$H_\Gamma^1(\Omega)$	$:= \{v \in H^1(\Omega)R; v(x) = 0 \text{ for } x \in \Gamma_0\}$
$H(\text{div}, \Omega)$	$:= \{\tau \in L_2(\Omega); \text{div } \tau \in L_2(\Omega)\}$, τ is a vector or a tensor
$H(\text{rot}, \Omega)$	$:= \{\eta \in L_2(\Omega)^2; \text{rot } \eta \in L_2(\Omega)\}$, $\Omega \subset \mathbb{R}^2$
$H^{-1}(\text{div}, \Omega)$	$:= \{\tau \in H^{-1}(\Omega)^d; \text{div } \tau \in H^{-1}(\Omega)\}$, $\Omega \subset \mathbb{R}^d$
θ, γ, w	rotation, shear term, and transverse displacement of beams and plates
t	thickness of a beam, membrane, or plate
ℓ	length of a beam
$W_h, \Theta_h, \Gamma_h, Q_h$	finite element spaces in plate theory
π_h	L_2 -projector onto Γ_h
R	restriction to Γ_h
P_h	L_2 -projector onto Q_h