Numerical Methods for Partial Differential Equations
CS555 / MATH555 / CSE510

Andreas Kloeckner

March 4, 2021
Outline

Introduction
   Notes
   Notes (unfilled, with empty boxes)
   About the Class
   Classification of PDEs
   Preliminaries: Differencing
   Interpolation Error Estimates (reference)

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems

Discontinuous Galerkin Methods for Hyperbolic Problems
Outline

**Introduction**
- Notes
  - Notes (unfilled, with empty boxes)
- About the Class
- Classification of PDEs
- Preliminaries: Differencing
- Interpolation Error Estimates (reference)

*Finite Difference Methods for Time-Dependent Problems*

*Finite Volume Methods for Hyperbolic Conservation Laws*

*Finite Element Methods for Elliptic Problems*

*Discontinuous Galerkin Methods for Hyperbolic Problems*
Outline

Introduction

Notes

Notes (unfilled, with empty boxes)

About the Class

Classification of PDEs

Preliminaries: Differencing

Interpolation Error Estimates (reference)

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems

Discontinuous Galerkin Methods for Hyperbolic Problems
Outline

Introduction
  Notes
  Notes (unfilled, with empty boxes)
  About the Class
  Classification of PDEs
  Preliminaries: Differencing
  Interpolation Error Estimates (reference)

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems

Discontinuous Galerkin Methods for Hyperbolic Problems
What’s the point of this class?

PDEs describe lots of things in nature:

Idea: Use them to
Survey

- Home dept
- Degree pursued
- Longest program ever written
  - in Python?
- Research area
Class web page


- Book Draft
- Notes, Class Outline
- Assignments (submission and return)
- Piazza
- Grading Policies/Syllabus
- Video
- Scribbles
- Demos (binder)
Sources for these Notes


▶ Various prior bits of material by Luke Olson and Stephen Bond.
These notes (and the accompanying demos) are open-source!

Bug reports and pull requests welcome:
https://github.com/inducer/numpde-notes

Copyright (C) 2020 Andreas Klöeckner

Permission is hereby granted, free of charge, to any person obtaining a copy of this software and associated documentation files (the “Software”), to deal in the Software without restriction, including without limitation the rights to use, copy, modify, merge, publish, distribute, sublicense, and/or sell copies of the Software, and to permit persons to whom the Software is furnished to do so, subject to the following conditions:

The above copyright notice and this permission notice shall be included in all copies or substantial portions of the Software.

THE SOFTWARE IS PROVIDED “AS IS”, WITHOUT WARRANTY OF ANY KIND, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO THE WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE AND NONINFRINGEMENT. IN NO EVENT SHALL THE AUTHORS OR COPYRIGHT HOLDERS BE LIABLE FOR ANY CLAIM, DAMAGES OR OTHER LIABILITY, WHETHER IN AN ACTION OF CONTRACT, TORT OR OTHERWISE, ARISING FROM, OUT OF OR IN CONNECTION WITH THE SOFTWARE OR THE USE OR OTHER DEALINGS IN THE SOFTWARE.
Outline

Introduction
Notes
Notes (unfilled, with empty boxes)
About the Class
Classification of PDEs
Preliminaries: Differencing
Interpolation Error Estimates (reference)

Finite Difference Methods for Time-Dependent Problems
Finite Volume Methods for Hyperbolic Conservation Laws
Finite Element Methods for Elliptic Problems
Discontinuous Galerkin Methods for Hyperbolic Problems
What does this do? \( \partial_t u = \partial_x u \)
What does this do? \( \partial_x^2 u + \partial_y^2 u = 0 \)
Some good questions

- What is a time-like variable? (Variables labeled $t$?)
- What if there are boundaries?
  - In space?
  - In time?
- Existence and Uniqueness of Solutions?
  - Depends on where we look (the *function space*)
  - In the case of the two examples? (if there are no boundaries?)

Some general takeaways:
Looking for $u : \Omega \rightarrow R^n$ where $\Omega \subseteq \mathbb{R}^d$ so that $u \in V$ and

\[ F(u, u_x, u_y, u_{xx}, u_{xy}, u_{yy}, \ldots, x, y, \ldots) = 0 \]

**Notation**

Used as convenient:

\[ u_x = \partial_x u = \frac{\partial u}{\partial x} \]
Properties of PDEs

What is the order of the PDE?

When is the PDE linear?

When is the PDE quasilinear?

When is the PDE semilinear?
Examples: Order, Linearity?

\[(xu^2)u_{xx} + (u_x + y)u_{yy} + u_x^3 + yu_y = f\]

\[(x + y + z)u_x + (z^2)u_y + (\sin x)u_z = f\]
Properties of Domains

May influence existence/uniqueness of solutions!
Function Spaces: Examples

Name some function spaces with their norms.

May also influence existence/uniqueness of solutions!
Solving PDEs

Closed-form solutions:
▶ If separation of variables applies to the domain: good luck with your ODE
▶ If not: Good luck! → Numerics

General Idea (that we will follow some of the time)
▶ Pick $V_h \subseteq V$ finite-dimensional
  ▶ $h$ is often a mesh spacing
▶ Approximate $u$ through $u_h \in V_h$
▶ Show: $u_h \to u$ (in some sense) as $h \to 0$

Example
About grand big unifying theories

Is there a grand big unifying theory of PDEs?
Collect some stamps

\[ a(x, y)u_{xx} + 2b(x, y)u_{xy} + c(x, y)u_{yy} + d(x, y)u_x + e(x, y)u_y + f(x, y)u = g(x, y) \]

<table>
<thead>
<tr>
<th>Discriminant value</th>
<th>Kind</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>( b^2 - ac &lt; 0 )</td>
<td>Elliptic</td>
<td>Laplace ( u_{xx} + u_{yy} = 0 )</td>
</tr>
<tr>
<td>( b^2 - ac = 0 )</td>
<td>Parabolic</td>
<td>Heat ( u_t = u_{xx} )</td>
</tr>
<tr>
<td>( b^2 - ac &gt; 0 )</td>
<td>Hyperbolic</td>
<td>Wave ( u_{tt} = u_{xx} )</td>
</tr>
</tbody>
</table>

Where do these names come from?
PDE Classification in Other Cases

Scalar first order PDEs?

First order systems of PDEs?
Classification in higher dimensions

\[ Lu := \sum_{i=1}^{d} \sum_{j=1}^{d} a_{i,j}(x) \frac{\partial^2 u}{\partial x_i \partial x_j} + \text{lower order terms} \]

Consider the matrix \( A(x) = (a_{ij}(x))_{i,j} \). May assume \( A \) symmetric. Why?

What cases can arise for the eigenvalues?
Elliptic PDE: Laplace/Poisson Equation

\[ \triangle u = \sum_{i=1}^{d} \frac{\partial^2 u}{\partial x_i^2} = \nabla \cdot \nabla u(x) = u_{xx} + u_{yy} = f(x) \quad (x \in \Omega) \]

Called Laplace equation if \( f = 0 \). With Dirichlet boundary condition

\[ u(x) = g(x) \quad (x \in \partial \Omega). \]

**Demo:** Elliptic PDE Illustrating the Maximum Principle
Demo: Elliptic PDE Radially Symmetric Singular Solution

Given $G(x) = C \log(|x|)$ as the free-space Green’s function, can we construct the solution to the PDE with a more general $f$?

What can we learn from this?
Elliptic PDEs: Justifying the Singular Solution

\[ u(x) = (G \ast f)(x) = \int_{\mathbb{R}^d} G(x - y)f(y)dy \]

Why?
Parabolic PDE: Heat Equation · Separation of Variables

\[ u_t = u_{xx} \quad ((x, t) \in [0, 1] \times [0, T]) \]

\[ u(x, 0) = g(x) \quad (x \in [0, 1]) \]

\[ u(0, t) = u(1, t) = 0 \quad (t \in [0, T]) \]
**Demo:** Parabolic PDE What can we learn from analytic and numerical solution?
Hyperbolic PDE: Wave Equation

\[ u_{tt} = c^2 u_{xx} \quad ((x, t) \in \mathbb{R} \times [0, T]) \]
\[ u(x, 0) = g(x) \quad (x \in \mathbb{R}) \]

with \( g(x) = \sin(\pi x) \).

Is this problem well-posed?

Can be rewritten in conservation law form:
Hyperbolic Conservation Laws

\[ q_t(x, t) + \nabla \cdot F(q(x, t)) = s(x) \]

Why is this called a conservation law?

\[ F : ? \rightarrow ? \]
Wave Equation as a Conservation Law

Rewrite the wave equation in conservation law form:
Solving Conservation Laws

Solve

\[ u_t = v_x \]
\[ v_t = u_x. \]

**Demo:** Hyperbolic PDE
Properties of the solution for hyperbolic equations:
Outline

Introduction
- Notes
- Notes (unfilled, with empty boxes)
- About the Class
- Classification of PDEs
- Preliminaries: Differencing
- Interpolation Error Estimates (reference)

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems

Discontinuous Galerkin Methods for Hyperbolic Problems
Interpolation and Vandermonde Matrices
Finite Differences Numerically

**Demo:** Finite Differences

**Demo:** Finite Differences vs Noise

**Demo:** Floating point vs Finite Differences
Taking Derivatives Numerically

Why *shouldn’t* you take derivatives numerically?

**Demo:** Taking Derivatives with Vandermonde Matrices
Find the order of accuracy of the finite difference formula 
\[ f'(x) \approx \frac{f(x + h) - f(x - h)}{2h}. \]
Outline

Introduction
Notes
Notes (unfilled, with empty boxes)
About the Class
Classification of PDEs
Preliminaries: Differencing
Interpolation Error Estimates (reference)

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems

Discontinuous Galerkin Methods for Hyperbolic Problems
**Interpolation Error**

If \( f \) is \( n \) times continuously differentiable on a closed interval \( I \) and \( p_{n-1}(x) \) is a polynomial of degree at most \( n \) that interpolates \( f \) at \( n \) distinct points \( \{x_i\} \ (i = 1, \ldots, n) \) in that interval, then for each \( x \) in the interval there exists \( \xi \) in that interval such that

\[
f(x) - p_{n-1}(x) = \frac{f^{(n)}(\xi)}{n!} (x - x_1)(x - x_2) \cdots (x - x_n).
\]

Set the error term to be \( R(x) := f(x) - p_{n-1}(x) \) and set up an auxiliary function:

\[
Y(t) = R(t) - \frac{R(x)}{W(t)} W(t) \quad \text{where} \quad W(t) = \prod_{i=1}^{n} (t - x_i).
\]

Note also the introduction of \( t \) as an additional variable, independent of the point \( x \) where we hope to prove the identity.
Interpolation Error: Proof cont’d

\[ Y(t) = R(t) - \frac{R(x)}{W(x)} W(t) \quad \text{where} \quad W(t) = \prod_{i=1}^{n} (t - x_i) \]

- Since \( x_i \) are roots of \( R(t) \) and \( W(t) \), we have \( Y(x) = Y(x_i) = 0 \), which means \( Y \) has at least \( n + 1 \) roots.
- From Rolle’s theorem, \( Y'(t) \) has at least \( n \) roots, then \( Y^{(n)} \) has at least one root \( \xi \), where \( \xi \in I \).
- Since \( p_{n-1}(x) \) is a polynomial of degree at most \( n - 1 \), \( R^{(n)}(t) = f^{(n)}(t) \). Thus

\[ Y^{(n)}(t) = f^{(n)}(t) - \frac{R(x)}{W(x)} n!. \]

- Plugging \( Y^{(n)}(\xi) = 0 \) into the above yields the result.
What is the connection between the error result and Chebyshev interpolation?

- The error bound suggests choosing the interpolation nodes such that the product $|\prod_{i=1}^{n}(x - x_i)|$, is as small as possible. The Chebyshev nodes achieve this.
- Error is zero at the nodes
- If nodes scoot closer together near the interval ends, then

$$ (x - x_1)(x - x_2) \cdots (x - x_n) $$

clamps down the (otherwise quickly-growing) error there.
Boil the error result down to a simpler form.

Assume $x_1 < \cdots < x_n$.

- $|f^{(n)}(x)| \leq M$ for $x \in [x_1,x_n]$,
- Set the interval length $h = x_n - x_1$.
  Then $|x - x_i| \leq h$.

Altogether—there is a constant $C$ independent of $h$ so that:

$$\max_x |f(x) - p_{n-1}(x)| \leq CMh^n.$$ 

For the grid spacing $h \to 0$, we have

$$E(h) = O(h^n).$$

This is called convergence of order $n$.

**Demo:** Interpolation Error
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems
  1D Advection
  Stability and Convergence
  Von Neumann Stability
  Dispersion and Dissipation
  A Glimpse of Parabolic PDEs

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems

Discontinuous Galerkin Methods for Hyperbolic Problems
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems
  1D Advection
  Stability and Convergence
  Von Neumann Stability
  Dispersion and Dissipation
  A Glimpse of Parabolic PDEs

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems

Discontinuous Galerkin Methods for Hyperbolic Problems
1D Advection Equation and Characteristics

\[ u_t + au_x = 0, \quad u(0, x) = g(x) \quad (x \in \mathbb{R}) \]

Solution?
Solving Advection with Characteristics

\[ u_t + au_x = 0, \quad u(0,x) = g(x) \quad (x \in \mathbb{R}) \]

Find the characteristic curve for advection.

Generalize this to a solution formula.

Does the solution formula admit solutions that aren’t obviously allowed by the PDE?
Finite Difference for Hyperbolic: Idea

\[ \{(x_k, t_\ell) : x_k = k h_x, t_\ell = \ell h_t\} \]

If \( u(x, t) \) is the exact solution, want

\[ u_{k,\ell} \approx u(x_k, t_\ell). \]

Condition at each grid point?

What are explicit/implicit schemes?
Designing Stencils

ETCS:

Terminology?

ITCS:

ETFS:

Write out ITCS:

ETBS:
Write out Crank-Nicolson:
What’s the core idea behind Lax-Wendroff?

Write out Lax-Wendroff.
Exploring Advection Schemes

**Demo:** Methods for 1D Advection

- Which of the schemes “work”?  
- Any restrictions worth noting?
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems
- 1D Advection
- Stability and Convergence
- Von Neumann Stability
- Dispersion and Dissipation
- A Glimpse of Parabolic PDEs

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems

Discontinuous Galerkin Methods for Hyperbolic Problems
A Matrix View of Two-Level Stencil Schemes

Define

\[
\mathbf{v}_\ell = \begin{bmatrix}
  u_{1,\ell} \\
  \vdots \\
  u_{N_x,\ell}
\end{bmatrix}, \quad \mathbf{v} = \begin{bmatrix}
  v_1 \\
  \vdots \\
  v_{N_t}
\end{bmatrix}, \quad \mathbf{u}_\ell = \begin{bmatrix}
  u(x_1, t_\ell) \\
  \vdots \\
  u(x_{N_x}, t_\ell)
\end{bmatrix}, \quad \mathbf{u} = \begin{bmatrix}
  u_1 \\
  \vdots \\
  u_{N_t}
\end{bmatrix}.
\]

Definition (Two-Level Finite Difference Scheme)

A finite difference scheme that can be written as

\[
\begin{bmatrix}
  u_{1,\ell} \\
  \vdots \\
  u_{N_x,\ell}
\end{bmatrix}, \quad \begin{bmatrix}
  v_1 \\
  \vdots \\
  v_{N_t}
\end{bmatrix}, \quad \begin{bmatrix}
  u(x_1, t_\ell) \\
  \vdots \\
  u(x_{N_x}, t_\ell)
\end{bmatrix}, \quad \begin{bmatrix}
  u_1 \\
  \vdots \\
  u_{N_t}
\end{bmatrix}
\]

is called a two-level linear finite difference scheme.
Rewriting Schemes in Matrix Form (1/2)

\[ P_h v_{\ell+1} = Q_h v_\ell + h_t b_\ell \]

Find \( P_h \) and \( Q_h \) for ETCS:
Find $P_h$ and $Q_h$ for Crank-Nicolson:
Truncation Error

**Definition (Truncation Error)**

**Demo:** Truncation Error Analysis via sympy
Error and Error Propagation

Express truncation error in our two-level framework:

\[ e_\ell = u_\ell - v_\ell. \]

Define \( e_\ell = u_\ell - v_\ell \). Understand the error as accumulation of truncation error:
Discrete and Continuous Norms

To measure properties of numerical solutions we need norms. Define a discrete $L^\infty$ norm.

Define a discrete $L^2$ norm.

Important features:
Consistency and Convergence

Assume $u, (\partial_x^{q_x})u, (\partial_t^{q_t})u \in L^2(\mathbb{R} \times [0, t^*])$.

**Definition (Consistency)**

A two-level scheme is **consistent** in the $L^2$-norm with order $q_t$ in time and $q_x$ in space if

**Definition (Convergence)**

A two-level scheme is **convergent** in the $L^2$-norm with order $q_t$ in time and $q_x$ in space if
Analyzing ETFS

\[
\frac{u_{k,\ell+1} - u_{k,\ell}}{h_t} + a \frac{u_{k+1,\ell} - u_{k,\ell}}{h_x} = 0
\]

Let’s understand more precisely what happens for this scheme.
Consider $u(x, 0) = 1_{[-1,0]}(x)$. Predict solution behavior.
Stability

\[ P_h v_{\ell+1} = Q_h v_\ell \]

Write down a matrix product to bring \( v_0 \) to \( v_\ell \):

Definition (Stability)

A two-level scheme is stable in the \( L^2 \)-norm if there exists a constant \( c > 0 \) independent of \( h_t \) and \( h_x \) so that

\[ \| (P_h^{-1} Q_h)^\ell P_h^{-1} \| \leq c \]

for all \( \ell \) and \( h_t \) such that \( \ell h_t \leq t^* \).
Theorem (Lax Convergence)

If a two-level FD scheme is

- consistent in the $L^2$-norm with order $q_t$ in time and $q_x$ in space, and
- stable in the $L^2$-norm,

then it is convergent in the $L^2$-norm with order $q_t$ in time and $q_x$ in space.
Lax Convergence: Proof (1/2)
Lax Convergence: Proof (2/2)

\[ e_\ell = h_t \sum_{m=1}^{\ell} (P_h^{-1} Q_h)^{\ell-m} P_h^{-1} \tau_{m-1}. \]
Conditions for Stability

\[ \left\| (P_h^{-1} Q_h)^\ell P_h^{-1} \right\| \leq c \]

Give a simpler, sufficient condition:

How can we show bounds on these matrix norms?
Stability of ETBS (1/3)

Theorem (Gershgorin)

For a matrix $A \in \mathbb{C}^{N \times N} = (a_{i,j})$,

$$\sigma(A) \subset \bigcup_{j=1}^{N} \bar{B} \left( a_{j,j}, \sum_{k \neq j} |a_{j,k}| \right).$$

ETBS:

$$\frac{u_{k,\ell+1} - u_{k,\ell}}{h_t} + a \frac{u_{k,\ell} - u_{k-1,\ell}}{h_x} = 0$$

Analyze stability of ETBS:
$P_h = I$ and $Q_h = \text{tridiag}(\lambda, 1 - \lambda, 0)$. 
Stability of ETBS (3/3)

Summarize ETBS stability:

Comments?
Outline

Introduction

**Finite Difference Methods for Time-Dependent Problems**
- 1D Advection
- Stability and Convergence
  - Von Neumann Stability
- Dispersion and Dissipation
- A Glimpse of Parabolic PDEs

**Finite Volume Methods for Hyperbolic Conservation Laws**

**Finite Element Methods for Elliptic Problems**

**Discontinuous Galerkin Methods for Hyperbolic Problems**
Discrete Time Fourier Transform

Assume \( x \) infinitely long. Define:

\[
\hat{x}(\theta) = \sum_{k} x_k e^{-i\theta k}
\]

When is this well-defined?
Inverting the Fourier Transform

To recover $x$:

$$x_k = \frac{1}{2\pi} \int_{-\pi}^{\pi} \hat{x}(\theta) e^{i\theta k} d\theta.$$
Getting to $L^2$

- Fourier Transform well defined for $x \in \ell^1$.
- Problem: We care about $L^2$, not $\ell^1$.

**Theorem (Parseval)**

If $\|x\|_2 < \infty$, then

$$\|x\|_2^2 = \frac{1}{2\pi} \int_{-\pi}^{\pi} |\hat{x}(\theta)|^2 \, d\theta < \infty.$$

Impact?
**Definition (Toeplitz Operator)**

An operator $T$ is a Toeplitz operator if $(Tx)_j = \sum_k x_k p_{j-k}$. In this case, $p$ is called the Toeplitz vector.

**Example: ETCS**

Let $\lambda = ah_t/2h_x$. Then

$$u_{k,\ell+1} = \lambda u_{k-1,\ell} + u_{k,\ell} - \lambda u_{k+1,\ell}.$$
Is ETCS Toeplitz?

\[(P_h u_{\ell+1})_j = u_{j,\ell+1} = \sum_k u_{k,\ell+1} p_{j-k}\]

\[(Q_h u_\ell)_j = \lambda u_{k-1,\ell} + u_{k,\ell} - \lambda u_{k+1,\ell} = \sum_k u_{k,\ell} q_{j-k}\]
Fourier Transforms of Toeplitz Operators (1/3)

\[ y_j = \sum_{k} x_k p_{j-k} \]
\[ \hat{y}(\theta) = \frac{1}{2\pi} \int_{-\pi}^{\pi} \hat{x}(\theta) \sum_j \left( \sum_k e^{i\varphi(k-j)p_{j-k}} \right) e^{i(\varphi-\theta)j} \, d\theta. \]
\[ \hat{y}(\theta) = \int_{-\pi}^{\pi} \hat{x}(\theta) \hat{p}(\varphi) \frac{1}{2\pi} \sum_j e^{i(\varphi - \theta)j} d\theta. \]
Fourier Transforms of Inverse Toeplitz Operators

Fourier transform $P_h^{-1} Q_h y$?
Bounding the Operator Norm

Bound $\|P_h^{-1} Q_h\|_2^2$ using Fourier:

Is the upper bound attained?
von Neumann Stability

Two-level finite difference scheme

\[ P_h v_{\ell+1} = Q_h v_\ell + h_t b_\ell, \]

where \( P_h \) and \( Q_h \) are Toeplitz operators with vectors \( p \) and \( q \).

Definition (Symbol of a Two-Level Finite Difference Scheme)

Let

\[ \hat{p}(\theta) = \sum_k p_k e^{-i\varphi_k}, \quad \hat{q}(\theta) = \sum_k q_k e^{-i\varphi_k}. \]

Then the symbol of the two-level FD method is \( s(\varphi) = \hat{q}(\varphi)/\hat{p}(\theta) \).

Definition (Von Neumann Stability)

If

\[ \max_\varphi |s(\varphi)| \leq 1, \quad \max_\varphi \left| \frac{1}{\hat{p}(\varphi)} \right| \leq c \]

for some constant \( c > 0 \), we say the scheme is von Neumann stable.
Comparison with Lax-Richtmyer Stability

Need \( \| (P_h^{-1} Q_h) \ell P_h^{-1} \| \leq c \).

Why is bounding the symbol the most salient part?

Main restriction of von Neumann stability?
von Neumann Stability: ETBS (1/2)

ETBS: Let $\lambda = ah_t/h_x$. $u_{k,\ell+1} = \lambda u_{k-1,\ell} + (1 - \lambda)u_{k,\ell}$. 
von Neumann Stability: ETBS (2/2)

Found: $|s(\varphi)|^2 = 1 + 2(\lambda - \lambda^2)(\cos \varphi - 1)$. 
von Neumann Stability: ETCS

Let $\lambda = \frac{ah_t}{h_x}$. Then

$$u_{k,\ell+1} = \frac{\lambda}{2} u_{k-1,\ell} + u_{k,\ell} - \frac{\lambda}{2} u_{k+1,\ell}.$$
von Neumann Stability: Crank-Nicolson

Let $\lambda = ah_t/(4h_x)$

$$-\lambda u_{k-1,\ell+1} + u_{k,\ell+1} + \lambda u_{k+1,\ell+1} = \lambda u_{k-1,\ell} + u_{k,\ell} - \lambda u_{k+1,\ell}.$$
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems
   1D Advection
   Stability and Convergence
   Von Neumann Stability
   Dispersion and Dissipation
   A Glimpse of Parabolic PDEs

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems

Discontinuous Galerkin Methods for Hyperbolic Problems
Saw numerically: interesting dispersion/dissipation behavior.
Want: theoretical understanding.

Consider linear, continuous (not yet discrete) differential operators

\[
L_1 u = u_t + a u_x,
\]
\[
L_2 u = u_t - D u_{xx} + a u_x \quad (D>0)
\]
\[
L_3 u = u_t + a u_x - \mu u_{xxx}.
\]

What could we use as a prototype solution?
A Prototype Solution of the PDE

Observation: all these operators are diagonalized by complex exponentials. Come up with a ‘prototype complex exponential solution’.

What type of function is this?
Wave-like Solutions of the PDE

\[ z(x, t) = z_0 e^{i(kx - \omega t)} \]

Observations in connection with \( L \)?

What is the dispersion relation?
Picking Apart the Dispersion Relation

Consider $\omega(k) = \alpha(k) + i\beta(k)$. Rewrite the wave solution with this.

How can we recognize dissipation?

What is the phase speed? How can we recognize dispersion?
Dispersion Relation: Examples

In each case, find the dispersion relation and identify properties.

$L_1 u = u_t + au_x$

$L_2 u = u_t - Du_{xx} + au_x \ (D > 0)$

$L_3 u = u_t + au_x - \mu u_{xxx}$
Numerical Dissipation/Dispersion Analysis

**Goal:** Want discrete finite difference scheme to match dissipation/dispersion behavior of continuous PDE.

Define a discrete wave-like function:

We want \( z \) to solve \( P_h z_{\ell+1} = Q_h z_\ell \). How can we connect the operators to the wave solution?
Toeplitz and Waves

\[ z_{j,\ell} = z_0 e^{i(kj h_x - \omega \ell h_t)}. \]

**Theorem (Waves Diagonalize Toeplitz Operators)**

Let \( T \) be a Toeplitz operator. Then \( T z_\ell = \lambda(k) z_\ell = \hat{t}(kh_x) z_\ell. \)
Waves and Two-Level Schemes

Since $P_h$ and $Q_h$ are Toeplitz, we must have

$$P_h z_{\ell+1} = \lambda_P(k) z_{\ell+1}, \quad Q_h z_{\ell} = \lambda_Q(k) z_{\ell}.$$ 

What does that mean?

Seen before?
So \( z_\ell \) is a solution of the finite difference scheme if \( \omega = \omega(kh_x) \) satisfies

\[
e^{-i\omega(\kappa)ht} = s(\kappa),
\]

where we let \( \kappa = kh_x \). Interpret \( \kappa \).

Let \( s(\kappa) = |s(\kappa)| e^{i\varphi(\kappa)} = e^{\log|s(\kappa)|+i\varphi(\kappa)} \). \( \omega(\kappa) \)?
Discrete Dispersion Relation (2/2)

\[ \omega(\kappa) = -\varphi(\kappa) + \frac{i \log |s(\kappa)|}{h_t}. \]

Plug that into the wave-like solution:

Criterion for stability?
Numerical Dispersion/Dissipation

Finite difference scheme $P_h u_{\ell+1} = Q_h u_{\ell}$ with symbol $s(k)$.

$$z_{j,\ell} = z_0 e^{\log|s(\kappa)| \ell} e^{ik \left( jh_x - \frac{-\varphi(\kappa)}{kh_t} \ell h_t \right)}$$

When is the scheme **dissipative**?

What is the **phase speed**?

Dispersion?
Dispersion/Dissipation Analysis of ETBS

Let $\lambda = ah_t/h_x$. Shown earlier: $s(kh_x) = 1 - \lambda(1 - e^{-ikh_x})$. 
Dispersion/Dissipation Analysis of ETBS: Fine Grid

\[ e^{-i\omega(\kappa)h_t} = 1 - \lambda(1 - e^{-ikh_x}) \]
Dispersion/Dissipation: Demo

- **Demo:** Experimenting with Dispersion and Dissipation
- **Demo:** Dispersion and Dissipation
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems
  1D Advection
  Stability and Convergence
  Von Neumann Stability
  Dispersion and Dissipation
  A Glimpse of Parabolic PDEs

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems

Discontinuous Galerkin Methods for Hyperbolic Problems
Heat Equation

Heat equation ($D > 0$):

$$u_t = Du_{xx}, \quad (x, t) \in \mathbb{R} \times (0, \infty),$$
$$u(x, 0) = g(x) \quad x \in \mathbb{R}.$$ 

Fundamental solution ($g(x) = \delta(x)$):

Why is this a weird model?
Schemes for the Heat Equation

Cook up some schemes for the heat equation.

Explicit Euler:

Implicit Euler:
Let $\lambda = D h_t / h_x^2$.

$$u_{k,\ell+1} = u_{k,\ell} + \lambda(u_{k+1,\ell} - 2u_{k,\ell} + u_{k-1,\ell}).$$
\[-2 \leq 2\lambda(\cos(\varphi) - 1) \leq 0.\]

Comment on the stability region found regarding speeds of propagation.
Von Neumann Analysis of Implicit Euler for Heat

Let \( \lambda = \frac{Dh_t}{h_x^2} \).

\[
  u_{k,\ell+1} - \lambda(u_{k+1,\ell+1} - 2u_{k,\ell+1} + u_{k-1,\ell+1}) = u_{k,\ell}
\]

Does the type of system we need to solve for implicit+parabolic correspond to another PDE?
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws
  Theory of 1D Scalar Conservation Laws
  Numerical Methods for Conservation Laws
  Higher-Order Finite Volume
  Outlook: Systems and Multiple Dimensions

Finite Element Methods for Elliptic Problems

Discontinuous Galerkin Methods for Hyperbolic Problems
Conservation Laws: Recap

\[ u_t + f(u)_x = 0, \]

where \( u \) is a function of \( x \) and \( t \in \mathbb{R}_0^+ \).

Rewrite in integral form:

Recall: Characteristic Curve: a function \( x(t) \) so that \( u(x(t), t) = u(x_0, 0) \).

\[ \begin{cases} \frac{dx(t)}{dt} = f'(u(x(t), t)), \\ x(0) = x_0. \end{cases} \]

What assumption underlies all this?
Consider Burger’s Equation:

\[
\begin{aligned}
    u_t + \left( \frac{u^2}{2} \right)_x &= 0, \\
    u(x, 0) &= g(x) = \sin(x).
\end{aligned}
\]

Interpret Burger’s equation.

Consider the characteristics at \( \pi/2 \) and \( 3\pi/2 \).
Weak Solutions

Define a weak solution:

\[
\frac{d}{dt} \int_{a}^{b} u(x, t) dx = f(u(a, t)) - f(u(b, t))
\]
Rankine-Hugoniot Condition (1/2)

Consider: Two $C^1$ segments separated by a curve $x(t)$ with no regularity.
\[(d/dt)G_a(x(t), t) = u(x(t), t)x'(t) - (f(u(x(t), t)) - f(u(a, t))).\]
Theorem (Rankine-Hugoniot and Weak Solutions)

If \( u \) is piecewise \( C^1 \) and is discontinuous only along isolated curves, and if \( u \) satisfies the PDE when it is \( C^1 \), and the Rankine-Hugoniot condition holds along all discontinuous curves, then \( u \) is a weak solution of the conservation law.
Consider the following Riemann problem:

\[ u_t + \left( \frac{u^2}{2} \right)_x = 0, \]

\[ u(x, 0) = \begin{cases} 
1 & x < 0, \\
-1 & x \geq 0.
\end{cases} \]
Riemann Problems: Example 2

\[ u_t + \left( \frac{u^2}{2} \right)_x = 0, \]

\[ u(x, 0) = \begin{cases} 
-1 & x < 0, \\
1 & x \geq 0.
\end{cases} \]

(IC sign flip compared to previous slide)
Bad Shocks and Good Shocks

In the shock version of the ‘ambiguous’ Riemann problem, where do the characteristics go?

Comment on the stability of that situation.
Ad-Hoc Idea: Ban Bad Shocks

Recall: what is $f'(u)$?

Devise a way to ban unstable shocks.
Vanishing Viscosity Solutions

Goal: neither uniqueness nor existence poses a problem.

How?
What are features of (physical) entropy?

**Definition (Entropy/Entropy Flux)**

An entropy $\eta(u)$ and an entropy flux $\psi(u)$ are functions so that $\eta$ is convex and

$$\eta(u)_t + \psi(u)_x = 0$$

for smooth solutions of the conservation law.
Finding Entropy-Flux Pairs

\[ \eta(u)_t + \psi(u)_x = 0. \] Find conditions on \( \eta \) and \( \psi \).

Come up with an entropy-flux pair for Burgers.
What's the evolution equation for the entropy?
\[ \eta(u)_t + \psi(u)_x = \varepsilon(\eta'(u)u_x)_x - \varepsilon\eta''(u)u_x^2. \]

Integrate this over \([x_1, x_2] \times [t_1, t_2]\).
Definition (Entropy solution)

The function $u(x, t)$ is the entropy solution of the conservation law if for all convex entropy functions and corresponding entropy fluxes, the inequality

$$\eta(u)_t + \psi(u)_x \leq 0$$

is satisfied in the weak sense.
Conservation of Entropy?

What can you say about conservation of entropy in time?
Total Variation

\[ TV(u) = \limsup_{\varepsilon \to 0} \frac{1}{\varepsilon} \int |u(x + \varepsilon) - u(x)| \, dx. \]

Simpler form if \( u \) is differentiable?

Hiking analog?
Total Variation and Conservation Laws

Theorem (Total Variation is Bounded [Dafermos 2016, Thm. 6.2.6])

Let $u$ be a solution to a conservation law with $f''(u) \geq 0$. Then:

$$TV(u(t + \Delta t, \cdot)) \leq TV(u(t, \cdot)) \quad \text{for } \Delta t \geq 0.$$ 

Theorem ($L^1$ contraction [Dafermos 2016, Thm. 6.3.2])

Let $u$, $v$ be viscosity solutions of the conservation law. Then

$$\|u(t + \Delta t, \cdot) - v(t + \Delta t, \cdot)\|_{L^1} \leq \|u(t, \cdot) - v(t, \cdot)\|_{L^1} \quad \text{for } \Delta t \geq 0.$$
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws
  Theory of 1D Scalar Conservation Laws
  Numerical Methods for Conservation Laws
  Higher-Order Finite Volume
  Outlook: Systems and Multiple Dimensions

Finite Element Methods for Elliptic Problems

Discontinuous Galerkin Methods for Hyperbolic Problems
Finite Difference for Conservation Laws? (1/2)

\[
\begin{cases}
  u_t + \left( \frac{u}{2} \right)_x^2 = 0 \\
  u(x, 0) = \begin{cases}
    1 & x < 0, \\
    0 & x \geq 0.
  \end{cases}
\end{cases}
\]

Entropy Solution?

Rewrite the PDE to ‘match’ the form of advection \( u_t + au_x = 0 \):

Equivalent?
Finite Difference for Conservation Laws? (2/2)

Recall the *upwind scheme* for \(u_t + au_x = 0\):

\[
\text{Write the upwind FD scheme for } u_t + uu_x = 0:
\]
Schemes in Conservation Form

**Definition (Conservative Scheme)**

A conservation law scheme is called **conservative** iff it can be written as

\[ f^* \ldots \]

where \( f^* \ldots \)

**Theorem (Lax-Wendroff)**

*If the solution \( \{u_{j, \ell}\} \) to a conservative scheme converges (as \( \Delta t, \Delta x \to 0 \)) to a solution \( u(x, t) \), then \( u(x, t) \) is a weak solution of the conservation law.*
Lax-Wendroff Theorem: Proof

Summation by parts: With $\Delta^+ a_k = a_{k+1} - a_k$ and $\Delta^- a_k = a_k - a_{k-1}$:

$$\sum_{k=1}^{N} a_k (\Delta^- \varphi_k) + \sum_{k=1}^{N} \varphi_k (\Delta^+ a_k) = -a_1 \varphi_0 + \varphi_N a_{N+1}.$$
Finite Volume Schemes

Finite volume: Idea?
Developing Finite Volume

\[
\int_{t_\ell}^{t_{\ell+1}} \int_{x_{j-1/2}}^{x_{j+1/2}} (u_t + f(u)_x) \, dx \, dt = 0
\]
Flux Integrals?

\[ \frac{1}{h_x} \int_{t_\ell}^{t_{\ell+1}} f(u_{j+1/2}) \, dt? \]
The Godunov Scheme

Altogether:

\[ \bar{u}_{j, \ell+1} = \bar{u}_{j, \ell} - \frac{h_t}{h_x} (f(u_{j+1/2, \ell}) - f(u_{j-1/2, \ell})). \]

Overall algorithm?

Heuristic time step restriction?
Riemann Problem

\[
\begin{aligned}
&\frac{\partial u}{\partial t} + f(u)\frac{\partial u}{\partial x} = 0, \\
&u(x, 0) = \begin{cases} 
  u_l & x < 0, \\
  u_r & x \geq 0
\end{cases}
\end{aligned}
\]

Exact solution in the Burgers case?
Riemann Solver for a General Conservation Law

To complete the scheme: Need $f^*(u^-, u^+)$. For Burgers: already known. For a general (convex/concave-$f$) conservation law?

Equivalent to

$$f^*(u^-, u^+) = \begin{cases} \max_{u^+ \leq u \leq u^-} f(u) & \text{if } u^- > u^+, \\ \min_{u^+ \leq u \leq u^-} f(u) & \text{if } u^- < u^+ \end{cases}$$
More Riemann Solvers

Downside of Godunov Riemann solver?
Back to Advection

Consider only $f(u) = au$ for now. Riemann solver inspiration from FD?
Side Note: First Order Upwind, Rewritten

\[
\frac{u_{j,\ell+1} - u_{j,\ell}}{h_t} + \frac{f^*(u_{j,\ell}, u_{j+1,\ell}) - f^*(u_{j-1,\ell}, u_{j,\ell})}{h_x}
\]

with

\[
f^*(u^-, u^+) = \frac{au^- + au^+}{2} - \frac{|a|}{2}(u^+ - u^-).
\]
Lax-Friedrichs

Generalize linear upwind flux for a nonlinear conservation law:

\[ f^*(u^-, u^+) = \frac{au^- + au^+}{2} - \frac{|a|}{2}(u^+ - u^-). \]

**Demo:** Finite Volume Burgers (Part I)
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws
  Theory of 1D Scalar Conservation Laws
  Numerical Methods for Conservation Laws
  Higher-Order Finite Volume
  Outlook: Systems and Multiple Dimensions

Finite Element Methods for Elliptic Problems

Discontinuous Galerkin Methods for Hyperbolic Problems
Improving Accuracy

Consider our existing discrete FV formulation:

\[ \bar{u}_{j,\ell+1} = \bar{u}_{j,\ell} - \frac{h_t}{h_x} (f(u_{j+1/2,\ell}) - f(u_{j-1/2,\ell})). \]

What obstacles exist to increasing the order of accuracy?

What order of accuracy can we expect?
Improving the Order of Accuracy

Improve temporal accuracy.

What’s the obstacle to higher spatial accuracy?

How can we improve the accuracy of that approximation?
Increasing Spatial Accuracy

Temporary Assumptions:

▶ $f'(u) \geq 0$
▶ $f^*_{j+1/2} = f(\bar{u}_j)$ (e.g. Godunov in this situation)

Reconstruct $u_{j+1/2}$ using $\{\bar{u}_{j-1}, \bar{u}_j, \bar{u}_{j+1}\}$. Accuracy? Names?

Compute fluxes, use increments over cell average:
Lax-Wendroff

For \( u_t + au_x \), from finite difference:

\[
f^*(u^-, u^+) = \frac{au^- + au^+}{2} - \frac{a^2}{2} \cdot \frac{\Delta t}{\Delta x} (u^+ - u^-).
\]

Taylor in time: \( u_{\ell+1} = u_\ell + \partial_t u_\ell \cdot h_t + \partial_t^2 u_\ell \cdot h_t/2 + O(h_t^3) \).

\[
\begin{align*}
\frac{u_{j,\ell+1} - u_{j,\ell}}{h_t} + \frac{f(u_{j+1,\ell}) - f(u_{j-1,\ell})}{2h_x} &= h_t \left[ f'(u_{j+1/2,\ell}) \frac{f(u_{j+1,\ell}) - f(u_{j,\ell})}{h_x} - f'(u_{j-1/2,\ell}) \frac{f(u_{j,\ell}) - f(u_{j-1,\ell})}{h_x} \right] \\
\text{As a Riemann solver:} & \quad f^*(u^-, u^+) = \frac{f(u^-) + f(u^+)}{2} - \frac{h_t}{2} [f'(u^\circ)(f(u^+) - f(u^-))] 
\end{align*}
\]
Monotone Schemes

<table>
<thead>
<tr>
<th>Definition (Monotone Scheme)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A scheme</td>
</tr>
</tbody>
</table>

\[
u_{j, \ell + 1} = u_{j, \ell} - \lambda (f^* (u_{j-p}, \ldots, u_{j+q}) - f^* (u_{j-p-1}, \ldots, u_{j+q-1}))
\]

\[=: G(u_{j-p-1}, \ldots, u_{j+q})\]

is called a **montone scheme** if \( G \) is a monotonically nondecreasing function \( G(\uparrow, \uparrow, \ldots, \uparrow) \) of each argument.
Monotonicity for Three-Point Schemes

Three-Point Scheme:

\[ G(u_{j-1}, u_j, u_{j+1}) = u_j - \lambda[f^*(u_j, u_{j+1}) - f^*(u_{j-1}, u_j)] . \]

When is this monotone?
Lax-Friedrichs is Monotone

\[ f^*(u^-, u^+) = \frac{f(u^-) + f(u^+)}{2} - \frac{\alpha}{2}(u^+ - u^-). \]

Show: This is monotone.
Monotone Schemes: Properties

Theorem (Good properties of monotone schemes)

- **Local maximum principle:**
  \[
  \min_{i \in \text{stencil around } j} u_i \leq G(u)_j \leq \max_{i \in \text{stencil around } j} u_i.
  \]

- **$L^1$-contraction:**
  \[
  \|G(u) - G(v)\|_{L^1} \leq \|u - v\|_{L^1}.
  \]

- **TVD:**
  \[
  TV(G(u)) \leq TV(u).
  \]

- **Solutions to monotone schemes satisfy all entropy conditions.**
Godunov’s Theorem

**Theorem (Godunov)**

*Monotone schemes are at most first-order accurate.*

What now?
Definition (Linear Schemes)

A scheme is called a linear scheme if it is linear when applied to a linear PDE:

\[ u_t + au_x = 0, \]

where \( a \) is a constant.

Write the general case of a linear scheme for \( u_t + u_x = 0 \):
Linear + TVD = ?

Theorem (TVD for linear Schemes)

For linear schemes, TVD $\Rightarrow$ monotone.

What does that mean?

Now what?
Theorem (Harten’s Lemma)

If a scheme can be written as

\[ \bar{u}_{j, \ell+1} = \bar{u}_{j, \ell} + \lambda (C_{j+1/2} \Delta + \bar{u}_j - D_{j-1/2} \Delta - \bar{u}_j) \]

with \( C_{j+1/2} \geq 0, \ D_{j+1/2} \geq 0, \ 1 - \lambda (C_{j+1/2} + D_{j+1/2}) \geq 0 \) and \( \lambda = \frac{h_t}{h_x} \), then it is TVD.

As a matter of notation, we have

\[ \Delta_+ u_j = u_{j+1} - u_j, \]
\[ \Delta_- u_j = u_j - u_{j-1}. \]

We have omitted the time subscript for the time level \( \ell \).
Harten’s Lemma: Proof
Minmod Scheme

Still assume \( f'(u) \geq 0 \).

\[
\begin{align*}
\tilde{u}^{*(1)}_{j+1/2} &= f\left( \bar{u}_j + \frac{1}{2}(\bar{u}_{j+1} - \bar{u}_j) \right), \\
\tilde{u}^{*(2)}_{j+1/2} &= f\left( \bar{u}_j + \frac{1}{2}(\bar{u}_j - \bar{u}_{j-1}) \right).
\end{align*}
\]

Design a ‘safe’ thing to use for \( \tilde{u} \):
Minmod is TVD

Show that Minmod is TVD:
Derive a time step restriction for Minmod.
What about Time Integration?

\[ u^{(1)} = u_\ell + h_t L(u_\ell), \quad u_{\ell+1} = \frac{u_\ell}{2} + \frac{1}{2} (u^{(1)} + h_t L(u^{(1)})) . \]

Above: A version of RK2 with \( L \) the ODE RHS. Will this cause wrinkles?
Total Variation is Convex

Show: $TV(\cdot)$ is a convex functional.
TVD and High Order

Can TVD schemes be high order everywhere? (aside from near shocks)
High Order at Smooth Extrema

- TVB Schemes [Shu ‘87]
- ENO [Harten/Engquist/Osher/Chakravarthy ‘87]
  - Define $W_j = w(x_{j+1/2}) = \int_{x_1/2}^{x_j+1/2} u(\xi, t) d\xi = h_x \sum_{i=1}^{j} \bar{u}_i$
    - Observe $u_{j+1/2} = w'(x_{j+1/2})$.
    - Approximate by interpolation/numerical differentiation.
  - Start with the linear function $p^{(1)}$ through $W_{j-1}$ and $W_j$
  - Compute divided differences on $(W_{j-2}, W_{j-1}, W_j)$
  - Compute divided differences on $(W_{j-1}, W_j, W_{j+1})$
  - Use the one with the smaller magnitude (of the divided differences) to extend $p^{(1)}$ to quadratic
    - (and so on, adding points on the side with the lowest magnitude of the divided differences)
- WENO [Liu/Osher/Chan ‘94]
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws
  - Theory of 1D Scalar Conservation Laws
  - Numerical Methods for Conservation Laws
  - Higher-Order Finite Volume
    - Outlook: Systems and Multiple Dimensions

Finite Element Methods for Elliptic Problems

Discontinuous Galerkin Methods for Hyperbolic Problems
Systems of Conservation Laws

Linear system of hyperbolic conservation laws, $A \in \mathbb{R}^{m \times m}$:

$$
\begin{align*}
    u_t + Au_x &= 0, \\
    u(x, 0) &= u_0(x).
\end{align*}
$$

Assumptions on $A$?
Linear System Solution

\[ \mathbf{v} = R^{-1} \mathbf{u}, \quad \mathbf{v}_t + \Lambda \mathbf{v}_x = 0. \]

Write down the solution.

What is the impact on boundary conditions? E.g. \((\lambda_p) = (-c, 0, c)\) for a BC at \(x = 0\) for \([0, 1]\)?
Consider system $u_t + f(u)_x = 0$. Write in quasilinear form:

When hyperbolic?
What about characteristics/shock speeds?

Are values of $u$ still constant along characteristics?
Shocks and Riemann Problems for Systems

\[ u_t + A u_x = 0, \]
\[ u(x, 0) = \begin{cases} u_l & x < 0, \\ u_r & x > 0. \end{cases} \]

Solution? (Assume strict hyperbolicity with \( \lambda_1 < \lambda_2 < \cdots < \lambda_m \).)
Shock Fans (1/2)

What does the solution look like?

Jump across the characteristic associated with $\lambda_p$?
Shock Fans (2/2)

Do those jumps satisfy Rankine-Hugoniot?

How can we find intermediate values of $u$?
Two Dimensions

\[ u_t + f(u)_x + g(u)_y = 0. \]

Finite volume methods generalize in principle:

However:
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems
  tl;dr: Functional Analysis
  Back to Elliptic PDEs
  Galerkin Approximation
  Finite Elements: A 1D Cartoon
  Finite Elements in 2D
  Approximation Theory in Sobolev Spaces
  Saddle Point Problems, Stokes, and Mixed FEM
  Non-symmetric Bilinear Forms

Discontinuous Galerkin Methods for Hyperbolic Problems
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems
  tl;dr: Functional Analysis
  Back to Elliptic PDEs
  Galerkin Approximation
  Finite Elements: A 1D Cartoon
  Finite Elements in 2D
  Approximation Theory in Sobolev Spaces
  Saddle Point Problems, Stokes, and Mixed FEM
  Non-symmetric Bilinear Forms

Discontinuous Galerkin Methods for Hyperbolic Problems
Consider

\[ f_n(x) = \begin{cases} 
-1 & x \leq -\frac{1}{n}, \\
\frac{3n}{2}x - \frac{n^3}{2}x^3 & -\frac{1}{n} < x < \frac{1}{n}, \\
1 & x \geq 1/n. 
\end{cases} \]

Converges to the step function. Problem?
A norm \( \| \cdot \| \) maps an element of a vector space into \([0, \infty)\). It satisfies:

- \( \| x \| = 0 \iff x = 0 \)
- \( \| \lambda x \| = |\lambda| \| x \| \)
- \( \| x + y \| \leq \| x \| + \| y \| \) (triangle inequality)
Definition (Convergent Sequence)

\[ x_n \to x \iff \|x_n - x\| \to 0 \quad \text{(convergence in norm)} \]

Definition (Cauchy Sequence)
**Banach Spaces**

### Definition (Complete/“Banach” space)

<p>| |</p>
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
</table>

What’s special about Cauchy sequences?

<p>| |</p>
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
</table>

Counterexamples?

<p>| |</p>
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
</table>
More on $C^0$

Let $\Omega \subseteq \mathbb{R}^n$ be open. Is $C^0(\Omega)$ with $\|f\|_\infty := \sup_{x \in \Omega} |f(x)|$ Banach?

Is $C^0(\bar{\Omega})$ with $\|f\|_\infty := \sup_{x \in \Omega} |f(x)|$ Banach?
$C^m$ Spaces

Let $\Omega \subseteq \mathbb{R}^n$.

Consider a multi-index $k = (k_1, \ldots, k_n)$ and define the symbols

Definition ($C^m$ Spaces)
**$L^p$ Spaces**

Let $1 \leq p < \infty$.

**Definition ($L^p$ Spaces)**

\[
L^p(\Omega) := \left\{ u : (u : \mathbb{R} \to \mathbb{R}) \text{ measurable}, \int_{\Omega} |u|^p \, dx < \infty \right\},
\]

\[
\|u\|_p := \left( \int_{\Omega} |u|^p \, dx \right)^{1/p}.
\]

**Definition ($L^\infty$ Space)**

\[
L^\infty(\Omega) := \left\{ u : (u : \mathbb{R} \to \mathbb{R}), |u(x)| < \infty \text{ almost everywhere} \right\},
\]

\[
\|u\|_\infty = \inf \{ C : |u(x)| \leq C \text{ almost everywhere} \}.
\]
\(L^p\) Spaces: Properties

**Theorem (Hölder’s Inequality)**

For \(1 \leq p, q \leq \infty\) with \(1/p + 1/q = 1\) and measurable \(u\) and \(v\),

\[
\|uv\|_1 \leq \|u\|_p \|v\|_q
\]

**Theorem (Minkowski’s Inequality (Triangle inequality in \(L^p\)))**

For \(1 \leq p \leq \infty\) and \(u, v \in L^p(\Omega)\),

\[
\|u + v\|_p \leq \|u\|_p + \|v\|_p
\]
Inner Product Spaces

Let $V$ be a vector space.

**Definition (Inner Product)**

An *inner product* is a function $\langle \cdot , \cdot \rangle : V \times V \to \mathbb{R}$ such that for any $f, g, h \in V$ and $\alpha \in \mathbb{R}$

\[
\langle f, f \rangle \geq 0, \\
\langle f, f \rangle = 0 \iff f = 0, \\
\langle f, g \rangle = \langle f, g \rangle, \\
\langle \alpha f + g, h \rangle = \alpha \langle f, h \rangle + \langle g, h \rangle.
\]

**Definition (Induced Norm)**

\[
\| f \| = \sqrt{\langle f, f \rangle}.
\]
Hilbert Spaces

**Definition (Hilbert Space)**

An inner product space that is complete under the induced norm.

Let $\Omega$ be open.

**Theorem ($L^2$)**

$L^2(\Omega)$ equals the closure of (set of all limits of Cauchy sequences in) $C_0^\infty(\Omega)$ under the induced norm $\| \cdot \|_2$.

**Theorem (Hilbert Projection)**
Weak Derivatives

Define the space $L^1_{loc}$ of locally integrable functions.

**Definition (Weak Derivative)**

$v \in L^1_{loc}(\Omega)$ is the **weak partial derivative** of $u \in L^1_{loc}(\Omega)$ of multi-index order $k$ if
Consider all these on the interval \([-1, 1]\).

\[ f_1(x) = 4(1 - x)x \]

\[ f_2(x) = \begin{cases} 
2x & \text{if } x \leq 1/2, \\
2 - 2x & \text{if } x > 1/2.
\end{cases} \]
Weak Derivatives: Examples (2/2)

\[ f_3(x) = \sqrt{\frac{1}{2}} - \sqrt{|x - 1/2|} \]
Sobolev Spaces

Let \( \Omega \subset \mathbb{R}^n \), \( k \in \mathbb{N}_0 \) and \( 1 \leq p < \infty \).

Definition \(((k, p)\text{-Sobolev Norm/Space})\)
More Sobolev Spaces

\( W^{0,2} \)

\( W^{s,2} \)

\( H_0^1(\Omega) \)
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems
  tl;dr: Functional Analysis
  Back to Elliptic PDEs
  Galerkin Approximation
  Finite Elements: A 1D Cartoon
  Finite Elements in 2D
  Approximation Theory in Sobolev Spaces
  Saddle Point Problems, Stokes, and Mixed FEM
  Non-symmetric Bilinear Forms

Discontinuous Galerkin Methods for Hyperbolic Problems
An Elliptic Model Problem

Let $\Omega \subset \mathbb{R}^n$ open, bounded, $f \in H^1(\Omega)$.

$$-\nabla \cdot \nabla u + u = f(x) \quad (x \in \Omega),$$

$$u(x) = 0 \quad (x \in \partial \Omega).$$

Let $V := H^1_0(\Omega)$. Integration by parts? (Gauss’s theorem applied to $ab$):

Weak form?
Motivation: Bilinear Forms and Functionals

\[ \int_\Omega \nabla u \cdot \nabla v + \int_\Omega uv = \int f v. \]

This is the weak form of the strong-form problem. The task is to find a \( u \in V \) that satisfies this for all test functions \( v \in V \).

Recast this in terms of bilinear forms and functionals:
Dual Spaces and Functionals

**Bounded Linear Functional**

Let \((V, \|\cdot\|)\) be a Banach space. A linear functional is a linear function \(g : V \to \mathbb{R}\). It is bounded \((\Leftrightarrow\) continuous\) if there exists a constant \(C\) so that \(|g(v)| \leq C \|v\|\) for all \(v \in V\).

**Dual Space**

Let \((V, \|\cdot\|)\) be a Banach space. Then the dual space \(V'\) is the space of bounded linear functionals on \(V\).

**Dual Space is Banach (cf. e.g. Trèves 1967)**

\(V'\) is a Banach space with the dual norm
Functionals in the Model Problem

Is $g$ from the model problem a bounded functional? (In what space?)

That bound felt loose and wasteful. Can we do better?
Riesz Representation Theorem (1/3)

Let $V$ be a Hilbert space with inner product $\langle \cdot, \cdot \rangle$.

**Theorem (Riesz)**

Let $g$ be a bounded linear functional on $V$, i.e. $g \in V'$. Then there exists a unique $u \in V$ so that $g(v) = \langle u, v \rangle$ for all $v \in V$. 


Riesz Representation Theorem: Proof (2/3)

Have \( w \in N(g)^\perp \setminus \{0\} \), \( \alpha = g(w) \neq 0 \), and \( z := v - (g(v)/\alpha)w \perp w \).
Uniqueness of $u$?
Back to the Model Problem

\[ a(u, v) = \langle \nabla u, \nabla v \rangle_{L^2} + \langle u, v \rangle_{L^2} \]

\[ g(v) = \langle f, v \rangle_{L^2} \]

\[ a(u, v) = g(v) \]

Have we learned anything about the solvability of this problem?
Poisson

Let $\Omega \subset \mathbb{R}^n$ open, bounded, $f \in H^{-1}(\Omega)$.

This is called the **Poisson problem** (with Dirichlet BCs).

Weak form?
Ellipticity

Let $V$ be a Hilbert space.

**$V$-Ellipticity**

A bilinear form $a(\cdot, \cdot) : V \times V \to \mathbb{R}$ is called **coercive** if there exists a constant $c_0 > 0$ so that

\[
|a(v, w)| \geq c_0 \|v\|^2
\]

and $a$ is called **continuous** if there exists a constant $c_1 > 0$ so that

\[
|a(v, w)| \leq c_1 \|v\| \|w\|
\]

If $a$ is both coercive and continuous on $V$, then $a$ is said to be $V$-elliptic.
Lax-Milgram Theorem

Let $V$ be Hilbert space with inner product $\langle \cdot, \cdot \rangle$.

Lax-Milgram, Symmetric Case

Let $a$ be a $V$-elliptic bilinear form that is also symmetric, and let $g$ be a bounded linear functional on $V$. Then there exists a unique $u \in V$ so that $a(u, v) = g(v)$ for all $v \in V$. 
Back to Poisson

Can we declare victory for Poisson?

Can this inequality hold in general, without further assumptions?
Theorem (Poincaré-Friedrichs Inequality)

Suppose $\Omega \subset \mathbb{R}^n$ is bounded and $u \in H^1_0(\Omega)$. Then there exists a constant $C > 0$ such that

$$\|u\|_{L^2} \leq C \|\nabla u\|_{L^2}.$$
Poincaré-Friedrichs Inequality (2/3)

Prove the result in $C_0^\infty(\Omega)$. 

Prove the result in $H^1_0(\Omega)$. 
Back to Poisson, Again

Show that the Poisson bilinear form is coercive.

Draw a conclusion on Poisson:
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems
  tl;dr: Functional Analysis
  Back to Elliptic PDEs
  Galerkin Approximation
  Finite Elements: A 1D Cartoon
  Finite Elements in 2D
  Approximation Theory in Sobolev Spaces
  Saddle Point Problems, Stokes, and Mixed FEM
  Non-symmetric Bilinear Forms

Discontinuous Galerkin Methods for Hyperbolic Problems
Some key goals for this section:

- How do we use the weak form to compute an approximate solution?
- What can we know about the accuracy of the approximate solution?

Can we pick one underlying principle for the construction of the approximation?
Galerkin Orthogonality

\[ a(u, v) = g(v) \quad \text{for all } v \in V, \quad a(u_h, v_h) = g(v_h) \quad \text{for all } v_h \in V_h. \]

Observations?
Céa’s Lemma
Let $V \subset H$ be a closed subspace of a Hilbert space $H$.

Céa’s Lemma
Let $a(\cdot, \cdot)$ be a coercive and continuous bilinear form on $V$. In addition, for a bounded linear functional $g$ on $V$, let $u \in V$ satisfy

$$a(u, v) = g(v) \quad \text{for all } v \in V.$$  

Consider the finite-dimensional subspace $V_h \subset V$ and $u_h \in V_h$ that satisfies

$$a(u_h, v_h) = g(v_h) \quad \text{for all } v_h \in V_h.$$  

Then
Céa’s Lemma: Proof

Recall Galerkin orthgonality: $a(u_h - u, v_h) = 0$ for all $v_h \in V_h$. Show the result.
Elliptic Regularity

**Definition ($H^s$ Regularity)**

Let $m \geq 1$, $H^m_0(\Omega) \subseteq V \subseteq H^m(\Omega)$ and $a(\cdot, \cdot)$ a $V$-elliptic bilinear form. The bilinear form $a(u, v) = \langle f, v \rangle$ for all $v \in V$ is called $H^s$ regular, if for every $f \in H^{s-2m}$ there exists a solution $u \in H^s(\Omega)$ and we have with a constant $C(\Omega, a, s)$,

**Theorem (Elliptic Regularity (cf. Braess Thm. 7.2))**

Let $a$ be a $H^1_0$-elliptic bilinear form with sufficiently smooth coefficient functions.
Elliptic Regularity: Counterexamples

Are the conditions on the boundary essential for elliptic regularity?

Are there any particular concerns for mixed boundary conditions?
Estimating the Error in the Energy Norm

Come up with an idea of a bound on $\|u - u_h\|_{H^1}$.

What’s still to do?
$L^2$ Estimates

Let $H$ be a Hilbert space with the norm $\| \cdot \|_H$ and the inner product $\langle \cdot, \cdot \rangle$. (Think: $H = L^2$, $V = H^1$.)

Theorem (Aubin-Nitsche)

Let $V \subseteq H$ be a subspace that becomes a Hilbert space under the norm $\| \cdot \|_V$. Let the embedding $V \hookrightarrow H$ be continuous. Then we have for the finite element solution $u \in V_h \subset V$:

if with every $g \in H$ we associate the unique (weak) solution $\varphi_g$ of the equation (also called the dual problem)
$L^2$ Estimates using Aubin-Nitsche

$$\|u - u_h\|_H \leq c_1 \|u - u_h\|_V \sup_{g \in H} \left[ \frac{1}{\|g\|_H} \inf_{v_h \in V_h} \|\varphi_g - v_h\|_V \right],$$

If $u \in H^1_0(\Omega)$, what do we get from Aubin-Nitsche?

So does Aubin-Nitsche give us an $L^2$ estimate?
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems
  tl;dr: Functional Analysis
  Back to Elliptic PDEs
  Galerkin Approximation
  Finite Elements: A 1D Cartoon
  Finite Elements in 2D
  Approximation Theory in Sobolev Spaces
  Saddle Point Problems, Stokes, and Mixed FEM
  Non-symmetric Bilinear Forms

Discontinuous Galerkin Methods for Hyperbolic Problems
Finite Elements in 1D: Discrete Form

\[ \Omega := [\alpha, \beta]. \] Look for \( u \in H_0^1(\Omega) \), so that \( a(u, \varphi) = \langle f, \varphi \rangle \) for all \( \varphi \in H_0^1(\Omega) \). Choose \( V_h = \text{span}\{\varphi_1, \ldots, \varphi_n\} \) and expand
\[ u_h = \sum_{i=1}^n u_h^i \varphi_i \in V_h. \] Find the discrete system.
Grids and Hats

Let \( l_i := [\alpha_i, \beta_i] \), so that \( \bar{\Omega} = \bigcup_{i=0}^{N} l_i \) and \( l_i \cap l_j = \emptyset \) for \( i \neq j \). Consider a grid

\[
\alpha = x_0 < \cdots < x_N < x_{N+1} = \beta,
\]

i.e. \( \alpha_i = x_i, \beta_i = x_{i+1} \) for \( i \in \{0, \ldots, N\} \). The \( \{x_i\} \) are called nodes of the grid. \( h_i := x_{i+1} - x_i \) for \( i \in \{0, \ldots, N\} \) and \( h := \max_i h_i \). \( V_h ? \) Basis?
Degrees of Freedom and Matrices

Define something more general than basis coefficients to solve for.

Define **shape functions** and assemble the **stiffness matrix**:
A Matrix Property for Efficiency

\[(A_h)_{i,j} = a(\hat{\varphi}_j, \hat{\varphi}_i).\]

Anything special about the matrix?
According to Céa, what’s our main missing piece in error estimation now?
Interpolation Error (1D-only)

For $v \in H^2(\Omega)$,

If $v \in H^1(\Omega) \setminus H^2(\Omega)$,

Is $I_h^1$ defined for $v \in H^2$? for $v \in H^1 \setminus H^2$?
Interpolation Error: Towards an Estimate

Provide an a-priori estimate.

What’s the relationship between $I^1_h u$ and $u_h$?
Is there a simple way of constructing the polynomial basis?
Construct a polynomial basis using this approach.
Demo: Developing FEM in 1D
**Going Higher Order**

\[ \Omega \subset \mathbb{R} \] with a grid as above.

Possible extension:

**Higher Order Approximation**

Let \( 0 \leq \ell \leq k \). Then for \( v \in H^{\ell+1}(\Omega) \),
Define some **degrees of freedom** (or **DoFs**) for high-order 1D FEM.
Define local form functions for high-order 1D FEM.
High-Order: Global Basis

Obtain the global shape functions for high-order 1D FEM.
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems
  tl;dr: Functional Analysis
  Back to Elliptic PDEs
  Galerkin Approximation
  Finite Elements: A 1D Cartoon
  Finite Elements in 2D
  Approximation Theory in Sobolev Spaces
  Saddle Point Problems, Stokes, and Mixed FEM
  Non-symmetric Bilinear Forms

Discontinuous Galerkin Methods for Hyperbolic Problems
A Boundary Value Problem

Consider the following elliptic PDE

\[-\nabla \cdot (\kappa(x) \nabla u) = f(x) \quad \text{for} \quad x \in \Omega \subset \mathbb{R}^2,\]

\[u(x) = 0 \quad \text{when} \quad x \in \partial \Omega.\]

Weak form?
Weak Form: Bilinear Form and RHS Functional

Hence the problem is to find $u \in V$, such that

$$a(u, v) = g(v), \quad \text{for all } v \in V = H^1_0(\Omega)$$

where...

Is this symmetric, coercive, and continuous?
Triangulation: 2D

Suppose the domain is a union of triangles $E_m$, with vertices $x_i$.

$$\bar{\Omega} = \bigcup_{i=1}^{M} E_m.$$
Elements and the Bilinear Form

If the domain, $\Omega$, can be written as a disjoint union of elements, $E_k$,

$$\Omega = \bigcup_{m=1}^{M} E_m \text{ with } E_i^\circ \cap E_j^\circ = \emptyset \text{ for } i \neq j,$$

what happens to $a$ and $g$?
Expand

$$u_N(x) = \sum_{i=1}^{N_p} u_i \varphi_i,$$

and plug into the weak form.
Global Lagrange Basis

Approximate solution \( u_h \): Piecewise linear on \( \Omega \)

The Lagrange basis for \( V_h \) consists of piecewise linear \( \varphi_i \), with…
Features of the basis?
Local Basis

What basis functions exist on each triangle?
Write expressions for the **nodal** linear basis in 2D.
Higher-Order, Higher-Dimensional Simplex Bases

What’s an $n$-simplex?

Give a higher-order polynomial space on the $n$-simplex:

Give nodal sets (on the $\triangle$) for $P^N$ and $\dim P^N$ in general.
Finding a Nodal/Lagrange Basis in General

Given a nodal set \((\xi_i)_{i=1}^{N_p} \subset \hat{E}\) (where \(\hat{E}\) is the reference element) and a basis \((\varphi_j)_{j=1}^{N_p} : \hat{E} \to \mathbb{R}\), find a Lagrange basis.
Higher-Order, Higher-Dimensional Tensor Product Bases

What’s a tensor product element?

Give a higher-order polynomial space on the $n$-simplex:

Give the nodal sets (on the quad) for $Q^N$. 
Tensor Product Elements: Lagrange Basis

Lagrange Basis for Tensor Product Elements?
Construct a mapping $T_m : \hat{E} \rightarrow E_m$. Reference element $\hat{E}$, global $\triangle E_m$.

What is the Jacobian of $T_m$?
More on Mappings

Is an affine mapping sufficient for a tensor product element?

How might we accomplish curvilinear elements using the same idea?
Constructing the Global Basis

Construct a basis on the element $E_m$ from the reference basis 
$\left( \hat{\phi}_j \right)_{j=1}^{N_p} : E_m \rightarrow \mathbb{R}$.

What’s the gradient of this basis?
Assembling a Linear System

Express the matrix and vector elements in

\[ \sum_{j=1}^{N_p} u_j a(\varphi_j, \varphi_i) = g(\varphi_i) \quad \text{for} \quad i = 1, \ldots, N_p. \]
Integrals on the Reference Element

Evaluate

$$\int_E \kappa(x) \nabla_x \varphi_i(x)^T \nabla_x \varphi_j(x) dx.$$  

And now the RHS functional.
Inhomogeneous Dirichlet BCs

Handle an inhomogeneous boundary condition $u(x) = \eta(x)$ on $\partial \Omega$. 

Demo

- Demo: Developing FEM in 2D
- Demo: 2D FEM Using Firedrake
- Demo: Rates of Convergence
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems
  tl;dr: Functional Analysis
  Back to Elliptic PDEs
  Galerkin Approximation
  Finite Elements: A 1D Cartoon
  Finite Elements in 2D
  Approximation Theory in Sobolev Spaces
  Saddle Point Problems, Stokes, and Mixed FEM
  Non-symmetric Bilinear Forms

Discontinuous Galerkin Methods for Hyperbolic Problems
Conditions on the Mesh

Let $\Omega$ be a polygonal domain.

Admissibility (Braess, Def. II.5.1)

A partition (mesh) $T = \{E_1, \ldots, E_M\}$ of $\Omega$ into triangular or quadrilateral elements is called admissible if

Give an example of a non-admissible partition.
Mesh Resolution, Shape Regularity

Definition (Diameter)

A family of partitions $\{\mathcal{T}_h\}$ is called shape regular if
Cone Conditions

Definition (Lipschitz Domain)
A bounded domain \( \Omega \subset \mathbb{R}^n \) is called a Lipschitz domain provided that...

Lipschitz domains satisfy a cone condition:

Theorem (Rellich Selection Theorem (Braess, Thm. II.1.9))
Let \( m \geq 0 \), let \( \Omega \) be Lipschitz. Then the imbedding \( H^{m+1}(\Omega) \to H^m(\Omega) \) is compact, i.e. any bounded sequence in the range of the imbedding has a convergent subsequence.
The Interpolation Operator

**Theorem (Interpolation Operator (Braess, Lemma II.6.2))**

Let $\Omega \subset \mathbb{R}^2$ be Lipschitz. Let $t \geq 2$, and $z_1, z_2, \ldots, z_s$ are $s := \frac{t(t+1)}{2}$ prescribed points in $\bar{\Omega}$ such that the interpolation operator $I : H^t \rightarrow \mathbb{P}^{t-1}$ is well-defined. Then there exists a constant $c$ so that for $u \in H^t(\Omega)$

**Theorem (Approx. for Congruent $\triangle$ (Braess, Remark II.6.5))**

Let $E_h := h\hat{E}$, i.e. a scaled version of a reference triangle, with $h \leq 1$. Then, for $0 \leq m \leq t$, there exists a $C$ so that
Approximation for Congruent Triangles: Proof (1/2)

Set up a function on $E_h$ and $\hat{E}$. Work out the scaling for the derivative.

Work out the scaling for the Sobolev seminorm.

Work out the scaling for the Sobolev norm. Recall $h \leq 1$. 
Approximation for Congruent Triangles: Proof (1/2)

\[ \| u - lu \|_{H^m(E_h)} \leq Ch^{t-m} |u|_{H^t(E_h)} \quad (0 \leq m \leq t) \]

\[ \triangleright \ \ |v|_{H^\ell(\hat{E})}^2 = |u|_{H^\ell(E_h)}^2 \]

\[ \triangleright \ \ |u|_{H^m(E_h)}^2 \leq C'h^{-2m+2} |v|_{H^m(\hat{E})}^2 \]

Prove the estimate.
Definition (Broken Norm)

Given a partition $\mathcal{T}_h = \{E_i\}_{i=1}^M$ and a function $u$ such that $u \in H^m(E_i)$,

Approximation Theorem (Braess, Theorem II.6.4)

Let $t \geq 2$, suppose $\mathcal{T}_h$ is a shape-regular triangulation of $\Omega$. Then there exists a constant $c$ such that, for $0 \leq m \leq t$ and $u \in H^t(\Omega)$,
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems
  tl;dr: Functional Analysis
  Back to Elliptic PDEs
  Galerkin Approximation
  Finite Elements: A 1D Cartoon
  Finite Elements in 2D
  Approximation Theory in Sobolev Spaces
  Saddle Point Problems, Stokes, and Mixed FEM
  Non-symmetric Bilinear Forms

Discontinuous Galerkin Methods for Hyperbolic Problems
Weak Forms as Minimization Problems

Let $V$ be a linear space, and $a : V \times V \to \mathbb{R}$ a bilinear form, and $g \in V'$. 

**Theorem (Solutions of Weak Forms are Quadratic Form Minimizers)**

*If $a$ is SPD, then*

attains its minimum over $V$ at $u$ iff $a(u, v) = g(v)$ for all $v \in V$. 


Example: Lagrange Multipliers in $\mathbb{R}^2$

$$f(x, y) = x^2 + y^2 \rightarrow \text{min!}$$

$$g(x, y) = x + y = 2$$

Write down the Lagrangian.

Write down a necessary condition for a constrained minimum.
Saddle Point Problems

$X, M$ Hilbert spaces. $a : X \times X \to \mathbb{R}$ and $b : X \times M \to \mathbb{R}$ continuous bilinear forms, $f \in X'$, $g \in M'$. Minimize

$$J(u) = \frac{1}{2} a(u, u) - \langle f, u \rangle \quad \text{subject to} \quad b(u, \mu) = \langle g, \mu \rangle \quad (\mu \in M).$$

Apply the method of the Lagrange multipliers.
Example: Saddle Point Problem in $\mathbb{R}^2$

$$f(x, y) = x^2 + y^2 \rightarrow \text{min}!$$

$$g(x, y) = x + y = 2$$

Lagrangian: $\mathcal{L}(x, y, \lambda) = f(x, y) + \lambda g(x, y) = x^2 + y^2 + \lambda(x + y - 2)$.

Show that $x = y = 1, \lambda = -2$ is a saddle point.
Stokes Equation

\[ \Delta u + \nabla p = -f \quad (x \in \Omega), \]
\[ \nabla \cdot u = 0 \quad (x \in \Omega), \]
\[ u = u_0 \quad (x \in \partial \Omega). \]

What are the pieces?
Stokes: Properties

\[ \Delta u + \nabla p = -f \quad (x \in \Omega), \]
\[ \nabla \cdot u = 0 \quad (x \in \Omega), \]
\[ u = u_0 \quad (x \in \partial \Omega). \]

Can we choose any \( u_0 \)?

Does Stokes fully determine the pressure?
Stokes: Variational Formulation

\[ \Delta u + \nabla p = -f, \quad \nabla \cdot u = 0 \quad (x \in \partial \Omega). \]

Choose some function spaces (for homogeneous \( u_0 = 0 \)).

Derive a weak form.
The Stokes weak form is clearly in saddle-point form.
Do all saddle point problems have unique solutions?
The inf-sup Condition

\[ a(u, v) + b(v, \lambda) = \langle f, v \rangle \quad (v \in X), \]
\[ b(u, \mu) = \langle g, \mu \rangle \quad (\mu \in M). \]

Theorem (Brezzi’s splitting theorem (Braess, III.4.3))

The saddle point problem has a unique solution if and only if

- The bilinear form \( a(\cdot, \cdot) \) is \( V \)-elliptic, where \( V = \{ u : b(u, \mu) = 0 \text{ for all } \mu \in M \} \), i.e. there exists \( c_0 > 0 \) so that

- There exists a constant \( c_2 > 0 \) so that (inf-sup or LBB condition):
Interpreting the inf-sup Condition

\[
\begin{bmatrix}
A & B^T \\
B & 0
\end{bmatrix} = M \begin{bmatrix}
A & -BA^{-1}B^T
\end{bmatrix} M^T
\]

\[a(v, v) \geq c_0 \|v\|_X^2, \quad \inf_{\mu \in M} \sup_{v \in X} \frac{b(v, \mu)}{\|v\|_X \|\mu\|_M} \geq c_2.\]

For any given \(v\), can we expect \(b(v, \mu)\) to be nonzero for all \(\mu\)?

What is the inf-sup condition saying?

Why does it suffice for \(a\) to be \(V\)-elliptic?
inf-sup and Stokes

\[
a(u, v) = \int_{\Omega} J_u : J_v, \quad \text{where } A : B = \text{tr}(AB^T),
\]

\[
b(v, q) = \int_{\Omega} \nabla \cdot v q.
\]

Find \((u, p) \in X \times M\) so that

\[
a(u, v) + b(v, p) = \langle f, v \rangle_{L^2} \quad (v \in X),
\]

\[
b(u, q) = 0 \quad (q \in M).
\]

**Theorem (Existence and Uniqueness for Stokes (Braess, III.6.5))**

There exists a unique solution of this system when \(f \in H^{-1}(\Omega)^n\).

(based on results due to Ladyšenskaya, Nečas)
Discretizations for Stokes

**Demo:** 2D Stokes Using Firedrake \((P^1-P^1)\)

Give a heuristic reason why \(P^1-P^1\) might not be great.

**Demo:** Bad Discretizations for 2D Stokes
Establishing a Discrete inf-sup Condition

Suppose \( b : X \times M \to \mathbb{R} \) satisfies inf-sup. Subspaces \( X_h \subseteq X, \ M_h \subseteq M \).

Fortin's Criterion ([Fortin 1977])

Suppose there exists a bounded projector \( \Pi_h : X \to X_h \) so that

If \( \|\Pi_h\| \leq c \) for some constant \( c \) independent of \( h \), then \( b \) satisfies the inf-sup-condition on \( X_h \times M_h \).
$H^1$-Boundedness of the $L^2$-Projector

Assume $H^2$-regularity and a uniform triangulations $\mathcal{T}_h$. (Not in general!)

$H^1$-Boundedness of the $L^2$-Projector (Braess Corollary II.7.8)

Let $\pi^0_h$ be the $L_2$-projector onto a finite element space $V_h \subset H^1(\Omega)$. Then, for an $h$-independent constant $c$,

Ingredients?
Does $H^1$ boundedness of the $H^1$ projector hold?

How would this break down without the uniformity assumption?
Bubbles and the MINI Element

What is a bubble function?

Let $B^3$ be the span of the bubble function and $T_h$ the triangulation. Define the MINI variational space $X_h \times M_h$. 

Computational impact of the bubble DOF?
The Bubble in Pictures

\[ r+s \leq 1 ? r \times s \times (1-r-s) : \frac{1}{0} \]
MINI Satisfies an inf-sup Condition (1/4)

MINI satisfies inf-sup (Braess Theorem III.7.2)

Assume $\Omega$ is convex or has a smooth boundary. Then the MINI variational space satisfies an inf-sup condition for every variational form that itself satisfies one.
MINI Satisfies an inf-sup Condition (2/4)

Create a projector onto the bubble space $B^3$.

What does this bubble projector do?

Do we have an estimate for the bubble projector?
MINI Satisfies an inf-sup Condition (3/4)

Make an overall projector $\Pi_h$ onto $X_h$.

Show Fortin’s criterion for $\Pi_h$. 

MINI Satisfies an inf-sup Condition (4/4)

$\| \pi_h^0 v \|_{H^1} \leq c_1 \| v \|_{H^1}$ for $L^2$ projector $\pi_h^0 : H^1_0 \to M_h$.

$\| v - \pi_h^0 v \|_{L^2} \leq c_2 h \| v \|_{H^1}$.

$\| \pi_h^1 v \|_{L^2} \leq c_3 \| v \|_{L^2}$.

Show $H^1$-boundedness of $\Pi_h$. 
Demo: 2D Stokes Using Firedrake (MINI and Taylor-Hood)
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems
  tl;dr: Functional Analysis
  Back to Elliptic PDEs
  Galerkin Approximation
  Finite Elements: A 1D Cartoon
  Finite Elements in 2D
  Approximation Theory in Sobolev Spaces
  Saddle Point Problems, Stokes, and Mixed FEM
  Non-symmetric Bilinear Forms

Discontinuous Galerkin Methods for Hyperbolic Problems
Lax-Milgram, General Case

Let $V$ be Hilbert space with inner product $\langle \cdot, \cdot \rangle$.

**Theorem (Lax-Milgram, General Case)**

Let $a$ be a $V$-elliptic bilinear form, and let $g$ be a bounded linear functional on $V$.

Then there exists a unique $u \in V$ so that $a(u, v) = g(v)$ for all $v \in V$. 
Lax-Milgram Proof (2/5)

\[ a(u, v) = \langle v, Tu \rangle. \] Show linearity of \( T \).

Show boundedness \( \Leftrightarrow \) continuity of \( T \).
Lax-Milgram Proof (3/5)

\[ a(u, v) = \langle v, Tu \rangle. \] Show that \( T \) has closed range. (Needed for Hilbert projection, which is needed for onto.)
$a(u, v) = \langle v, Tu \rangle$. Show that $T$ is onto $V$. 
Show existence of the solution $u$.

Show uniqueness of the solution $u$. 

Lax-Milgram Proof (5/5)
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems

Discontinuous Galerkin Methods for Hyperbolic Problems
  Case Study: Maxwell’s as a Conservation Law
  Evaluating Schemes for Advection
  Developing DG
  Fluxes and Stability
  Implementation Concerns
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems

Discontinuous Galerkin Methods for Hyperbolic Problems
  Case Study: Maxwell’s as a Conservation Law
  Evaluating Schemes for Advection
  Developing DG
  Fluxes and Stability
  Implementation Concerns
Conservation laws

Goal: Solve *conservation laws* on bounded domain $\Omega \subset \mathbb{R}^n$:

$$q_t + \nabla \cdot F(q) = 0$$

Example: Maxwell’s Equations

$$\partial_t D - \nabla \times H = -j,$$
$$\nabla \cdot D = \rho,$$
$$\partial_t B + \nabla \times E = 0,$$
$$\nabla \cdot B = 0.$$
Rewriting Maxwell’s

Let $\mathbf{q} = (D_x, D_y, D_z, B_x, B_y, B_z)^T$. Consider $D = \epsilon E$ and $B = \mu H$.

\[
\partial_t D - \nabla \times H = -0, \quad \partial_t B + \nabla \times E = 0.
\]

Rewrite in conservation law form: $\mathbf{q}_t + \nabla \cdot F(\mathbf{q}) = 0$

Could we also define $\mathbf{q} = (E_x, E_y, E_z, H_x, H_y, H_z)^T$?
Solving $q_t + aq_x = 0$: Finite Differences

\[ D_t^- + aD_x^- = 0 \]

\[ D_t^+ f := \frac{f(t + \Delta t) - f(t)}{\Delta t} \]
Solving $q_t + aq_x = 0$: Finite Volume

$$\bar{q}_k := \int_{(k-1/2)\Delta x}^{(k+1/2)\Delta x} q(x) \, dx$$

$$\Delta x \partial_t \bar{q}_k + f^{k+1/2} - f^{k-1/2} = 0$$

$f^{k\pm1/2}$: flux “reconstructions”
Solving $q_t + a q_x = 0$: Finite Elements

$$\int_{\Omega} q_t^N \phi + a q_x^N \phi \, dx = 0$$

for $\phi$ in a test space.
Do we really want high order?

Observation: Significant potential for savings without impacting accuracy by using high-order elements over long times of integration.

Time to compute solution at 5% error

Big assumption?

Figure from talk by Jan Hesthaven
Summarizing

Want flexibility of finite elements *without* the drawbacks.
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems

Discontinuous Galerkin Methods for Hyperbolic Problems
  Case Study: Maxwell’s as a Conservation Law
  Evaluating Schemes for Advection
  Developing DG
  Fluxes and Stability
  Implementation Concerns
Developing the Scheme

What do do about unbounded domains?
Dealing with the Mesh, Part I

For each cell $E_k$, find a ref-to-global map $T_k$:

\[ T_k : \hat{E} \rightarrow E_k \]

\[ \mathbf{x} = (x, y, z) = T_k(r, s, t) = T_k(\mathbf{r}) \]

- $T_k$ affine for straight-sided simplices: $T_k(\mathbf{r}) = A\mathbf{r} + \mathbf{b}$
- Curved elements also possible: iso/sub/super-parametric
Dealing with the Mesh, Part II

Based on knowledge of how to do this on $\hat{E}$:

Can now \textit{integrate} on $\Omega$:

and \textit{differentiate} on $\Omega$:

Jacobian of $T^{-1}_k$?
Dealing with the Mesh, Part III

Approximation basis set on $E_k$?

What function space do we get if $\Psi$ is non-affine?
Going Galerkin

\[ \int_{E_k} q_t^k \phi + (\nabla \cdot F^k) \phi \, dx = 0 \]

Integrate by parts:

Problem?
Strong-Form DG

Weak form:

$$0 = \int_{E_k} q_t^k \phi dx - \int_{E_k} F^k \cdot \nabla \phi dx + \int_{\partial E_k} (F^k \cdot \hat{n})^* \phi dx$$

Integrate by parts again:
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems

Discontinuous Galerkin Methods for Hyperbolic Problems
  Case Study: Maxwell’s as a Conservation Law
  Evaluating Schemes for Advection
  Developing DG
  Fluxes and Stability
  Implementation Concerns
Accuracy and Stability

In DG: what provides accuracy? what provides stability?

Following slides based on material by Tim Warburton
Stability: Basic Setup (1/2)

\[ 0 = \int_{E_k} q_t^{k} \phi dx - \int_{E_k} F^{k} \cdot \nabla \phi dx + \int_{\partial E_k} (F^{k} \cdot \hat{n}) \phi dS_x \]
Stability: Basic Setup (2/2)

\[
\frac{\partial_t \| q_k \|_{2,E_k}^2}{2} = \int_{E_k} a q_k \partial_x q_k \, dx - \int_{\partial E_k} (a q_k n_x)^* q_k \, dS_x
\]
Stability: Going Global

\[ \frac{\partial_t \|q_k\|_2^2, E_k}{2} = \int_{\partial E_k} \frac{a(q_k)^2 n_x}{2} - (aq_k n_x)^* q_k dS_x \]
Gather up

\[
\frac{\partial_t \|q_k\|_{2,\Omega}^2}{2} = \sum_{\text{faces} f} \left( \int_{f} \frac{a(q_k^+)^2 n_x^+}{2} - (aq_k n_x)^* q_k^+ dS_x \right) \\
+ \int_{f} \frac{a(q_k^-)^2 n_x^-}{2} - (aq_k n_x)^* q_k^- dS_x \right)
\]
Picking a Flux

Want:

\[ (*) = \left( an_x \frac{q_k^- + q_k^+}{2} - (aq_k n_x)^* \right) \left( q_k^- - q_k^+ \right) \leq 0 \]

Ideas?
Picking a flux, attempt two

Want:

\[(*) = \left( an_x \frac{-q_k^- + q_k^+}{2} - (aq_k n_x)^* \right) (q_k^- - q_k^+) \leq 0 \]

More ideas?
Comparing Fluxes (1/3)

Central

Upwind

Upwind penalizes jumps!

Figure from talk by Jan Hesthaven
Comparing Fluxes (2/3)

Inter-element jumps are better controlled for this example by upwinding.

Red: central fluxes (\alpha=0)
Blue: upwind fluxes (\alpha=1)

Figure from lecture by Tim Warburton
Comparing Fluxes (3/3)

Central Fluxes v. Upwind Fluxes

Red: central fluxes (alpha=0)
Blue: upwind fluxes (alpha=1)

Peak errors are not quite so peaky for upwind fluxes.

Wednesday, January 26, 2011

Figure from lecture by Tim Warburton
Stability Analysis

Clif notes on flux choice?

Swept under the rug: Boundary conditions

Element coupling (and BCs) done weakly
Accuracy

Stability: (preliminary version) done!
Accuracy: Depends on approximation properties!
Systems of Conservation Laws

What to do about systems?
What about multiple dimensions?

We’ve dealt with 1D systems.

How about the move to multiple dimensions?
Simultaneous Diagonalization

2D second-order wave equation across a boundary with normal $n$:

Demo: Finding Numerical Fluxes for DG (Part 1)
Jumps and Averages

Jump and average of a scalar quantity:

Jump and average of a vector quantity:
Wanted to solve Maxwell’s equation in the time domain. Numerical flux?

Either look in the literature:

\[ \hat{n} \cdot (F_N - F_N^*) := \frac{1}{2} \left( \{Z\}^{-1} \hat{n} \times (Z^+ [H] - \alpha \hat{n} \times [E]) \right) \]

\[ \{Y\}^{-1} \hat{n} \times (-Y^+ [E] - \alpha \hat{n} \times [H]) \].

or derive yourself: Demo: Finding Numerical Fluxes for DG (Part 2)

Good news: Scheme mathematically complete.
Outline

Introduction

Finite Difference Methods for Time-Dependent Problems

Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems

Discontinuous Galerkin Methods for Hyperbolic Problems
  Case Study: Maxwell's as a Conservation Law
  Evaluating Schemes for Advection
  Developing DG
  Fluxes and Stability
  Implementation Concerns
Implementing DG

Weak form:

\[ 0 = \int_{E_k} q_t^k \phi \, dx - \int_{E_k} F^k \cdot \nabla \phi \, dx + \int_{\partial E_k} (F^k \cdot n)^* \phi \, dx \]

What do the DoFs mean?
Modes

Function spaces same as for FEM: $P^N, Q^N$.

Numerically: better to use orthogonal polynomials with

$$\int_{\hat{E}} \phi_i \phi_j = \delta_{i,j}$$
Nodes

Define set of interpolation nodes $\left(\xi_i\right)_{i=1}^{N_p}$ and $\ell_i$ their Lagrange basis. Define generalized Vandermonde matrix

$$V_{ij} := \phi_j(\xi_i)$$

$\xi_i$ determine $\text{cond}(V)!$
In Matrix Form

\[ 0 = \int_{E_k} q^k_t \phi \, dx - \int_{E_k} F^k \cdot \nabla \phi \, dx + \int_{\partial E_k} (F^k \cdot n)^* \phi \, dx \]

Write in matrix form:
Explicit Time Integration

\[ 0 = \mathcal{M}^k \partial_t u^k - \sum_\nu S^{k,\nu} [F(u^k)] + \sum_{A \subset \partial E_k} \mathcal{M}^{k,A}(\hat{n} \cdot F)^* \]

How can we do time integration on this weak form?
Trick: Multiple face mass matrices

Applying multiple face mass matrices at once:
DG and Modern Computers: Possible Advantages

DG on modern processor architectures: Why?