Numerical Methods for Partial Differential Equations
CS555 / MATH552 / CSE510

Andreas Kloeckner

Spring 2022
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
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What’s the point of this class?

PDEs describe lots of things in nature:

- Fluid flow (Navier-Stokes equations)
- Electromagnetism (Maxwell’s equations)
- Waves (Elasticity, Acoustics)
- Plasmas (Magnetohydrodynamics)

Idea: Use them to

- Make predictions (and check them, to validate the model: science!)
- Use predictions (for design of cars, airplanes, reactors, …)
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

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Discontinuous Galerkin Methods for Hyperbolic Problems
What does this do? $\partial_t u = \partial_x u$

- Slope in $x$ and $t$ matches
- Single profile on an $x/t$ diagonal
- Which one? (left-leaning)
- We’ll deal with this a lot.
  - Advection equation, one-way wave equation
  - General solution: $u(x, t) = u_0(x + t)$
What does this do? \( \partial_x^2 u + \partial_y^2 u = 0 \)

- Second derivative measures “bendiness” of a function
- “Bendiness” in \( x \) and \( y \) need to add up to zero
- Can a function like this have a maximum?
Some good questions

- What is a time-like variable? (Variables labeled $t$?)

A variable across which information does not flow ‘backward’.

- What if there are boundaries? (space/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:

- Simple techniques can go a long way.
- Develop/make use of physical intuition.
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?

The highest (total, i.e. summing over axes) order of derivative occurring in $F$.

When is the PDE linear?

If $u$ and $v$ are solutions, $\alpha u + \beta v$ are, too.

When is the PDE quasilinear?

The dependency in $F$ on the highest-order partial derivatives is linear in $u$.

When is the PDE semilinear?

If it is quasi-linear and if the high-order terms have coefficients that depend only on space.
Examples: Order, Linearity?

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

Second-order quasilinear

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

First-order semilinear
Properties of Domains

- smooth
- with corners
- with *reentrant* corners
- with cusps

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

Name some function spaces with their norms.

<table>
<thead>
<tr>
<th>Space</th>
<th>Description</th>
<th>Norm Formula</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C(\Omega)$</td>
<td>$f$ continuous, $|f|<em>\infty := \sup</em>{x \in \Omega}</td>
<td>f(x)</td>
</tr>
<tr>
<td>$C^k(\Omega)$</td>
<td>$f$ $k$-times continuously differentiable</td>
<td></td>
</tr>
<tr>
<td>$C^{0,\alpha}(\Omega)$</td>
<td>$|f|<em>\alpha := |f|</em>\infty + \sup_{x \neq y} \frac{</td>
<td>f(x) - f(y)</td>
</tr>
<tr>
<td>$C_L(\Omega)$</td>
<td>$</td>
<td>f(x) - (y)</td>
</tr>
<tr>
<td>$L_p(\Omega)$</td>
<td>$|f|_{p,\Omega} := \sqrt[p]{\int_D</td>
<td>f(x)</td>
</tr>
</tbody>
</table>

Why do these only define equivalence classes?

$L_2$ special because...?

$W^1_p(\Omega)$ | $\|f\|_{W^1_p(\Omega)} := (\|f\|_{p,\Omega} + \|f'\|_{p,\Omega}) < \infty$ |

$H^1(\Omega)$ | equivalent to $W^1_2(\Omega)$, also a Hilbert space |

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: $u_h \rightarrow u$ (in some sense) as $h \rightarrow 0$

Example

$u(x) = \sin x$ where $V_h$ is piecewise constant functions with grid spacing $h$. 
Is there a grand big unifying theory of PDEs?

No. Frustratingly, studying PDEs is a little bit like stamp collecting. For instance, there are broad classes of second-order PDEs that behave mostly alike.
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?

Quadratic forms: \( ax^2 + 2bxy + cy^2 + \) lower order terms
Where does this come from? The search for characteristic curves.
Will see these again later. See Hogg \textquoteleft 17 for a good description.
PDE Classification in Other Cases

Scalar first order PDEs?

Classified as hyperbolic. (See later.)

First order systems of PDEs?

Can be classified into hyperbolic/elliptic/parabolic as well, using slightly more complicated method, depending on the direction of the characteristics. See Hogg ‘17 or Loret ‘08.
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?

Schwarz’s theorem. So: real-valued eigenvalues.

What cases can arise for the eigenvalues?

<table>
<thead>
<tr>
<th>Case</th>
<th>Kind</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \lambda_j(x) = 0 ) for some ( \lambda )</td>
<td>parabolic</td>
</tr>
<tr>
<td>( \lambda_j(x) ) all have the same sign</td>
<td>elliptic</td>
</tr>
<tr>
<td>( \lambda_j(x) ) all but one have the same sign</td>
<td>hyperbolic</td>
</tr>
<tr>
<td>( \lambda_j(x) &gt; 1 ) eigenvalue per sign, nonsingular</td>
<td>ultra-hyperbolic</td>
</tr>
</tbody>
</table>
Elliptic PDE: Laplace/Poisson Equation

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

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 [cleared]
**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 $f$?

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

What can we learn from this?

Solutions to the Laplace equation are globally coupled. The value of $f$ at any point influences the solution *everywhere* (if only a little)
Elliptic PDEs: Justifying the Singular Solution

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

Why?

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

\[ = \int_{\mathbb{R}^d} \delta(x - y)f(y)dy = f(x) \]
Parabolic PDE: Heat Equation \cdot Separation of Variables

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

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

\[ u(0, t) = u(1, t) = 0 \quad (t \in [0, T]) \]

Looking for \( u(x, t) = v(t) \cdot w(x) \).

Plug into PDE: \( v'(t) \cdot w(x) = v(t) \cdot w''(x) \). Divide:

\[ \frac{v'(t)}{v(t)} = C = \frac{w''(x)}{w(x)} , \]

where \( C \) is constant since it is independent of \( x \) and \( t \).

\[ \blacktriangleright \quad w'' = Cw \text{ with BCs yields } w(x) = \alpha \cdot \sin(m\pi x) \text{ and } C = -m^2\pi^2 \text{ or any linear combination; Fourier to match } g. \]

\[ \blacktriangleright \quad \text{Focus on specific value of } m: \quad v' = Cv \text{ with ICs yields } v(t) = \exp(-m^2\pi^2 t). \]
Demo: Parabolic PDE [cleared] What can we learn from analytic and numerical solution?

- Heat equation ‘washes out’ the solution
- Appears to obey a maximum principle
- Appears to smooth the data
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?

No, missing initial condition on \( u_t \).

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

Can be rewritten in conservation law form:

\[ q_t(x) + \nabla \cdot F(q(x)) = s(x) \]
Hyperbolic Conservation Laws

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

Why is this called a (system of) conservation law(s)?

- Balance between a conserved quantity \( q \) and a flux \( F \).
  - Integrate, consider divergence theorem (for \( n = 1 \))
  - Flux prescribes the ‘flow direction’. When is flux divergence < 0?
  - \( s \) is a source term.

\( F : \mathbb{R}^n \rightarrow \mathbb{R}^n \times \mathbb{R}^d \)

- \( q(x, t) \in \mathbb{R}^n \)
- \( F : \mathbb{R}^n \rightarrow \mathbb{R}^n \times \mathbb{R}^d \)
Rewrite the wave equation in conservation law form:

Introduce a new variable $v$ and let

$$u_t = cv_x$$
$$v_t = cu_x.$$ 

Observe $u_{tt} = cv_{xt} = c^2 u_{xx}$. Define $q := [u \ v]^T$. 
Solving Conservation Laws

Solve

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

\[ q_t + \begin{bmatrix} 0 & -c \\ -c & 0 \end{bmatrix} q_x = q_t + A q_x = 0 \]

Diagonalize: Define \( \tilde{q} := V^{-1} q \),

\[ \tilde{q}_t + V^{-1} A V \tilde{q}_x = \tilde{q}_t + \begin{bmatrix} c & 0 \\ 0 & -c \end{bmatrix} \tilde{q}_x = 0 \]

\( \rightarrow \) two advection equations

Solution, for some \( \phi_l, \phi_r: u(t, x) = \phi_l(x + ct) + \phi_r(x - ct) \)

Demo: Hyperbolic PDE [cleared]
Properties of the solution for hyperbolic equations:

- Has *conserved quantities*
- $q$, “energy” \(\rightarrow\) HW1
- Maintains smoothness of IC
- Typical trick: Project to one dimension, diagonalize, understand advection behavior.
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Discontinuous Galerkin Methods for Hyperbolic Problems
Limit the set of functions to a linear combination from an interpolation basis $\varphi_i$.

$$f(x) = \sum_{j=0}^{N_{\text{func}}} \alpha_j \varphi_j(x)$$

Interpolation becomes solving the linear system:

$$y_i = f(x_i) = \sum_{j=0}^{N_{\text{func}}} \alpha_j \varphi_j(x_i) \quad \leftrightarrow \quad V\alpha = y.$$  

Want unique answer: Pick $N_{\text{func}} = N \rightarrow V$ square. $V$ is called the (generalized) Vandermonde matrix.

$$V \ (\text{coefficients}) = (\text{values at nodes}).$$
Numerical Differentiation: How?

How can we take derivatives numerically?

Let $\mathbf{x} = (x_i)_{i=1}^n$ be nodes and $(\varphi_i)_{i=1}^n$ an interpolation basis. Find interpolation coefficients $\alpha = (\alpha_i)_{i=1}^n = V^{-1}f(\mathbf{x})$. Then

$$f(\xi) \approx p_{n-1}(\xi) = \sum_{i=1}^{n} \alpha_i \varphi_i(\xi).$$

Then, simply take a derivative:

$$f'(\xi) \approx p'_{n-1}(\xi) = \sum_{i=1}^{n} \alpha_i \varphi'_i(\xi).$$

$\varphi'_i$ are known because the interpolation basis $\varphi_i$ is known!

Demo: Taking Derivatives with Vandermonde Matrices [cleared]
Demo: Finite Differences [cleared]
Demo: Finite Differences vs Noise [cleared]
Demo: Floating point vs Finite Differences [cleared]
Why *shouldn’t* you take derivatives numerically?

- ‘Unbounded’
  A function with small $\|f\|_\infty$ can have arbitrarily large $\|f'\|_\infty$

- Amplifies noise
  Imagine a smooth function perturbed by small, high-frequency wiggles

- Subject to cancellation error

- Inherently less accurate than integration
  - Interpolation: $h^n$
  - Quadrature: $h^{n+1}$
  - Differentiation: $h^{n-1}$
    (where $n$ is the number of points)
Find the order of accuracy of the finite difference formula

\[ f'(x) \approx \frac{f(x + h) - f(x - h)}{2h}. \]

\[
\begin{align*}
    f'(x) & = f'(x) - \frac{1}{2h} \left[ f(x) + hf'(x) + \frac{h^2}{2} f''(x) + \frac{h^3}{6} f'''(x) + O(h^4) \right] \\
    & \quad + \frac{1}{2h} \left[ f(x) - hf'(x) + \frac{h^2}{2} f''(x) - \frac{h^3}{6} f'''(x) + O(h^4) \right] \\
    & = \frac{1}{2h} \cdot \frac{h^3}{6} f'''(x) \quad \text{as } h \to 0.
\end{align*}
\]
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Discontinuous Galerkin Methods for Hyperbolic Problems
Truncation Error in Interpolation

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:

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

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

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

- Since \( x_i \) are roots of \( R(t) \) and \( W(t) \), we have \( Y_x(x) = Y_x(x_i) = 0 \), which means \( Y_x \) has at least \( n + 1 \) roots.

- From Rolle’s theorem, \( Y'_x(t) \) has at least \( n \) roots, then \( Y_x^{(n)} \) 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

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

- Plugging \( Y_x^{(n)}(\xi) = 0 \) 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.
- If nodes are edge-clustered, $\prod_{i=1}^{n}(x - x_i)$ clamps down the (otherwise quickly-growing) error there.
- Confusing: *Chebyshev approximating polynomial* (or “polynomial best-approximation”). Not the Chebyshev interpolant.
- Chebyshev nodes also do not minimize the Lebesgue constant.
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** [cleared]
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  1D Advection
  Stability and Convergence
  Von Neumann Stability
  Dispersion and Dissipation
  A Glimpse of Parabolic PDEs

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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?

Generalize to 1D conservation law: \( u_t + f(u)_x = 0 \). Find solution.

**Characteristic Curve:** Define a function \( x(t) \) so that \( u(x(t), t) = u(x_0, 0) \). Suppose we consider \( x \) defined by the IVP

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

Then

\[
\frac{du(x(t), t)}{dt} = u_x x'(t) + u_t = u_x f'(u(x(t), t)) + u_t = f(u)_x + u_t = 0.
\]

So \( u(x(t), t) = u(x(0), 0) = g(x_0) \).
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.

Here \( x(t) = x_0 + at \).

Generalize this to a solution formula.

General solution of advection: \( u(t, x) = g(x - at) \). \( a \): Advection speed.

Does the solution formula admit solutions that aren’t obviously allowed by the PDE?

Solution formula allows nonsmooth profiles. Unclear: Those are not differentiable.

\( \rightarrow \) Idea (later): weaken the notion of a derivative
Finite Difference for Hyperbolic: Idea

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

If \( u(x, t) \) is the exact solution, want \( u_{k,\ell} \approx u(x_k, t_\ell) \).

Condition at each grid point?

- Pick a derivative stencil for each derivative term in the PDE
- Get system of equations
- Solve

What are explicit/implicit schemes?

Implicit require solution of a system of equations
**Designing Stencils**

**ETCS:**

**ITCS:**

**ETFS:**

**ETBS:**

**Terminology?**

- **E** Explicit / **I** Implicit
- **T** Time / **S** Space
- **F** Forward: right
- **B** Backward: left
- **Upwind:** left if \( a > 0 \)
- **Downwind:** right if \( a > 0 \)

**Write out ITCS:**

\[
\frac{u_{k,\ell+1} - u_{k,\ell}}{ht} + a \frac{u_{k+1,\ell+1} - u_{k-1,\ell+1}}{2hx} = 0
\]
Write out Crank-Nicolson:

\[
\frac{u_{k,\ell+1} - u_{k,\ell}}{h_t} + \frac{a}{2} \left[ \frac{u_{k+1,\ell+1} - u_{k-1,\ell+1}}{2h_x} + \frac{u_{k+1,\ell} - u_{k-1,\ell}}{2h_x} \right] = 0
\]
What’s the core idea behind Lax-Wendroff?

- Write out a Taylor expansion in time
- Use the PDE to replace time $\partial$ with space $\partial$
- Allows two-level schemes of any order of accuracy

Write out Lax-Wendroff.

$u_t = -au_x$ so also $u_{tt} = -a(u_x)_t = -a(u_t)_x = a^2 u_{xx}$.

\[
  u_{k,\ell+1} - u_{k,\ell} \approx h_t u_t(x_k, t_\ell) + \frac{h_t^2}{2} u_{tt}(x_k, t_\ell)
\]

\[
  = -h_t a u_x(x_k, t_\ell) + \frac{h_t^2}{2} a^2 u_{xx}(x_k, t_\ell)
\]

\[
  \approx -h_t a \frac{u_{k+1,\ell} - u_{k-1,\ell}}{2h_x} + \frac{h_t^2 a^2}{2} \cdot \frac{u_{k+1,\ell} - 2u_{k,\ell} + u_{k-1,\ell}}{h_x^2}
\]
Exploring Advection Schemes

**Demo:** Methods for 1D Advection [cleared]

- 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

Numerical solution vectors:

\[
\mathbf{v}_{\ell} = \begin{bmatrix}
    u_{1,\ell} \\
    \vdots \\
    u_{N_x,\ell}
\end{bmatrix}, \quad
\mathbf{v} = \begin{bmatrix}
    \mathbf{v}_1 \\
    \vdots \\
    \mathbf{v}_{N_t}
\end{bmatrix}, \quad
\mathbf{v} = \begin{bmatrix}
    \mathbf{v}_1 \\
    \vdots \\
    \mathbf{v}_{N_t}
\end{bmatrix}.
\]

True solution vectors:

\[
\mathbf{u}_{\ell} = \begin{bmatrix}
    u(x_{1,\ell}) \\
    \vdots \\
    u(x_{N_x,\ell})
\end{bmatrix}, \quad
\mathbf{u} = \begin{bmatrix}
    \mathbf{u}_1 \\
    \vdots \\
    \mathbf{u}_{N_t}
\end{bmatrix}.
\]

Definition (Two-Level Finite Difference Scheme)

A finite difference scheme that can be written as

\[
P_h \mathbf{v}_{\ell+1} = Q_h \mathbf{v}_{\ell} + h_t \mathbf{b}_{\ell}
\]

is called a two-level linear finite difference scheme.

- Mostly \( \mathbf{b}_{\ell} = 0 \), i.e. homogeneous schemes, no source terms.
- \( P_h \) and \( Q_h \) may depend on both \( h_x \) and \( h_t \).
- \( P_h \) and \( Q_h \) and the spatial grid may also be infinite.
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:

ETCS:

\[ \frac{u_{k,\ell + 1} - u_{k,\ell}}{h_t} + a \frac{u_{k+1,\ell} - u_{k-1,\ell}}{2h_x} = 0. \]

Equivalently:

\[ u_{k,\ell + 1} = u_{k,\ell} + \frac{ah_t}{2h_x} (-u_{k+1,\ell} + u_{k-1,\ell}). \]

So

\[ P_h = I, \quad Q_h = \text{tridiag} \left( \frac{ah_t}{2h_x}, 1, -\frac{ah_t}{2h_x} \right). \]
Find $P_h$ and $Q_h$ for Crank-Nicolson:

\[
P_h = \text{tridiag} \left(-\frac{ah_t}{4h_x}, 1, \frac{ah_t}{4h_x}\right),
\]

and

\[
Q_h = \text{tridiag} \left(\frac{ah_t}{4h_x}, 1, -\frac{ah_t}{4h_x}\right).
\]
Truncation Error

Definition (Truncation Error)

The local truncation error $\tau_{k,\ell}$ is the error that remains when a finite difference method is applied to a smooth exact solution $u$ at $(x_k, t_\ell)$.

Demo: Truncation Error Analysis via sympy [cleared]
Express definition of truncation error in our two-level framework:

\[ P_h u_{\ell+1} = Q_h u_\ell + \tau_\ell h_t. \]

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

Recall \( P_h v_{\ell+1} = Q_h v_\ell \). Subtract from the truncation error definition to find:

\[
\begin{align*}
e_0 &= 0 \\
P_h e_{\ell+1} &= Q_h e_\ell + \tau_\ell h_t \\
e_{\ell+1} &= P_h^{-1} Q_h e_\ell + P_h^{-1} \tau_\ell h_t.
\end{align*}
\]
Discrete and Continuous Norms

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

$$\|e\|_\infty = \max_{k, \ell} |e_{k, \ell}|.$$ 

Define a discrete $L^2$ norm.

$$\|e\|_2 = \sqrt{\sum_{k, \ell} e_{k, \ell}^2 h_x h_t}.$$ 

Unless otherwise given: $\|\cdot\| = \|\cdot\|_2$.

Important features:

- Value of discrete norm should not change wildly if $h_x$ and $h_t$ change (and, along with them, the number of nodes).
- Ideal: approximate a continuous norm.
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

\[
\max_{\ell, \ell h_t \leq t^*} \| \tau_\ell \| = O(h_x^{q_x} + h_t^{q_t}) \quad \text{as } (h_x, h_t) \to (0, 0).
\]

**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

\[
\max_{\ell, \ell h_t \leq t^*} \| e_\ell \| = O(h_x^{q_x} + h_t^{q_t}) \quad \text{as } (h_x, h_t) \to (0, 0).
\]
Analyzing ETFS (1/2)

Let’s understand more precisely what happens for this scheme. Assume \( a > 0 \).

Rewrite as

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

For \( \lambda = ah_t / h_x \).

\[
{u_k,\ell+1 = u_k,\ell - ah_t \over h_x} (u_{k+1,\ell} - u_k,\ell) = (1 + \lambda)u_k,\ell - \lambda u_{k+1,\ell}
\]
Analyzing ETFS (2/2)

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

Consider \( u(x, 0) = 1_{[-1,0]}(x) \). Predict solution behavior.

\[
\begin{align*}
  u_{0,0} &= 1 & u_{1...,0} &= 0 \\
  u_{0,1} &= (1 + \lambda) & u_{1...,1} &= 0 \\
  u_{0,2} &= (1 + \lambda)^2 & u_{1...,2} &= 0
\end{align*}
\]

So the right half never “sees” the traveling bump; this can’t be convergent. Meanwhile,

\[
\begin{align*}
  u(0, t) &\approx u_{0, t/h_t} = \left(1 + \frac{ah_t}{h_x}\right)^{t/h_t} = \left(1 + \frac{at/h_x}{t/h_t}\right)^{t/h_t} \xrightarrow{h_t\to 0} \exp\left(\frac{at}{h_x}\right)
\end{align*}
\]

**Demo:** Methods for 1D Advection [cleared] (Revisit ETFS)
Stability

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

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

\[ v_\ell = (P_h^{-1} Q_h)^\ell v_0 \]

**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

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

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

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.

- A stronger result holds: The above is actually “if and only if”. (called the Lax Equivalence Theorem or Lax-Richtmyer Theorem)

- Think of this as an important ‘meta-theorem’ of numerical analysis (or “fundamental theorem of NA“):

  \[
  \text{Consistent} + \text{Stable} \Rightarrow \text{Convergent}
  \]

- A related result holds for ODEs, due to Dahlquist.
Recall error propagation:

\[ P_h e_{\ell+1} = Q_h e_{\ell} + \tau_{\ell} h_t \]

So:

\[ e_{\ell+1} = P_h^{-1} Q_h e_{\ell} + P_h^{-1} \tau_{\ell} h_t. \]

Since \( e_0 = 0 \),

\[ e_1 = h_t P_h^{-1} \tau_0, \]
\[ e_2 = h_t (P_h^{-1} Q_h) P_h^{-1} \tau_0 + h_t P_h^{-1} \tau_1. \]

By induction,

\[ e_\ell = h_t \sum_{m=1}^{\ell} (P_h^{-1} Q_h)^{\ell-m} P_h^{-1} \tau_{m-1}. \]
Lax Convergence: Proof (2/2)

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

Let \( \ell h_t \leq t^* \). Taking the norm of both sides,

\[
\| e_\ell \| \leq h_t \sum_{m=1}^{\ell} \left\| (P_h^{-1} Q_h)^{\ell-m} P_h^{-1} \tau_{m-1} \right\| \\
\leq h_t \sum_{m=1}^{\ell} \left\| (P_h^{-1} Q_h)^{\ell-m} P_h^{-1} \right\| \| \tau_{m-1} \| \\
\leq c \text{ (stab.)} \\
\leq h_t \ell c \cdot \max_{\ell: \ell h_t \leq t^*} \| \tau_\ell \| \leq c t^* \max_{\ell: \ell h_t \leq t^*} \| \tau_\ell \| \\
\text{cons.} \quad O(h_x^{q_x} + h_t^{q_t}).
\]
Conditions for Stability

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

Give a simpler, sufficient condition:

\[ \| P_h^{-1} Q_h \| \leq 1, \quad \| P_h^{-1} \| \leq c. \]

Also called Lax-Richtmyer stability.

How can we show bounds on these matrix norms?

- Observe: bounds have to hold for all \( h_t \) and \( h_x \).
- Generally: cumbersome.
- Possibly easiest: approach via singular values.
- Bound singular values: For example using Gershgorin.
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:

Let $\lambda = ah_t/h_x$. Then $u_{k,\ell+1} = \lambda u_{k-1,\ell} + (1 - \lambda)u_{k,\ell}$. So $P_h = I$ and $Q_h = \text{tridiag}(\lambda, 1 - \lambda, 0)$. $\|P_h^{-1}\| \leq 1$ trivially.
Stability of ETBS (2/3)

\[ P_h = I \text{ and } Q_h = \text{tridiag}(\lambda, 1 - \lambda, 0). \]

\[ \|Q_h\| = \sqrt{\rho(Q_h^T Q_h)}, \]

where \(Q_h^T Q_h = \text{tridiag}(\lambda(1 - \lambda), (1 - \lambda)^2 + \lambda^2, \lambda(1 - \lambda))\). Assume \(0 \leq \lambda \leq 1\) for now, then \(\lambda(1 - \lambda) \geq 0\). Let \(\Lambda \in \sigma(Q_h^T Q_h)\).

\[
\begin{align*}
2\lambda^2 - 2\lambda &\leq \Lambda - (1 - \lambda)^2 - \lambda^2 \leq 2\lambda - 2\lambda^2, \\
1 - 4\lambda + 4\lambda^2 &\leq \Lambda \leq 1, \\
0 &\leq (1 - 2\lambda)^2 \leq \Lambda \leq 1.
\end{align*}
\]

So \(|\Lambda| \leq 1\), which implies \(\|Q_h^T Q_h\| \leq 1\), which means \(\|Q_h\| \leq 1\).

If \(\lambda > 1\), analogously:

\(|\Lambda| \geq 1\), which implies \(\|Q_h^T Q_h\| \geq 1\), which means \(\|Q_h\| \geq 1\).
Summarize ETBS stability:

We learn that ETBS is stable if $0 \leq \lambda \leq 1$. Rewriting, we obtain

$$\frac{ah_t}{h_x} < 1 \iff h_t \leq \frac{h_x}{a}.$$ 

This type of stability is called **conditional stability**, and the condition we found a **Courant-Friedrichs-Lewy (CFL)** condition.

Comments?

Way cumbersome to prove. Is there something easier that gives necessary/sufficient conditions?
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Discontinuous Galerkin Methods for Hyperbolic Problems
Discrete (Space) Fourier Transform

Assume $\mathbf{x}$ infinitely long. Define:

$$\hat{\mathbf{x}}(\theta) = \sum_{k \in \mathbb{Z}} x_k e^{-i \theta k}$$

When is this well-defined?

$$|\hat{\mathbf{x}}(\theta)| = \left| \sum_k x_k e^{-i \theta k} \right| \leq \sum_k |x_k|,$$

Well-defined if $\sum_k |x_k|$ is absolutely convergent. ($\sum_k = \sum_{k \in \mathbb{Z}}$)
Inverting the Fourier Transform

To recover $x$: 

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

Proof?

$$\frac{1}{2\pi} \int_{-\pi}^{\pi} \sum_j x_j e^{-i\theta j} e^{i\theta k} d\theta = \frac{1}{2\pi} \sum_j x_j \int_{-\pi}^{\pi} e^{i\theta (k-j)} d\theta = \sum_j x_j \delta_{j,k} = x_k.$$
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?

Can extend definition of Fourier transform to $L^2$. 

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**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 $\lambda = ah_t/2hx$. Then

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

Is ETCS Toeplitz?
Is ETCS Toeplitz?

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

\[p_{j-k} = \begin{cases} 
1 & k = j, \\
0 & \text{otherwise}.
\end{cases}\]

\[p_m = \delta_{0,m}.\]

\[(Q_h u_\ell)_j = \lambda u_{j-1,\ell} + u_{j,\ell} - \lambda u_{j+1,\ell} = \sum_k u_{k,\ell} q_{j-k}\]

\[q_{j-k} = \begin{cases} 
\lambda & k = j - 1, \\
1 & k = j, \\
-\lambda & k = j + 1, \\
0 & \text{otherwise}.
\end{cases}\]

\[q_m = \begin{cases} 
\lambda & m = 1, \\
1 & m = 0, \\
-\lambda & m = -1, \\
0 & \text{otherwise}.
\end{cases}\]

Both \(P_h\) and \(Q_h\) are Toeplitz.
Fourier Transforms of Toeplitz Operators (1/3)

\[ y_j = \sum_k x_k p_{j-k} \]

\[ \hat{y}(\theta) = \sum_j \sum_k x_k p_{j-k} e^{-i\theta j} \]

\[ = \sum_j \sum_k \left( \frac{1}{2\pi} \int_{-\pi}^{\pi} \hat{x}(\varphi) e^{i\varphi k} d\varphi \right) p_{j-k} e^{-i\theta j} \]

\[ = \frac{1}{2\pi} \int_{-\pi}^{\pi} \hat{x}(\varphi) \sum_j \sum_k e^{i\varphi k} p_{j-k} e^{-i\theta j} d\varphi \]

\[ = \frac{1}{2\pi} \int_{-\pi}^{\pi} \hat{x}(\varphi) \sum_j \left( \sum_k e^{i\varphi(k-j)} p_{j-k} \right) e^{i(\varphi-\theta)j} d\varphi. \]
\[ \hat{y}(\theta) = \frac{1}{2\pi} \int_{-\pi}^{\pi} \hat{x}(\varphi) \sum_j \left( \sum_k e^{i\varphi(k-j)} p_{j-k} \right) e^{i(\varphi-\theta)j} d\varphi. \]

Consider
\[ \sum_k e^{i\varphi(k-j)} p_{j-k} = \sum_k e^{-i\varphi(j-k)} p_{j-k} \overset{\ell=j-k}{=} \hat{p}(\varphi). \]

So
\[ \hat{y}(\theta) = \int_{-\pi}^{\pi} \hat{x}(\varphi) \hat{p}(\varphi) \frac{1}{2\pi} \sum_j e^{i(\varphi-\theta)j} d\varphi. \]
Fourier Transforms of Toeplitz Operators (3/3)

\[
\hat{y}(\theta) = \int_{-\pi}^{\pi} \hat{x}(\varphi)\hat{p}(\varphi) \frac{1}{2\pi} \sum_j e^{i(\varphi-\theta)j} d\varphi.
\]

Define \( w_j = (1/2\pi)e^{i\varphi j} \). Then \( \hat{w}(\theta) = \frac{1}{2\pi} \sum_k e^{i(\varphi-\theta)k} \). So

\[
\hat{y}(\theta) = \int_{-\pi}^{\pi} \hat{x}(\varphi)\hat{p}(\varphi)\hat{w}(\theta) d\varphi.
\]

To determine \( \hat{w}(\theta) \), consider

\[
(1/2\pi)e^{i\varphi j} = w_j = \frac{1}{2\pi} \int_{-\pi}^{\pi} \hat{w}(\theta)e^{i\theta j} d\theta.
\]

Observe that (by uniqueness of the FT) \( \hat{w}(\theta) = \delta(\varphi - \theta) \) would do the trick. Therefore \( \hat{y}(\theta) = \hat{x}(\theta)\hat{p}(\theta) \).
Fourier Transforms of Inverse Toeplitz Operators

Recall \((P\mathbf{x})_j = \sum_k p_{j-k} x_k\).

What is the Fourier transform \(\hat{\mathbf{z}}(\theta)\) of \(P_h^{-1}\mathbf{x}\)?

- Inverse is also Toeplitz (by linearity and translation invariance).
- Fourier transform of \(P_h P_h^{-1} \mathbf{x}\) is \(\hat{\mathbf{x}}\) for any \(\mathbf{x}\).
- Therefore \(\hat{p}(\theta) \hat{\mathbf{z}}(\theta) = \hat{\mathbf{x}}(\theta)\).
- By uniqueness of Fourier t. (unproven): \(\hat{\mathbf{z}}(\theta) = \frac{1}{\hat{p}(\theta)} \hat{\mathbf{x}}(\theta)\).

Fourier transform \(P_h^{-1} Q_h \mathbf{y}\)?

\[\frac{\hat{\mathbf{q}}(\theta)}{\hat{p}(\theta)} \hat{\mathbf{y}}(\theta).\]
Bounding the Operator Norm

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

$$\|P_h^{-1}Q_h\|^2_2 = \sup_{x \neq 0} \frac{\|P_h^{-1}Q_hx\|^2_2}{\|x\|^2_2} = \sup_{x \neq 0} \frac{h_x}{2\pi} \int_{-\pi}^{\pi} \left| \frac{\hat{q}(\theta)}{\hat{p}(\theta)} \hat{x}(\theta) \right|^2 d\theta$$

$$\leq \sup_{x \neq 0} \frac{\max_{\varphi \in [-\pi, \pi]} \left| \frac{\hat{q}(\varphi)}{\hat{p}(\varphi)} \right|^2 \int_{-\pi}^{\pi} |\hat{x}(\theta)|^2 d\theta}{\int_{-\pi}^{\pi} |\hat{x}(\theta)|^2 d\theta} = \max_{\varphi \in [-\pi, \pi]} \left| \frac{\hat{q}(\varphi)}{\hat{p}(\varphi)} \right|^2.$$

Similarly, $\|P_h^{-1}\|^2_2 \leq \max_{\varphi \in [-\pi, \pi]} |1/\hat{p}(\varphi)|^2$.

Is the upper bound attained?

If $\hat{x}(\theta) = \delta(\theta - \varphi^*)$, where $\varphi^*$ maximizes $|\hat{q}(\theta)/\hat{p}(\theta)|$, then yes. (So $x_k = (1/2\pi) e^{i\varphi^* k}$.)
von Neumann Stability

Two-level finite difference scheme

\[ P_h \mathbf{v}_{\ell+1} = Q_h \mathbf{v}_\ell + h_t \mathbf{b}_\ell, \]

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

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

Implied by von Neumann stability.

Why is bounding the symbol the most salient part?

If \( \|P_h^{-1}Q_h\| \leq 1 \) encounters problems, there often also doesn’t exist a \( c \) so that \( \|P_h^{-1}\| \leq c \).

Main restriction of von Neumann stability?

- Only works on infinite/periodic grids.
- Have BCs? Analysis gets more difficult.
von Neumann Stability: ETBS (1/2)

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

\[ P_h = I, \quad Q_h = \text{tridiag}(\lambda, 1 - \lambda, 0). \]

Auxiliary result: Fourier transform of $r_k = \delta_{k,j}$.

\[
\hat{r}(\varphi) = \sum_k r_k e^{-i\varphi k} = \sum_k \delta_{k,j} e^{-i\varphi k} = e^{-i\varphi j}.
\]

\[(Q_hx)_j = \sum_k q_{j-k}x_k, \text{ so}\]
\[(Q_hx)_0 = q_0x_0 + x_{-1}q_1 + x_1q_{-1} + \cdots, \text{ so}\]
\[
q = (\ldots, 0, 0, 1 - \lambda, \lambda, 0, \ldots).
\]

\[
\hat{p}(\varphi) = 1, \quad \hat{q}(\varphi) = \lambda e^{-i\varphi} + (1 - \lambda) = 1 - \lambda(1 - e^{-i\varphi}).
\]

\[
|s(\varphi)|^2 = \left| \frac{\hat{q}(\varphi)}{\hat{p}(\varphi)} \right|^2 = (1 - \lambda(1 - e^{-i\varphi}))(1 - \lambda(1 - e^{i\varphi}))
= 1 + 2(\lambda - \lambda^2)(\cos \varphi - 1).
\]
Found: \(|s(\varphi)|^2 = 1 + 2(\lambda - \lambda^2)(\cos \varphi - 1)|.

Maximize: take derivative w.r.t. \(\varphi\), set to 0:

\[
\frac{d}{d\varphi} \left(1 + 2(\lambda - \lambda^2)(\cos \varphi - 1)\right) = -2(\lambda - \lambda^2) \sin \varphi = 0
\]

if and only if \(\varphi \in \mathbb{Z}\pi\).

For \(m \in \mathbb{Z}\), \(s(m\pi) = 1 + 2(\lambda - \lambda^2)((-1)^m - 1)\). For \(m\) even, \(s(m\pi) = 1\).

For \(m\) odd, \(s(m\pi) = 1 - 4(\lambda - \lambda^2) = (1 - 2\lambda)^2\).

Thus \(|s(\varphi)|^2 \leq 1\) if and only if

\[
|1 - 2\lambda| \leq 1 \iff 0 \leq \lambda \leq 1 \iff 0 \leq h_t \leq \frac{h_x}{a}.
\]

Found: conditionally von Neumann stable with CFL as before.
von Neumann Stability: ETCS

Let $\lambda = ah_t/h_x$. Then

$$u_{k,\ell+1} = \frac{\lambda}{2} u_{k-1,\ell} + u_{k,\ell} - \frac{\lambda}{2} u_{k+1,\ell}.$$  

$$P_h = I, \quad Q_h = \text{tridiag}(\lambda/2, 1, -\lambda/2).$$

So $\hat{p}(\varphi) = 1$, and

$$\hat{q}(\varphi) = \frac{\lambda}{2} e^{-i\varphi} + 1 - \frac{\lambda}{2} e^{-i\varphi(-1)} = 1 - \lambda \sin(\varphi)i.$$  

So

$$\max_{\varphi} |s(\varphi)|^2 = \max_{\varphi} \left| \frac{\hat{q}(\varphi)}{\hat{p}(\varphi)} \right|^2 = 1 + \lambda^2 \sin^2(\varphi) \geq 1.$$  

Not von Neumann stable $\Rightarrow$ not Lax-Richtmyer stable.
von Neumann Stability: Crank-Nicolson

Let $\lambda = a h_t / (4 h_x)$

\[-\lambda u_{k-1,\ell+1} + u_{k,\ell+1} + \lambda u_{k+1,\ell+1} = \lambda u_{k-1,\ell} + u_{k,\ell} - \lambda u_{k+1,\ell}.\]

$$P_h = \text{tridiag}(-\lambda, 1, \lambda), \quad Q_h = \text{tridiag}(\lambda, 1, -\lambda).$$

\[
\hat{p}(\varphi) = -\lambda e^{-i\varphi} + 1 + \lambda e^{i\varphi} = 1 + 2\lambda i \sin(\varphi),
\]

\[
\hat{q}(\varphi) = \lambda e^{-i\varphi} + 1 - \lambda e^{i\varphi} = 1 - 2\lambda i \sin(\varphi).
\]

$$|s(\varphi)|^2 = \frac{1 + 4 \sin^2(\varphi)}{1 + 4 \sin^2(\varphi)} = 1.$$

Crank-Nicolson is unconditionally von Neumann stable.
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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

\[
L_1u = u_t + au_x,
L_2u = u_t - Du_{xx} + au_x \quad (D > 0)
L_3u = u_t + au_x - \mu u_{xxx}.
\]

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’.

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

What type of function is this?

- For \( k, \omega \) real: traveling wave with speed \( c = \omega / k \).
  
  \[ z(x - ct, 0) = z_0 e^{i(k(x - ct))} = z(x, t). \]

- For \( k \) imaginary: an evanescent wave in \( x \).

- For \( \text{Im} \omega < 0 \): a wave decaying in time.
Wave-like Solutions of the PDE

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

\[ L_2 u = u_t - Du_{xx} + au_x \ (D > 0). \] Plug in \( z \).

\[ Lz = (-i\omega + iak + Dk^2)z. \]

Observations in connection with \( L \)?

- \( Lz = \lambda(\omega, k)z. \)
- \( z(x, t) \) is a solution iff \( Lz = 0 \) iff \( \lambda(\omega, k) = 0. \)

What is the dispersion relation?

The equation \( \lambda(\omega, k) = 0 \) is called the dispersion relation for the PDE \( L \).
Picking Apart the Dispersion Relation

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

$$z(x, t) = z_0 e^{i(kx - \omega(k)t)}$$
$$= z_0 e^{i(kx - \alpha(k)t - i\beta(k)t)}$$
$$= z_0 e^{\beta(k)t} e^{i(kx - \alpha(k)t)}.$$

How can we recognize dissipation?

If $\beta(k) < 0$, we call the PDE dissipative.

What is the phase speed? How can we recognize dispersion?

- The phase speed of $z(x, t)$ is $v_{ph} = \alpha(k)/k$.
- If $v_{ph}$ is a constant ($\Leftrightarrow \alpha(k)$ is linear in $k$), all waves move at the same speed.
- If that’s not the case, we call the PDE dispersive.
Dispersion Relation: Examples

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

$L_1 u = u_t + au_x$

- $\lambda(\omega, k) = i(ak - \omega) = 0$, i.e. $\omega = ak$.
- Neither dissipative nor dispersive.

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

- $\lambda(\omega, k) = -i\omega + iak + Dk^2$, i.e. $\omega = ak - iDk^2$.
- Dissipative, but not dispersive.

$L_3 u = u_t + au_x - \mu u_{xxx}$

- $\lambda(\omega, k) = -i\omega + iak + i\mu k^3$, i.e. $\omega = ak + \mu k^3$.
- Dispersive, but not dissipative.
Goal: Want discrete finite difference scheme to match dissipation/dispersion behavior of continuous PDE.

Define a discrete wave-like function:

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

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

\( P_h \) and \( Q_h \) consist of Toeplitz operators.
Toeplitz and Waves

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

**Theorem (Waves Diagonalize Toeplitz Operators)**

Let \( T \) be a Toeplitz operator. Then \( T z_\ell = \lambda(k)z_\ell = \hat{t}(kh_x)z_\ell. \)

\[
(Tz_\ell)_j = \sum_m z_{m,\ell} t_{j-m} = \sum_m z_0 e^{i(k m h_x - \omega \ell h_t)} t_{j-m}
\]

\[
= \sum_m z_0 e^{i(k(m-j)h_x)} e^{i(k j h_x - \omega \ell h_t)} t_{j-m}
\]

\[
= \left( \sum_{m'} e^{-ikm' h_x} t_{m'} \right) z_0 e^{i(k j h_x - \omega \ell h_t)}. \]

\[ \Rightarrow \lambda(k) = \sum_{m} e^{-ikm h_x} t_m = \hat{t}(kh_x). \]
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?

$$\begin{align*}
\lambda P(k) z_{\ell+1} &= \lambda Q(k) z_\ell \\
\lambda P(k) z_0 e^{i(kjhx - \omega(\ell+1)ht)} &= \lambda Q(k) z_0 e^{i(kjhx - \omega\ell ht)} \\
e^{-i\omega h t} &= \frac{\lambda Q(k)}{\lambda P(k)} = \frac{\hat{q}(kh_x)}{\hat{p}(kh_x)} = s(kh_x),
\end{align*}$$

which is the symbol of of of the finite difference method.

Seen before?

Used in von Neumann stability analysis.
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 $\kappa$.

A number proportional to the number of wavelengths per point.

Let $s(\kappa) = |s(\kappa)| e^{i\varphi(\kappa)} = e^{\log|s(\kappa)| + i\varphi(\kappa)}$. $\omega(\kappa)$?

$$\omega(\kappa) = \frac{-\varphi(\kappa) + i \log |s(\kappa)|}{ht}.$$
Discrete Dispersion Relation (2/2)

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

Plug that into the wave-like solution:

\[
\begin{align*}
  z_{j,\ell} &= z_0 e^{i(kjhx - \omega \ell h_t)} \\
  &= z_0 e^{i \left( kjhx - \frac{-\varphi(\kappa) + i \log |s(\kappa)|}{h_t} \ell h_t \right)} \\
  &= z_0 e^{\log |s(\kappa)| \ell} e^{ik \left( jh_x - \frac{-\varphi(\kappa)}{kh_t} \ell h_t \right)}
\end{align*}
\]

Criterion for stability?

\[ |s(\kappa)| \leq 1 \text{ (as before)} \]
Numerical Dispersion/Dissipation

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

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

When is the scheme dissipative?

If $|s(kh_x)| < 1$, the scheme is called **dissipative**. Dissipation occurs exponentially in time, with factor $s(kh_x)$.

What is the phase speed?

The scheme has **phase speed** $v_{ph} = \frac{-\varphi(kh_x)}{kh_t}$.

Dispersion?

If $v_{ph}$ is independent of $k$, all waves move with the same speed. If not, the scheme is called **dispersive**.
Dispersion/Dissipation Analysis of ETBS

Let $\lambda = ah_t/h_x$. Shown earlier: $s(kh_x) = 1 - \lambda(1 - e^{-ikh_x})$.

\[ s(\kappa) = (1 - \lambda) + \lambda e^{-i\kappa}. \]

If we sweep $\kappa$, $s(\kappa)$ traces a circle:

For small $\lambda$, the circle moves towards $s(kh_x) = 1$, implying lower dissipation per step.

Overall, we obtain

\[ e^{-i\omega(\kappa)h_t} = 1 - \lambda(1 - e^{-ikh_x}). \]
Dispersion/Dissipation Analysis of ETBS: Fine Grid

\[ e^{-i\omega(\kappa)h_t} = 1 - \lambda(1 - e^{-ikh_x}) \]

If \( kh_x \) is small, \( e^{-ikh_x} \approx 1 - ikh \), so that

\[ s(kh_x) \approx (1 - \lambda) + \lambda(1 - ikh_x) = 1 - i\lambda kh_x. \]

For small \( \omega(kh_x) \), approximate \( e^{-i\omega(kh_x)h_t} = 1 - i\omega(kh_x)h_t \).

Setting the two (approximately) equal yields

\[ 1 - i\omega(kh_x)h_t \approx 1 - i\lambda kh_x \quad \Rightarrow \quad \omega(kh_x)h_t \approx \lambda kh_x = \frac{ah_t}{h_x} kh_x, \]

i.e. \( \omega(kh_x) \approx ak \), or \( v_{ph} \approx (-ak)/(kh_t) = -a/h_t \), which is independent of \( k \). Thus we expect little dispersion for waves with low number of wavelengths per point.
Dispersion/Dissipation: Demo

- Demo: Experimenting with Dispersion and Dissipation [cleared]
- Demo: Dispersion and Dissipation [cleared]
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Heat Equation

Heat equation \((D > 0)\):

\[
\begin{align*}
  u_t &= Du_{xx}, \quad (x, t) \in \mathbb{R} \times (0, \infty), \\
  u(x, 0) &= g(x) \quad x \in \mathbb{R}.
\end{align*}
\]

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

\[
  u(x, t) = \frac{1}{\sqrt{4\pi t}} e^{-x^2/4t}.
\]

Why is this a weird model?

Infinite speed of propagation of information
Schemes for the Heat Equation

Cook up some schemes for the heat equation.

Explicit Euler:

\[
\frac{u_{k,\ell+1} - u_{k,\ell}}{h_t} - D \frac{u_{k+1,\ell} - 2u_{k,\ell} + u_{k-1,\ell}}{h_x^2} = 0
\]

Implicit Euler:

\[
\frac{u_{k,\ell+1} - u_{k,\ell}}{h_t} - D \frac{u_{k+1,\ell+1} - 2u_{k,\ell+1} + u_{k-1,\ell+1}}{h_x^2} = 0
\]
Von Neumann Analysis of Explicit Euler for Heat (1/2)

Let \( \lambda = Dh_t/h_x^2 \).

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

Thus

\[
    P_h = I, \quad Q_h = \text{tridiag}(\lambda, 1 - 2\lambda, \lambda).
\]

\[
    \hat{p}(\varphi) = 1, \quad \hat{q}(\varphi) = \lambda e^{-i\varphi} + (1 - 2\lambda) + \lambda e^{i\varphi} = 1 - 2\lambda + 2\lambda \cos(\varphi).
\]

We want \(|s(\varphi)| \leq 1\), thus we need

\[
    -1 \leq 1 + 2\lambda(\cos(\varphi) - 1) \leq 1
\]

\[
    \iff -2 \leq 2\lambda(\cos(\varphi) - 1) \leq 0.
\]
Since \( |\cos(\phi)| \leq 1 \), also \(-2 \leq \cos(\phi) - 1 \leq 0\). For the lower bound,

\[-2 \leq -4\lambda \iff \frac{1}{2} \geq \frac{Dh_t}{h_x^2} \iff h_t \leq \frac{h_x^2}{2D}.

Observe \( h_t = O(h_x^2) \), which is often prohibitively small.

Comment on the stability region found regarding speeds of propagation.

- Saw: heat equation has infinite speed of information propagation
- Explicit Euler has finite speed of information propagation (how fast?)
Von Neumann Analysis of Implicit Euler for Heat

Let \( \lambda = D h_t / h_x^2 \).

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

\[
P_h = \text{tridiag}(-\lambda, 1 + 2\lambda, -\lambda), \quad Q_h = I.
\]

\[
\hat{p}(\varphi) = 1 + 2\lambda(1 - \cos(\varphi)), \quad \hat{q}(\varphi) = 1.
\]

To obtain \( |s(\varphi)| \leq 1 \), consider \( 1 \leq |1 + 2\lambda(1 - \cos(\varphi))| \), which is always true.

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

- Yes, elliptic.
- Focus on solving those later.
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  Outlook: Systems and Multiple Dimensions

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Discontinuous Galerkin Methods for Hyperbolic Problems
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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:

\[
\frac{d}{dt} \int_a^b u(x, t)dx + f(u(b, t)) - f(u(a, t)) = 0 \quad \text{for any} \ a, \ b.
\]

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?

Smooth Solution.
Going Nonlinear: Burgers’ Equation

Make a simple modification to advection $u_t + au_x = 0$ to make it nonlinear.

\[ u_t + uu_x = 0 \]

Is that a sensible modification?

Yes: it is the core part of the momentum equation in Euler’s equations of gas dynamics in 1D.

\[ \partial_t u + u \cdot \nabla u + \frac{\nabla p}{\rho} = g \]

Is that still a conservation law?

Yes: $u_t + (u^2/2)_x = 0$. Called Burgers’ Equation.
Demo: ETBS for Volume Burgers [cleared]

What do you think of these results?

No good, very bad. Conservation of $\int u$ should hold at least to the order of accuracy of the scheme!

We clearly need to rethink our plan here. We will begin by learning about the theory of conservation laws.
Burgers’ Equation

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

Interpret Burgers’ equation.

\[f(u) = \frac{u^2}{2}. \text{ So } f'(u) = u.\]

Characteristic speed is given by ‘how much stuff there is’/‘the density’

Consider the characteristics at \(\frac{\pi}{2}\) and \(3\frac{\pi}{2}\).

\[f(u) = \frac{u^2}{2}. \text{ So } f'(u) = u.\]

\[\begin{align*}
\quad x = \frac{\pi}{2}: \quad f'(\sin x) &= 1. \\
\quad x = 3\frac{\pi}{2}: \quad f'(\sin x) &= -1.
\end{align*}\]

They intersect!
Weak Solutions

\[ \frac{d}{dt} \int_{a}^{b} u(x, t) \, dx = f(u(a, t)) - f(u(b, t)) \]

Define a weak solution:

- If \( u \) satisfies the integral form for almost all \( (a, b) \) then \( u \) is called a weak solution. (physically meaningful)
- If for any \( \varphi \in C^1_0(\mathbb{R} \times [0, \infty)) \) (compact support),

\[
- \int_{0}^{\infty} \int_{-\infty}^{\infty} (u \varphi_t + f(u) \varphi_x) \, dx \, dt - \int_{-\infty}^{\infty} u^0(x) \varphi(x, 0) \, dx = 0,
\]

then in \( u \) is called a weak solution. (more meaningful mathematically)

Turns out: equivalent. (not shown)
Rankine-Hugoniot Condition (1/2)

Consider: Two $C^1$ segments separated by a curve $x(t)$ with no regularity.

\[
\left(\frac{d}{dt}\right) \left( \int_a^{x(t)} u(x, t) \, dx + \int_{x(t)}^b u(x, t) \, dx \right) + f(u(b, t)) - f(u(a, t)) = 0
\]

\[
G_a(x(t), t) := \int_a^{x(t)} u(x, t) \, dx
\]

\[
G_b(x(t), t) := \int_{x(t)}^b u(x, t) \, dx
\]

\[
\frac{d}{dt} G_a(x(t), t) = \frac{\partial G_a(x(t), t)}{\partial x} \cdot \frac{dx(t)}{dt} + \frac{\partial G_a}{\partial t}
\]

\[
= u(x(t), t) x'(t) + \int_a^{x(t)} u_t(x, t) \, dx
\]

\[
= u(x(t), t) x'(t) - \int_a^{x(t)} f(u)_x(x, t) \, dx
\]

\[
= u(x(t), t) x'(t) - \left( f(u(x(t), t)) - f(u(a, t)) \right),
\]

and $dG_b(x(t), t)/dt$ analogously.
\[(d/dt)G_a(x(t), t) = u(x(t), t)x'(t) - (f(u(x(t), t)) - f(u(a, t))).\]

Discontinuity at \(u(x(t), t)\): \((d/dt)G_a\) doesn’t exist. One-sided limits:

\[
\begin{align*}
\left[ \frac{dG_a(x(t), t)}{t} \right]^+ & = u^+ x'(t) - (f(u^+) - f(u(a, t))), \\
\left[ \frac{dG_b(x(t), t)}{t} \right]^+ & = -u^+ x'(t) - (f(u(b, t)) - f(u^+)).
\end{align*}
\]

Adopted shorthand: \(u^- := u(x(t)^-, t), \quad u^+ := u(x(t)^+, t)\).

Plug into integral form: \(u^- x'(t) - f(u^-) - u^+ x'(t) + f(u^+) = 0\).

\[x'(t) = \frac{f(u^+) - f(u^-)}{u^+ - u^-}.
\]

This is the called the Rankine-Hugoniot Condition.
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.
Riemann Problems: Example 1

Consider the following Riemann problem:

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

The IC is just propagated in time (at “speed 0”) to form a weak solution (a shock).
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)

The propagated ICs also form a weak solution. But consider

\[ u(x, t) = \begin{cases} 
-1 & x \leq -t, \\
x/t & -t < x < t, \\
1 & x > t.
\end{cases} \]

This is also a weak solution (a rarefaction wave).

Conclusion: Our current notion of weak solution is too weak.
Bad Shocks and Good Shocks

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

- Out of the shock.
- In the first example, the shock is self-steepening.
- In the second example, it is not.

Comment on the stability of that situation.

Smearing out the initial profile or adding viscosity would wash out the solution into a rarefaction fan.
Ad-Hoc Idea: Ban Bad Shocks

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

Characteristic speed.

Devise a way to ban unstable shocks.

A discontinuity propagating with speed $s$ (cf. Rankine-Hugoniot) satisfies the entropy condition if

$$f'(u^-) > s > f'(u^+).$$

If $f$ is convex, $f'$ is monotonically non-decreasing, and the Rankine-Hugoniot speed automatically falls between $f'(u^-)$ and $f'(u^+).$ So for convex $f,$ $f'(u^-) > f'(u^+)$ is sufficient (and implies $u^- > u^+$ by convexity).
Vanishing Viscosity Solutions

Goal: neither uniqueness nor existence poses a problem.

How?

Consider adding an artificial viscosity:

\[ u_\varepsilon t + f(u_\varepsilon)_x = \varepsilon u_{\varepsilon,x} \]

with small \( \varepsilon > 0 \).

By ‘washing out’ the solution, the viscous term increases smoothness, and, we hope, restores uniqueness.

Then we would wish to define a vanishing viscosity weak solution as

\[ \lim_{\varepsilon \to 0} u_\varepsilon(x, t) = u(x, t) \]

in some norm.
What are features of (physical) entropy?

- Constant along particle paths in smooth flow
- Jumps to higher values across a shock

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 \( \psi \).

For smooth \( u \), the chain rule gives \( \eta'(u)u_t + \psi'(u)u_x = 0 \). Similarly, we can rewrite the conservation law:

\[
\begin{align*}
    u_t + f'(u)u_x &= 0 \\
    \Leftrightarrow \quad \eta'(u)u_t + \eta'(u)f'(u)u_x &= 0.
\end{align*}
\]

This gives us \( \psi'(u) = -\eta'(u)(u_t/u_x) = \eta'(u)f'(u) \).

Lots of solutions for scalar conservation laws. For systems and in multiple dimensions: may have no solutions.

Come up with an entropy-flux pair for Burgers.

\[ f(u) = u^2/2. \] If we take \( \eta(u) = u^2 \), then \( \psi'(u) = 2u \cdot u \), i.e. \( \psi(u) = 2u^3/3 \).
Back to Vanishing Viscosity (1/2)

\[ u_t + f(u)_x = \varepsilon u_{xx} \]

What’s the evolution equation for the entropy?

Note: Viscosity solutions are always smooth. Allowed to do derivative gymnastics.

\[ \eta'(u) u_t + \eta'(u) f'(u) u_x = \varepsilon \eta'(u) u_{xx} \]

\[ \iff \eta(u)_t + \psi(u)_x = \varepsilon (\eta'(u) u_x)_x - \varepsilon \eta''(u) u_x^2. \]
Back to Vanishing Viscosity (2/2)

\[ \eta(u)_t + \psi(u)_x = \varepsilon(\eta'(u)u_x)_x - \varepsilon\eta''(u)u_x^2. \]

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

\[
\int_{t_1}^{t_2} \int_{x_1}^{x_2} \eta(u)_t + \psi(u)_x \, dx \, dt
= \varepsilon \int_{t_1}^{t_2} [\eta'(u(x_2, t))u_x(x_2, t) - \eta'(u(x_1, t))u_x(x_1, t)] \, dt
- \varepsilon \int_{t_1}^{t_2} \int_{x_1}^{x_2} \eta''(u)u_x^2 \, dx \, dt. \]

As \(\varepsilon \to 0\), the first term goes to zero. The second term involves an integral over the square of the derivative of a steepening \(u\) (as \(\varepsilon \to 0\)), and so will not vanish. Accordingly, \(\eta(u)_t + \psi(u)_x \leq 0\) weakly.
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?

\[ 0 \geq \int_{t_1}^{t_2} \int_{x_1}^{x_2} \eta(u)_t + \psi(u)_x \, dx \, dt \]

\[ = \left[ \int_{x_1}^{x_2} \eta(u(x, t)) \, dx \right]_{t_1}^{t_2} + \left[ \int_{t_1}^{t_2} \psi(u(x, t)) \, dt \right]_{x_1}^{x_2}, \]

so that

\[ \int_{x_1}^{x_2} \eta(u(x, t_2)) \, dx \leq \int_{x_1}^{x_2} \eta(u(x, t_1)) \, dx - \left[ \int_{t_1}^{t_2} \psi(u(x, t)) \, dt \right]_{x_1}^{x_2} \]

\(\text{Outflow/Inflow}\)

If \(u\) is compactly supported, then we can choose \(x_1\) and \(x_2\) on either side of \(u\)’s support and obtain that entropy can only decrease. (fluid flow: math. entropy = \(-\rho \cdot \text{phys. entropy}\))
Total Variation

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

Simpler form if \( u \) is differentiable?

\[
TV(u) = \int |u'(x)| \, dx
\]

Hiking analog?

Elevation change
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:

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

- For smooth solutions (and non-crossing characteristics), all function values live \( \Rightarrow \) TV stays unchanged.
- For solutions with shocks, local minima and maxima may disappear into the shock \( \Rightarrow \) TV decreases.

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

Let \( u, v \) be viscosity solutions of the conservation law. Then

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

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

Entropy Solution?

\[
    u(x, t) = \begin{cases} 
        1 & x \leq \frac{1}{2} t, \\
        0 & x > \frac{1}{2} t.
    \end{cases}
\]

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

\[
    u_t + uu_x = 0.
\]

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

Recall the upwind scheme for $u_t + au_x = 0$:

$$u_{j,\ell+1} = u_{j,\ell} - a \cdot \Delta t \left( \frac{\Delta t}{\Delta x} (u_{j,\ell} - u_{j-1,\ell}) \right).$$

Write the upwind FD scheme for $u_t + uu_x = 0$:

$$u_{j,\ell+1} = u_{j,\ell} - \frac{\Delta t}{\Delta x} u_{j,\ell} (u_{j,\ell} - u_{j-1,\ell}).$$

- For $j \neq 0$, $u_{j,0} - u_{j-1,0} = 0$
- For $j = 0$, $u_{j,0} = 0$.

Altogether,

$$u_{j,\ell+1} = u_{j,\ell}.$$

Bad.
Definition (Conservative Scheme)

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

\[ u_{j,\ell+1} = u_{j,\ell} - \frac{\Delta t}{\Delta x} \left[ f_{j+1/2}^*(u_{\ell}) - f_{j-1/2}^*(u_{\ell}) \right], \]

where \( f^* \)...

- is Lipschitz continuous,
- satisfies \( f^*(u, \cdots, u) = f(u) \) (consistency).

Theorem (Lax-Wendroff)

*If the solution \( \{ u_{j,\ell} \} \) to a conservative scheme converges (as \( \Delta t, \Delta x \to 0 \)) boundedly almost everywhere to a function \( u(x, t) \), then \( u \) 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 $\Delta^- a_k = a_k - a_{k-1}$:

\[
\sum_{k=1}^{N} a_k(\Delta^- \varphi_k) + \sum_{k=1}^{N} \varphi_k(\Delta^+ a_k) = -a_1 \varphi_0 + \varphi_N a_{N+1}.
\]

Let $\varphi_{j,\ell} = \varphi(x_j, t_{\ell})$ for $\varphi \in C^1_0$ (compact support). Then

\[
0 = \sum_{\ell=1}^{\infty} \sum_j \left( \frac{\Delta^+_2 u_j,\ell}{h_t} + \frac{\Delta^+_1 f_j^*,\ell}{h_x} \right) \varphi_{j,\ell} h_x h_t
\]

\[
= \sum_{\ell=1}^{\infty} \sum_j \left( \frac{\Delta^-_2 \varphi_{j,\ell}}{h_t} u_j,\ell + \frac{\Delta^-_1 \varphi_{j,\ell}}{h_x} f_j^*,\ell \right) h_x h_t - \sum_j u_{j,1} \phi_{j,0} h_x
\]

\[
\xrightarrow{\text{DCT}} f^*(u,u) = u \rightarrow \int_0^{\infty} \int_{-\infty}^{\infty} (\varphi_t u + \varphi_x f(u)) dx dt - \int_{-\infty}^{\infty} u(x,0) \phi(x,0) dx = 0.
\]
Consider the solution constant in each cell: $\bar{u}_j$

$\bar{u}_j$ is the cell average of cell $I_j$:

$$\bar{u}_j = \frac{1}{h_x} \int_{x_{j-1/2}}^{x_{j+1/2}} u(x) \, dx$$

Choose $h_x, h_t$ so that $\max |f'(u)| h_t < h_x$.

Then in a sequence of cells $(A, B, C, D, E)$, the solution in cell $C$ in the next timestep is not influenced at all by the solution in cells $A$ and $E$.

Idea: Solve Riemann problem at each cell interface.
Developing Finite Volume

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

\[
\frac{1}{h_x} \int_{x_{j-1/2}}^{x_{j+1/2}} u^{\ell+1} dx - \frac{1}{h_x} \int_{x_{j-1/2}}^{x_{j+1/2}} u^{\ell} dx
\]

\[
+ \frac{1}{h_x} \int_{t^\ell}^{t^{\ell+1}} f(u_{j+1/2}) dt - \frac{1}{h_x} \int_{t^\ell}^{t^{\ell+1}} f(u_{j-1/2}) dt = 0
\]

\[
\Leftrightarrow \bar{u}_{j,\ell+1} - \bar{u}_{j,\ell}
\]

\[
+ \frac{1}{h_x} \int_{t^\ell}^{t^{\ell+1}} f(u_{j+1/2}) dt - \frac{1}{h_x} \int_{t^\ell}^{t^{\ell+1}} f(u_{j-1/2}) dt = 0.
\]
Flux Integrals?

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

The substitution

\[ \bar{x} = ax, \quad \bar{t} = at. \]

leaves the conservation law and the Riemann ICs invariant.

⇒ The Riemann solution must be self-similar under scaling.

Thus: the Riemann solution \( u(x, t) \) can be viewed as function of only one variable \( \xi = x/t \).

Thus \( u \) is constant along \( x = x_{j\pm1/2} \), so that

\[ \frac{1}{h_x} \int_{t_\ell}^{t_{\ell+1}} f(u_{j+1/2}) \, dt = \frac{h_t}{h_x} f(u_{j+1/2}). \]
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?

- Reconstruct \( u_{j\pm1/2,\ell}^- \) and \( u_{j\pm1/2,\ell}^+ \)
- Evolve the Riemann problem at \( x_{j\pm1/2} \): Numerical flux / Riemann solver: \( f^*(u_{j\pm1/2,\ell}, u_{j\pm1/2,\ell}^-) \)
- Average the Riemann solutions to obtain \( \bar{u}_{j,\ell+1} \)

Heuristic time step restriction?

Will run into problems if wave from one cell interface interacts with other interface: \( h_t \leq h_x / \max_j |f'(u_j)| \)
Riemann Problem

\[
\begin{cases}
    u_t + f(u)_x = 0, \\
    u(x, 0) = \begin{cases}
    u_l & x < 0, \\
    u_r & x \geq 0
\end{cases}
\end{cases}
\]

Exact solution in the Burgers case?

\[
u(x, t) = \begin{cases}
    u_l & x < st, \\
    u_r & x \geq st, \\
    u_l & x < u_l t, \\
    x/t & u_l t \leq x < u_r t, \\
    u_r & x \geq u_r t,
\end{cases}
\]

\[
s = \frac{f(u_r) - f(u_l)}{u_r - u_l} = \frac{1}{2} [u_r^2 - u_l^2] = \frac{1}{2} (u_l + u_r).
\]

Why is the rarefaction part independent of \(u_l\) and \(u_r\)?
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?

Assume $f''(u) > 0$.
Let $u_s$ such that $f'(u_s) = 0$ (called the stagnation state: why?)

\[
f^*(u^-, u^+) = \begin{cases} 
  f(u^-) & \text{if shock with } s > 0, \\
  f(u^+) & \text{if shock with } s \leq 0, \\
  f(u^-) & \text{if rarefaction with } f'(u^-) \geq 0, \\
  f(u^+) & \text{if rarefaction with } f'(u^+) \leq 0, \\
  f(u_s) & \text{if rarefaction with } f'(u^-) \leq 0 \leq f'(u^+). 
\end{cases}
\]

Equivalent to

\[
f^*(u^-, u^+) = \begin{cases} 
  \max_{u^- \leq u \leq u^-} f(u) & \text{if } u^- > u^+, \\
  \min_{u^- \leq u \leq u^+} f(u) & \text{if } u^- \leq u^+. 
\end{cases}
\]
Downside of Godunov Riemann solver?

Not easy/efficient to implement in general. Want simpler Riemann solvers.
Consider only $f(u) = au$ for now. Riemann solver inspiration from FD?

For $a \geq 0$, want ETBS:

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

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

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

Clearly equivalent to a finite volume scheme! Upwind numerical flux?

\[
f^*(u^-, u^+) = \begin{cases} 
    au^- & a \geq 0 \\
    au^+ & a < 0 
\end{cases} = \frac{au^- + au^+}{2} - \frac{|a|}{2}(u^+ - u^-).
\]
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

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

\[ \frac{u_{j, \ell+1} - u_{j, \ell}}{h_t} + a \frac{u_{j+1, \ell} - u_{j-1, \ell}}{2h_x} = \frac{|a|}{2} \cdot \frac{h_x}{2} \cdot \frac{u_{j+1, \ell} - 2u_{j, \ell} + u_{j-1, \ell}}{h_x^2}, \]

i.e. it is equivalent to ETCS (unstable!) with a second-order discretization of $\partial_x^2$, i.e. a dissipation, with a coefficient that vanishes as $h_x \to 0$. 
Lax-Friedrichs

Generalize linear upwind flux for a nonlinear conservation law:

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

Choice of \( \alpha \) (consistent with linear)? Idea: \( \alpha = |f'((u^- + u^+)/2)| \)

Unfortunately: may converge to a weak solution that violates the entropy condition (not shown). Better:

\[ \alpha = \max (|f'(u^-)|, |f'(u^+)|). \]

Called **local Lax-Friedrichs**. Global variant (with global max) also OK.

**Demo:** Finite Volume Burgers [cleared] (Part I)
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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?

- Temporal Accuracy
- Spatial Accuracy
- Nonsmoothness (in both space and time)

What order of accuracy can we expect?

- Near shocks: no convergence in \( L^\infty \), first-order in \( L^2 \).
- Elsewhere: hopefully, as high as we would like
Improving the Order of Accuracy

Improve temporal accuracy.

Rewrite FV using the method of lines:

\[
\frac{d\tilde{u}_j(t)}{dt} + \frac{f^*(u_{j+1/2}^-(t), u_{j+1/2}^+(t)) - f^*(u_{j-1/2}^-(t), u_{j-1/2}^+(t))}{h_x} = 0.
\]

What’s the obstacle to higher spatial accuracy?

Letting \( u_{j+1/2}^- = \tilde{u}_j = u_{j-1/2}^+ \).

How can we improve the accuracy of that approximation?

Include more cells in the reconstruction of the state \( u_{j+1/2}^\pm \).
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?

\[
\begin{align*}
u_{j+1/2}^{(1)} &= \frac{1}{2}(\bar{u}_j + \bar{u}_{j+1}), \quad (2\text{nd order central}) \\
u_{j+1/2}^{(2)} &= \frac{3}{2}\bar{u}_j - \frac{1}{2}\bar{u}_{j-1}, \quad (2\text{nd order upwind})
\end{align*}
\]

Compute fluxes, use increments over cell average:

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

Demo: Finite Volume Burgers [cleared] (Part II)
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: $u_{\ell+1} = u_\ell + \partial_t u_\ell \cdot h_t + \partial^2_t u_\ell \cdot h_t/2 + O(h^3_t)$.

<table>
<thead>
<tr>
<th>$u_t$</th>
<th>$-f(u)_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_{tt}$</td>
<td>$-(f(u)_t)_x = -(f'(u)u_t)_x = (f'(u)f(u)_x)_x$.</td>
</tr>
</tbody>
</table>

$$\frac{u_{j,\ell+1} - u_{j,\ell}}{h_t} + \frac{f(u_{j+1,\ell}) - f(u_{j-1,\ell})}{2h_x}$$

$$= \frac{h_t}{2h_x} \left[ f'(u_{j+1/2,\ell}) \frac{f(u_{j+1,\ell}) - f(u_{j,\ell})}{h_x} - f'(u_{j-1/2,\ell}) \frac{f(u_{j,\ell}) - f(u_{j-1,\ell})}{h_x} \right]$$

As a Riemann solver:

$$f^*(u^-, u^+) = \frac{f(u^-) + f(u^+)}{2} - \frac{h_t}{h_x} [f'(u^o)(f(u^+) - f(u^-))].$$
Monotone Schemes

Definition (Monotone Scheme)

A scheme

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

is called a monotone 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?

If \( f^*(\uparrow, \downarrow) \), then \( G(\uparrow, ?, \uparrow) \). To clean up the second argument, consider

\[ \frac{\partial G}{\partial u_j} = 1 - \lambda[f_1^* - f_2^*] \geq 0. \]

(The subscripts indicate partial derivatives with respect to the first and second argument.)

If \( \lambda(f_1^* - f_2^*) \leq 1 \), then \( G(\uparrow, \uparrow, \uparrow) \).

Note: Also obtain a time-step restriction.
Lax-Friedrichs is Monotone

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

Show: This is monotone.

Let \( \alpha = \max_u |f'(u)|. \)

\[ f_1^* = \frac{1}{2}[f'(u_j) + \alpha] \geq 0, \]

\[ f_2^* = \frac{1}{2}[f'(u_{j+1}) - \alpha] \leq 0. \]

So \( f^*(\uparrow, \downarrow). \) Assume \( h_t \) is chosen small enough so that \( \lambda(f_1^* - f_2^*) \leq 1 \) is satisfied.
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?

Maybe relax this condition? Maybe only ask for TVD?
Linear Schemes

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 \( u_t + u_x = 0 \):

\[
 u_{j,\ell+1} = \sum_{k=-K}^{K} c_k(\lambda) u_{j-k,\ell},
\]

where \( c_k(\lambda) \) are constants which may depend on \( \lambda = h_t/h_x \). Such a linear scheme is monotone iff \( c_k(\lambda) \geq 0 \) for all \( k \).

Also called positive schemes.
Linearity + TVD = ?

**Theorem (TVD for Linear Schemes)**

For linear schemes, TVD $\Rightarrow$ monotone.

What does that mean?

Linear TVD schemes are at most first order accurate.

Now what?

Not all bad: Implies that nonlinear TVD schemes at least stand a chance.
Harten’s Lemma

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 \( \lambda = h_t/h_x \), 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

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

\[
= \Delta_{+} \bar{u}_{j, \ell} + \lambda \left( C_{j+3/2} \Delta_{+} \bar{u}_{j+1} - D_{j+1/2} \Delta_{+} \bar{u}_{j} \right)
\]

\[
= \Delta_{+} \bar{u}_{j, \ell} + \lambda \left( C_{j+3/2} \Delta_{+} \bar{u}_{j+1} + \lambda C_{j+3/2} \Delta_{+} \bar{u}_{j+1} + \lambda D_{j-1/2} \Delta_{-} \bar{u}_{j} \right)
\]

\[
|\Delta_{+} \bar{u}_{j, \ell+1}| \leq \left[ 1 - \lambda \left( C_{j+1/2} + D_{j+1/2} \right) \right] |\Delta_{+} \bar{u}_{j}|
\]

\[
+ \lambda C_{j+3/2} |\Delta_{+} \bar{u}_{j+1}| + \lambda D_{j-1/2} |\Delta_{-} \bar{u}_{j}|.
\]

\[
\text{TV}(\bar{u}_{\ell+1}) = \sum_{j} |\Delta_{+} \bar{u}_{j, \ell+1}| \leq \sum_{j} \left[ 1 - \lambda \left( C_{j+1/2} + D_{j+1/2} \right) \right] |\Delta_{+} \bar{u}_{j}| \leq \text{TV}(u_{\ell}).
\]
Minmod Scheme

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

$$f_{j+1/2}^{*,(1)} = f\left(\bar{u}_j + \frac{1}{2}(\bar{u}_{j+1} - \bar{u}_j)\right), \quad f_{j+1/2}^{*,(2)} = f\left(\bar{u}_j + \frac{1}{2}(\bar{u}_j - \bar{u}_{j-1})\right).$$

Design a ‘safe’ thing to use for $\tilde{u}$:

$$\minmod(a, b) := \begin{cases} 
  a & |a| < |b|, \ ab > 0, \\
  b & |b| < |a|, \ ab > 0, \\
  0 & ab \leq 0,
\end{cases} \quad \tilde{u}_j := \minmod(\tilde{u}_j^{(1)}, \tilde{u}_j^{(2)}).$$

Intuition: TV growth driven by local extrema
→ if slopes have different signs, revert to first order.

Then consider $f_{j+1/2}^{*,(3)} = f(\bar{u}_j + \tilde{u}_j)$. Called a slope limiter.
Minmod is TVD

Show that Minmod is TVD:

Rewrite

$$\bar{u}_{j,\ell+1} = \bar{u}_j - \lambda [f(\bar{u}_j + \tilde{u}_j) - f(\bar{u}_{j-1} + \tilde{u}_{j-1})] = \bar{u}_j - \lambda [-D_{j-1/2} \Delta_- \bar{u}_j],$$

with

$$D_{j-1/2} = \frac{f(\bar{u}_j + \tilde{u}_j) - f(\bar{u}_{j-1} + \tilde{u}_{j-1})}{\bar{u}_j - \bar{u}_{j-1}} = f'(\xi) \frac{\tilde{u}_j - \tilde{u}_{j-1} + \bar{u}_j - \bar{u}_{j-1}}{\tilde{u}_j - \tilde{u}_{j-1}}$$

$$= f'(\xi) \begin{bmatrix} 1 + \frac{\tilde{u}_j}{\bar{u}_j - \bar{u}_{j-1}} & - \frac{\tilde{u}_{j-1}}{\bar{u}_j - \bar{u}_{j-1}} \\ 0 \leq \cdot \leq \frac{1}{2} & 0 \leq \cdot \leq \frac{1}{2} \end{bmatrix} \geq 0.$$
Minmod: CFL restriction?

Derive a time step restriction for Minmod.

\[ D_{j-1/2} \leq \frac{3}{2} f'(\xi) \leq \frac{3}{2} \max_u |f'(u)|. \]

Plugging this into the Harten CFL bound gives:

\[ 1 - \lambda D_{j-1/2} \geq 1 - \frac{3}{2} \lambda \max_u |f'(u)| \geq 0 \iff \lambda \max |f'(\xi)| \leq \frac{2}{3}. \]
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?

Use: TV is convex. \( TV(\alpha u + (1-\alpha)v) \leq \alpha TV(u) + (1-\alpha) TV(v) \).

\[
TV(u_{\ell+1}) = TV \left( \frac{u_\ell}{2} + \frac{1}{2}(u^{(1)} + h_t L(u^{(1)})) \right) \\
\leq \frac{1}{2} TV(u_\ell) + \frac{1}{2} TV(u^{(1)} + h_t L(u^{(1)})) \\
\leq \frac{1}{2} TV(u_\ell) + \frac{1}{2} TV(u^{(1)}) \\
\leq \frac{1}{2} TV(u_\ell) + \frac{1}{2} TV(u_\ell) = TV(u_\ell).
\]

General idea: time steppers out of convex comb. of Fw Euler.

(\text{SSP / Strong-Stability Preserving Schemes}) Above: SSPRK(2,2)
Total Variation is Convex

Show: TV(·) is a convex functional.

With $0 \leq \alpha \leq 1$:

\[
\begin{align*}
\text{TV}(\alpha u + (1 - \alpha)v) & \\
& \leq \sum_j |\alpha(u_j - u_{j-1}) + (1 - \alpha)(v_j - v_{j-1})| \\
& \leq \sum_j \alpha|u_j - u_{j-1}| + (1 - \alpha)|v_j - v_{j-1}| \\
& = \alpha \text{TV}(u) + (1 - \alpha) \text{TV}(v).
\end{align*}
\]
TVD and High Order

Can TVD schemes be high order everywhere? (aside from near shocks)

Consider \( u_t + u_x = 0 \).

The solution has an error of \( h_x^2 \), which means the approximation to the derivative has error \( h_x \): first order. [Osher/Chakravarthy ‘84]
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]
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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, $A \in \mathbb{R}^{m \times m}$:

$$u_t + Au_x = 0,$$
$$u(x, 0) = u_0(x).$$

Assumptions on $A$?

System is hyperbolic [cf. Loret ‘08] if $A$ is diagonalizable with real eigenvalues.

Let $Ar_p = \lambda_p r_p$ ($p = 1, \ldots, m$). Called strictly hyperbolic if the eigenvalues are distinct. $AR = R\Lambda$.

Substitution $v = R^{-1}u$ attains $v_t + \Lambda v_x = 0$, called characteristic variables.

Recall: Rewrote wave equation in this form early on.
Linear System Solution

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

Write down the solution.

\[ u(x, t) = \sum_p r_p v_p(x - \lambda_p t, 0), \]

where

\[ \mathbf{v}(x, 0) = R^{-1} \mathbf{u}(x, 0). \]

What is the impact on boundary conditions? E.g. \((\lambda_p) = (-c, 0, c)\) for a BC at \(x = 0\) for \([0, 1]\)?

Can only impose BCs on incoming waves! E.g. only one BC (on \(v_3\)) at \(x = 0\).
Consider system $u_t + f(u)_x = 0$. Write in quasilinear form:

$$u_t + A(u)u_x = 0 \quad \text{with} \quad A(u) = J_f(u).$$

When hyperbolic?

A diagonalizable w/real eigenvalues. “Strictly” hyperbolic for distinct eigenvalues. Both now local properties.
What about characteristics/shock speeds?

- By considering eigenstates: can still define characteristics. $m$ characteristics through each point.
- Characteristic locations no longer obey an ODE.

Are values of $u$ still constant along characteristics?

No, only the coefficients of the eigenstates are constant along characteristics, and only locally.
Shocks and Riemann Problems for Systems

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

Solution? (Assume strict hyperbolicity with \( \lambda_1 < \lambda_2 < \cdots < \lambda_m \).)

\[ u_l = \sum_{p=1}^{m} \alpha_p r_p, \quad u_r = \sum_{p=1}^{m} \beta_p r_p. \]

Then \( v_p(x, 0) = \begin{cases} \alpha_p & x < 0, \\ \beta_p & x > 0. \end{cases} \)

Let \( P(x, t) \) be the maximum value of \( p \) for which \( x - \lambda_p t > 0 \), then

\[ u(x, t) = \sum_{p=1}^{P(x,t)} \beta_p r_p + \sum_{p=P(x,t)+1}^{m} \alpha_p r_p. \]
What does the solution look like?

Fan of values constant between each characteristic.

Jump across the characteristic associated with $\lambda_p$?

$$[u] = (\beta_p - \alpha_p)r_p.$$
Do those jumps satisfy Rankine-Hugoniot?

\[ \mathbf{f} = A[u] = (\beta_p - \alpha_p)Ar_p = \lambda_p[u], \]

where \( \lambda_p \) is the propagation speed of the jump.

How can we find intermediate values of \( u \)?

“Split up” the jump into a sum of jumps:

\[ u_r - u_l = (\beta_1 - \alpha_1)r_1 + \cdots + (\beta_m - \alpha_m)r_m. \]

Use Rankine-Hugoniot as a constraint.
This works much the same way in the nonlinear case.
Two Dimensions

\[ u_t + f(u)_x + g(u)_y = 0. \] Finite volume methods generalize in principle:

\[
\frac{d\bar{u}_{ij}(t)}{dt} + \frac{1}{h^2} \int_{y_{j-1/2}}^{y_{j+1/2}} f(u(x_{i+1/2}, y, t)) - f(u(x_{i-1/2}, y, t)) \, dy \\
+ \frac{1}{h^2} \int_{x_{i-1/2}}^{x_{i+1/2}} g(u(x, y_{j+1/2}, t)) - g(u(x, y_{j-1/2}, t)) \, dx
\]

Downside: Stencil full \((n \times n)\), not star-shaped (cf. FD)

However:

- If a method is TVD in two dimensions, it is at most first order accurate except in trivial cases. [Goodman/Leveque ‘85].
- The ‘reconstruction’ idea in complex geometry can become computationally expensive at high order.

Later: discontinuous Galerkin (DG) for high order with c. laws.
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Discontinuous Galerkin Methods for Hyperbolic Problems
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Discontinuous Galerkin Methods for Hyperbolic Problems
Function Spaces

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?

\( f_n \) continuous, step function not. Want: limits that preserve smoothness properties. Limits defined by norms.
**Definition (Norm)**

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)

\( x_n \to x :\Leftrightarrow \|x_n - x\| \to 0 \) (convergence in norm)

Definition (Cauchy Sequence)

For all \( \epsilon > 0 \) there exists an \( n \) for which \( \|x_\nu - x_\mu\| \leq \epsilon \) for \( \mu, \nu \geq n \).
Banach Spaces

Definition (Complete/“Banach” space)

Cauchy $\Rightarrow$ Convergent

What’s special about Cauchy sequences?

Limits appear out of thin air. Can be used to construct things.

Counterexamples?

- $\mathbb{Q}$ with absolute value
- $C^0$ with $L^2$ norm
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?

$f(x) = 1/x$ clearly satisfies $f \in C^0(\Omega)$, but its norm is unbounded, so $\|\cdot\|_\infty$ is not a norm on this space.

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

Assume $(f_i)_i$ is Cauchy.

- For each $x$, $(f_i(x))_i$ is Cauchy, so a pointwise limit exists. Call that $f$.

- Let $\varepsilon > 0$. There exists $N$ so that $|f_n(x) - f_m(x)| < \varepsilon$ for all $n, m \geq N$ and $x \in \bar{\Omega}$. Taking the limit $m \to \infty$ yields $|f_n(x) - f(x)| < \varepsilon$, i.e. uniform convergence, forcing $f$ to be continuous.
**$C^m$ Spaces**

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

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

$$D^k f = \frac{\partial^{\lvert k \rvert}}{\partial x_1^{k_1} \cdots \partial x_n^{k_n}}, \quad \lvert k \rvert = k_1 + \cdots + k_n.$$ 

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

$$C^m(\Omega) = \left\{ f \in C^0(\Omega) : D^k f \in C^0 \text{ for all } k \text{ with } \lvert k \rvert \leq m \right\},$$

$$C^\infty(\Omega) = \left\{ f \in C^0(\Omega) : D^k f \in C^0(\Omega) \text{ for all } k \right\},$$

$$C^m_0(\Omega) = \left\{ f \in C^m(\Omega) : f \text{ has compact support} \right\},$$

where compact support means that there is a compact (closed and bounded) set $S \subset \Omega$ for which $f(x) = 0$ if $x \notin S$. 
$L^p$ 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 $\langle \cdot, \cdot \rangle : V \times V \rightarrow \mathbb{R}$ such that for any $f, g, h \in V$ and $\alpha \in \mathbb{R}$

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

**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)**

Let $M \subseteq V$ be a closed subspace of a Hilbert space $V$. For any $u \in V$ there exists a unique $v \in M$ such that $u = v + w$ with $w \in M^\perp$.

$M^\perp = \{ w \in V : \langle z, w \rangle_V = 0 \text{ for all } z \in M \}$. 
Weak Derivatives

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

$$L^1_{\text{loc}}(\Omega) = \left\{ u : (u : \mathbb{R} \to \mathbb{R}) \text{ measurable,} \right.$$  
$$\left. \int_{\Omega} |u(x)\varphi(x)| \, dx < \infty \text{ for every } \varphi \in C^\infty_0(\Omega) \right\}$$

**Definition (Weak Derivative)**

$\nu \in L^1_{\text{loc}}(\Omega)$ is the weak partial derivative of $u \in L^1_{\text{loc}}(\Omega)$ of multi-index order $k$ if

$$\int_{\Omega} \nu \varphi \, dx = (-1)^{|k|} \int_{\Omega} uD^k \varphi \, dx \quad \text{for all } \varphi \in C^\infty_0(\Omega).$$

In this case, $D^k_{\text{w}} u := \nu$. 
Weak Derivatives: Examples (1/2)

Consider all these on the interval $[-1, 1]$.

$$f_1(x) = 4(1 - x)x$$

$$D_w f_1(x) = 4 - 8x.$$ For ("strongly") differentiable functions, weak and strong derivatives coincide.

$$f_2(x) = \begin{cases} 2x & x \leq 1/2, \\ 2 - 2x & x > 1/2. \end{cases}$$

"Kinks" in the function are allowed (but jumps are not):

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

$$f_3(x) = \sqrt{\frac{1}{2}} - \sqrt{|x - 1/2|}$$

Even cusps are allowed:

$$D_w f_3(x) = \begin{cases} 
\frac{1}{2\sqrt{1/2-x}} & x < 1/2, \\
-\frac{1}{2\sqrt{x-1/2}} & x > 1/2.
\end{cases}$$
Sobolev Spaces

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

**Definition ((k, p)-Sobolev Norm/Space)**

\[
\|u\|_{k,p} := \sqrt[p]{\sum_{|\alpha| \leq k} \|D^\alpha_w u\|_p^p},
\]

\[
|u|_{k,p} := \sqrt[p]{\sum_{|\alpha| = k} \|D^\alpha_w u\|_p^p}.
\]

\[
\mathcal{W}^{k,p}(\Omega) := \left\{ u : (u : \Omega \rightarrow \mathbb{R}), \|u\|_{k,p} < \infty \right\}.
\]
More Sobolev Spaces

$W^{0,2}?$

Equal to $L^2$.

$W^{s,2}?$

Also called $H^s$, a Hilbert space, with an induced norm. From what scalar product?

$H^1_0(\Omega)?$  

Closure of the space $C_0^\infty(\Omega)$ under $\|u\|_{k,p}$.  
The Sobolev way of saying zero on the boundary.
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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 $ab$):

$$\int_{\Omega} \nabla a \cdot b + \int_{\Omega} a \nabla \cdot b = \int_{\Omega} \nabla \cdot (ab) = \int_{\partial \Omega} \hat{n} \cdot (ab).$$

Weak form?

Multiply by test function $v \in V$, integrate by parts:

$$\int_{\Omega} \nabla u \cdot \nabla v - \int_{\partial \Omega} \hat{n} \cdot (v \nabla u) + \int_{\Omega} uv = \int_{\Omega} fv.$$
Motivation: Bilinear Forms and Functionals

\[ \int_{\Omega} \nabla u \cdot \nabla v + \int_{\Omega} uv = \int_{\Omega} fv. \]

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:

\[
\begin{align*}
a(u, v) &= \langle \nabla u, \nabla v \rangle + \langle u, v \rangle, \\
g(v) &= \langle f, v \rangle,
\end{align*}
\]

where \( \langle \cdot, \cdot \rangle \) is the \( L^2 \) inner product. Then the weak form is equivalent to

\[ a(u, v) = f(v) \quad \text{for all } v \in V. \]

This motivates further study of Hilbert spaces and objects in them.
**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 (\(\iff\) 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

\[
\|g\|_{V'} = \sup_{v \in V \setminus \{0\}} \frac{|g(v)|}{\|v\|_V}.
\]
Functionals in the Model Problem

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

Must use same space as rest of problem: \( H^1(\Omega) \).

\[
\|g\|_{V'} = \sup_{v \in H^1 \setminus \{0\}} \frac{|\langle f, v \rangle_{L^2}|}{\|v\|_{H^1}} \leq \frac{\|f\|_{L^2} \|v\|_{L^2}}{\|v\|_{L^2} + \|Dw v\|_{L^2}} \leq \frac{\|f\|_{L^2} \|v\|_{L^2}}{\|v\|_{L^2}} = \|f\|_{L^2}
\]

using Cauchy-Schwarz. Find: \( f \in L^2 \) leads to bounded \( g \) in \( H^1 \).

That bound felt loose and wasteful. Can we do better?

Define negative-index Sobolev norms:

\[
\|f\|_{H^{-1}} = \sup_{v \in H^1(\Omega) \setminus \{0\}} \frac{|\langle f, v \rangle_{L^2}|}{\|v\|_{H^1}}.
\]

Bound (by definition) \( |g(v)| \leq \|f\|_{H^{-1}} \|v\|_{H^1} \). Allows \( f \in H^{-1} \).
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 $v \in V$.

Let $g \in V'$. $N(\cdot)$ below represents the nullspace.

**Case 1.** $N(g) = V$. $u = 0$ works, unique by scalar product axioms.

**Case 2.** $N(g) \neq V$. Let $w \in N(g)^\perp \setminus \{0\}$. Let $\alpha = g(w) \neq 0$.

$$g \left( \frac{g(v)}{\alpha} w \right) = \frac{g(v)}{\alpha} g(w) = g(v) \quad \text{for all } v \in V.$$

Let $v \in V$ be arbitrary, and let $z := v - (g(v)/\alpha)w$. (Feel reminded of Gram-Schmidt?) Then $g(z) = g(v) - g(v) = 0$, i.e. $z \in N(g)$, i.e. $\langle z, w \rangle_V = 0$ since $w \in N(g)^\perp$. 

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Riesz Representation Theorem: Proof (2/3)

Have $w \in N(g) \perp \{0\}$, $\alpha = g(w) \neq 0$, and $z := v - (g(v)/\alpha)w$ \perp w.

$$0 = \left< v - \frac{g(v)}{\alpha}w, w \right> \iff \left< \frac{g(v)}{\alpha}w, w \right> = \left< v, w \right> \quad \text{for all } v \in V.$$ 

Multiplying by $\alpha/\left< w, w \right>$ yields

$$g(v) = \left< v, \frac{g(w)}{\left< w, w \right> V} w \right>.$$
Uniqueness of $u$?

Suppose we have two: $u$ and $\hat{u}$ so that

$$g(v) = \langle u, v \rangle = \langle \hat{u}, v \rangle \quad \Rightarrow \quad \langle u - \hat{u}, v \rangle = 0 \quad \text{for all} \quad v \in V,$$

Plugging in $v = u - \hat{u}$ yields $u - \hat{u} = 0$ by the properties of the inner product.
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?

In this particular case, observe that \( a(u, v) = \langle u, v \rangle_{H^1} \). By the Riesz Representation theorem and knowing that \( g \) is a bounded linear functional in \( H^1 \), we know that there exists a unique \( u \) so that

\[ a(u, v) = \langle u, v \rangle_{H^1} = g(v). \]
Poisson

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

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

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

Weak form?

\[
\int_{\Omega} \nabla u \cdot \nabla vdx = \int_{\Omega} f(x)v(x)dx \quad \text{for all} \ v \in V.
\]

We know that $g$ is a bounded linear functional in $H^1_0$, but $a(u, v)$ is no longer identical to our inner product. Maybe we can come up with some conditions that make $a$ ‘sufficiently similar’ to an inner product?
Ellipticity

Let $V$ be Hilbert space.

**$V$-Ellipticity**

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

$$c_0 \|u\|_V^2 \leq a(u, u) \quad \text{for all } u \in V,$$

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

$$|a(u, v)| \leq c_1 \|u\|_V \|v\|_V \quad \text{for all } u, v \in V.$$

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 $v \in V$.

$a$ defines an inner product $\langle u, v \rangle_a = a(u, v)$ on $V$, with linearity and symmetry trivial, and:

- Show $a(u, u) \geq 0$.
  
  $a(u, u) \geq c_0 \|u\|^2_V \geq 0$ by coercivity,

- Show $a(u, u) = 0 \Rightarrow u = 0$.
  
  $0 = a(u, u) \geq c_0 \|u\|^2_V \geq 0$, i.e. $\|u\|_V = 0$, i.e. $u = 0$.

From the Riesz representation theorem, there exists a unique $u \in V$ so that $a(u, v) = \langle u, v \rangle_a = g(v)$.
Can we declare victory for Poisson?

**Continuity of \( a \) holds:**

\[
\left| \int_{\Omega} \nabla u \cdot \nabla v \, dx \right| = |\langle \nabla u, \nabla v \rangle_{L^2}| \leq \| \nabla u \|_{L^2} \| \nabla v \|_{L^2} \leq \| u \|_{H^1} \| v \|_{H^1}.
\]

However coercivity is less clear:

\[
\int_{\Omega} \nabla u \cdot \nabla u \, dx \geq c_1 \left( \int_{\Omega} \nabla u \cdot \nabla u \, dx + \int_{\Omega} u^2 \, dx \right).
\]

Can this inequality hold in general, without further assumptions?

No: a constant would violate it.
Poincaré-Friedrichs Inequality (1/3)

**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

$$\|u\|_{L^2} \leq C \|\nabla u\|_{L^2}.$$ 

Outline: Helpful identity, result in $C_0^\infty(\Omega)$, result in $H^1_0(\Omega)$.

A helpful identity. For $u \in C_0^\infty(\Omega)$,

$$\nabla \cdot (u^2 \mathbf{x}) = \partial_{x_1} (u^2 x_1) + \cdots + \partial_{x_n} (u^2 x_n)$$

$$= u^2 + 2(u \partial_{x_1} u)x_1 + \cdots + u^2 + 2(u \partial_{x_n} u)x_n$$

$$= nu^2 + 2u(\nabla u \cdot \mathbf{x}).$$

$$\Rightarrow u^2 = \frac{1}{n} \nabla \cdot (u^2 \mathbf{x}) - \frac{2}{n} u(\nabla u \cdot \mathbf{x}).$$
Poincaré-Friedrichs Inequality (2/3)

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

\[
\|u\|_{L^2}^2 = \int_\Omega u^2 \, dx = \int_\Omega \frac{1}{n} \nabla \cdot (u^2 x) - \frac{2}{n} u(\nabla u \cdot x) \, dx
\]

\[
= \frac{1}{n} \int_{\partial \Omega} \hat{n} \cdot (u^2 x) \, ds_x - \frac{2}{n} \int_\Omega u(\nabla u \cdot x) \, dx
\]

\[
\leq \frac{2}{n} \max_{x \in \Omega} |x| \int_\Omega |u \nabla u| \, dx \leq \frac{2}{n} \max_{x \in \Omega} |x| \|u\|_{L^2} \|\nabla u\|_{L^2}
\]

\[
\Rightarrow \|u\|_{L^2} \leq \frac{2}{n} \max_{x \in \Omega} |x| \|\nabla u\|_{L^2} \cdot C.
\]
Prove the result in $H_0^1(\Omega)$.

Let $u \in H_0^1(\Omega)$. Since $C_0^\infty(\Omega)$ is dense in $H_0^1(\Omega)$, let $(u_k) \subset C_0^\infty$. Then the inequality holds for each $u_k$, and $\|u_k\|_{L^2} \rightarrow \|u\|_{L^2}$ and $\|\nabla u_k\|_{L^2} \rightarrow \|\nabla u\|_{L^2}$.
Show that the Poisson bilinear form is coercive.

\[ \frac{1}{C^2 + 1} \| u \|^2_{H^1(\Omega)} = \frac{1}{C^2 + 1} \left( \| u \|^2_{L^2(\Omega)} + \| \nabla u \|^2_{L^2} \right) \leq \| \nabla u \|^2_{L^2} = a(u, u) \]

Draw a conclusion on Poisson:

Because of coercivity and continuity of \( a \), the Poisson weak form admits a unique solution in \( H^1_0(\Omega) \).
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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?

Considered: Weak form \( a(u, v) = g(v) \) for all \( v \in V \subseteq H \), where \( H \) is a Hilbert space. (Think of \( V \) as \( H_0^1 \) for example.)

Idea: Choose a finite-dimensional subspace \( V_h \subset V \), find a solution \( u_h \in V_h \) to the weak-form problem

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

This is called Ritz-Galerkin 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?

Observe that the ‘continuous’ weak form also allows \( v_h \) to be plugged in:

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

Subtracting the two leads to Galerkin Orthogonality:

\[ a(u_h - u, v_h) = 0 \quad \text{for all } v_h \in V_h, \]

i.e. using \( a(\cdot, \cdot) \) as a (sort of) inner product, the error \( u - u_h \) is orthogonal to the space of test functions.
Céa’s Lemma

Let $V \subset H$ be a closed subspace of a Hilbert space $H$.

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

$$\|u - u_h\|_V \leq \frac{c_1}{c_0} \inf_{v_h \in V_h} \|u - v_h\|_V.$$
Céa’s Lemma: Proof

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

For any $v_h \in V_h$,

$$
c_0 \| u - u_h \|^2_V \leq a(u - u_h, u - u_h) \quad \text{(coercivity)}
= a(u - u_h, u - v_h) + a(u - u_h, v_h - u_h)
= a(u - u_h, u - v_h) \quad \text{(Galerkin orth.)}
\leq c_1 \| u - u_h \|_V \| u - v_h \|_V.
$$

Dividing by $\| u - u_h \|_V$ completes the proof.
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 $C(\Omega, a, s)$,

$$\|u\|_{H^s} \leq C(\Omega, a, s) \|f\|_{H^{s-2m}}.$$ 

Theorem (Elliptic Regularity (cf. Braess Thm. 7.2))
Let $a$ be a $H^1_0$-elliptic bilinear form with sufficiently smooth coefficient functions.

- If $\Omega$ is convex, then then Dirichlet problem is $H^2$ regular.
- Let $s \geq 2$. If $\partial \Omega$ is $C^s$, the Dirichlet problem is $H^s$ regular.
Elliptic Regularity: Counterexamples

Are the conditions on the boundary essential for elliptic regularity?

Consider \( \Delta u = 0 \), \( u(e^{i\phi}) = \sin(2/3\phi) \), \( u = 0 \) elsewhere.

- \( u(z) = \text{Im}(z^{2/3}) \) with \( z = x + iy \in \mathbb{C} \).
- Derivative: \( (2/3)z^{-1/3} \): unbounded \( \Rightarrow u \notin H^2 \!\).  

Are there any particular concerns for mixed boundary conditions?

Homogeneous Neumann on dashed line with (e.g.) left half, Dirichlet elsewhere.

- Solution could be found by solving on whole domain using reflected Dirichlet BCs.
- Reentrant corner \( \Rightarrow u \notin H^2 \) (in gen.)
Estimating the Error in the Energy Norm

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

\[
\|u - u_h\|_{H^1} \leq C \inf_{v_h \in V_h} \|u - v_h\|_{H^1} \leq C \|u - I_h u\|_{H^1} \\
\quad \leq C_1 h \|u\|_{H^2} \leq c_2 h \|f\|_{L^2}.
\]

What’s still to do?

▶ we still need to figure out what $V_h$ will be,
▶ $I_h$ is some interpolation operator that we will define more precisely later, and
▶ we need to worry about the interpolation error bound (“TBD”)
▶ Finally, $H^1$ is kind of a weird norm. Can we get an error estimate in $L^2$?
$L^2$ 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 $V \to H$ be continuous. Then we have for the finite element solution $u \in V_h \subset V$:

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

if with every $g \in H$ we associate the unique (weak) solution $\varphi_g$ of the equation (also called the dual problem)

$$a(w, \varphi_g) = \langle g, w \rangle \text{ for all } w \in V,$$
The norm of an element in a Hilbert space can be determined via the scalar product: 

\[ \| w \|_H = \sup_{g \in H} \frac{\langle g, w \rangle}{\| g \|_H}. \]

\[ \langle g, u - u_h \rangle = a(u - u_h, \varphi_g) = a(u - u_h, \varphi_g - v_h) \]

\[ \leq \text{cont. } a \| u - u_h \|_V \| \varphi_g - v_h \|_V. \]

Since this argument is valid for any \( v_h \in V_h \), we obtain

\[ \langle g, u - u_h \rangle \leq c_1 \| u - u_h \|_V \inf_{v_h \in V_h} \| \varphi_g - v_h \|_V. \]

Plugging into the norm relationship yields

\[ \| u - u_h \|_H = \sup_{g \in H} \frac{\langle g, w \rangle}{\| g \|_H} \leq c_1 \| u - u_h \|_V \sup_{g \in H} \left[ \frac{1}{\| g \|_H} \inf_{v_h \in V_h} \| \varphi_g - v_h \|_V \right]. \]
\( L^2 \) 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?

As before (e.g. Poisson: symmetry of \( a \): **primal** prob. = **dual** prob.):

\[
\inf_{v_h \in V_h} \| \varphi_g - v_h \|_{H^1} \leq C \| \varphi_g - I_h \varphi_g \|_{H^1} \leq C_1 h \| \varphi_g \|_{H^2} \leq c_2 h \| g \|_{L^2}.
\]

So \( \| u - u_h \|_{L^2} \leq Ch \| u - u_h \|_{H^1}. \)

So does Aubin-Nitsche give us an \( L^2 \) estimate?

Had (aside from missing pieces): \( \| u - u_h \|_{H^1} \leq c_2 h \| f \|_{L^2}. \)

If we have \( f \in L^2(\Omega) \) and hence \( u \in H^2(\Omega) \) (**\( H^2 \) regularity), then

\[
\| u - u_h \|_{L^2} \leq Ch^2 \| f \|_{L^2}.
\]
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Discontinuous Galerkin Methods for Hyperbolic Problems
Finite Elements in 1D: Discrete Form

\[ \Omega := [\alpha, \beta]. \]
Look for \( u \in H^1_0(\Omega) \), so that \( a(u, \varphi) = \langle f, \varphi \rangle \) for all \( \varphi \in H^1_0(\Omega) \). Choose \( V_h = \text{span}\{\varphi_1, \ldots, \varphi_n\} \) and expand
\[ u_h = \sum_{i=1}^{n} u^i_h \varphi_i \in V_h. \]
Find the discrete system.

\[
a \left( \sum_{i=1}^{n} u^i_h \varphi_i, \varphi \right) = \langle f, \varphi \rangle \quad \text{for all } \varphi \in V_h,
\]

We may as well choose the basis \( (\varphi_i) \) to represent \( \varphi \in V_h \):

\[
a \left( \sum_{i=1}^{n} u^i_h \varphi_i, \varphi_j \right) = \langle f, \varphi_j \rangle \quad \text{for all } j \in \{1, \ldots, n\}.
\]

This could lead to a linear system \( Au = b \), where \( A = \{a_{i,j}\} \in \mathbb{R}^{n\times n} \) with \( a_{i,j} = a(\varphi_i, \varphi_j) \), \( u = \{u^i_h\} \), \( b_j = \langle f, \varphi_j \rangle \), but we choose not to go this route.
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 \( h := \max_i h_i \).

For \( i \in \{0, \ldots, N + 1\} \), let

\[
\varphi_i(x) := \begin{cases} 
\frac{1}{h_{i-1}}(x - x_{i-1}) & x \in l_{i-1}, \\
\frac{1}{h_i}(x_{i+1} - x) & x \in l_i, \\
0 & \text{otherwise}
\end{cases} \in P_{h}^1.
\]

Observe: The set \( \{\varphi_i\}_i \) forms a basis of \( P_{h}^1 \).
Degrees of Freedom and Matrices

Define something more general than basis coefficients to solve for.

▶ For \( i \in \{0, \ldots, N + 1\} \), let \( \gamma_i : C(\bar{\Omega}) \to \mathbb{R} \).

Here: \( v \mapsto \gamma_i(v) := v(x_i) \in \mathbb{R} \).

Generally: could be derivatives etc. (cf. splines).

▶ \( \{\gamma_i\}_{i=0}^{N+1} \) are global degrees of freedom in \( P_h^1 \).

▶ \( \{\gamma_i\}_{i=0}^{N+1} \) forms a basis of the dual space \( (P_h^1)' \).

(i.e. uniquely determine \( \varphi \in V_h \), global unisolvence)

Define shape functions and assemble the stiffness matrix:

Shape functions \( \hat{\varphi} \in V_h \) satisfy \( \gamma_j(\hat{\varphi}_i) = \delta_{i,j} \) for \( i, j \in \{0, \ldots, N + 1\} \).

\[
a(u_h, \hat{\varphi}_i) = \langle f, \varphi_i \rangle \iff \sum_{j=1}^{N} \underbrace{\gamma_j(u_h)}_{=u_h^i} \underbrace{a(\hat{\varphi}_j, \hat{\varphi}_i)}_{(A_h)_{i,j}} = \langle f, \varphi_i \rangle \quad (j = 1, \ldots, N)
\]

\[
(A_h)_{i,j} = \langle f, \varphi_j \rangle \\
(b_h)_i = \langle f, \varphi_i \rangle
\]
A Matrix Property for Efficiency

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

Anything special about the matrix?

Only \(a_{i,i}, a_{i,i+1}, a_{i,i-1} \neq 0\) in the \(i\)th row of \(A\) is nonzero. Sparse.
Error Estimation

According to Céa, what's our main missing piece in error estimation now?

An interpolation operator

$$I_h^1 : C^0(\bar{\Omega}) \rightarrow P_h^1,$$

$$v \mapsto \sum_{i=0}^{N+1} \gamma_i(v) \hat{\phi}_i \in P_h^1.$$

Next: need to estimate its accuracy.
Interpolation Error (1D-only)

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

$$
\| v - I_h^1 v \|_{L^2} \leq h^2 |v|_{H^2} \quad \text{for all } h > 0,
$$

$$
| (v - I_h^1 v) |_{H^1} \leq h |v|_{H^2} \quad \text{for all } h > 0.
$$

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

$$
\| v - I_h^1 v \|_{L^2} \leq h |v|_{H^1} \quad \text{for all } h > 0,
$$

$$
\lim_{h \to 0} | (v - I_h^1 v) |_{H^1} = 0.
$$

Is $I_h^1$ defined for $v \in H^2$? for $v \in H^1 \setminus H^2$?

Depends on the dimension $n$ and the domain $\Omega$. Need to consider the Sobolev Embedding Theorem.
Interpolation Error: Towards an Estimate

Provide an \textit{a-priori} estimate.

\[
\| u - u_h \|_{H^1} \leq \frac{c_1}{c_0} \inf_{v_h \in P_h^1} \| u - v_h \|_{H^1} \leq \frac{c_1}{c_0} \| u - l_h^1 u \|_{H^1} \leq \frac{c_1}{c_0} h |u|_{H^2}.
\]

What’s the relationship between \( l_h^1 u \) and \( u_h \)?

None!
Is there a simple way of constructing the polynomial basis?

The basis functions \( \{ \phi_i \}_{i=1}^N \) can be viewed as a composition of:

- grid-independent reference basis functions on a reference element, and
- geometric transformations from the reference element to the grid.
Construct a polynomial basis using this approach.

Let $\hat{\kappa} = [0, 1]$ be the reference interval and consider the affine transformations $T_i : \hat{x} \in \hat{\kappa} \mapsto x = x_i + \hat{x} h_i$ for $i \in \{0, \ldots, N\}$. Define the shape functions

\[ \hat{\varphi}_0(\hat{x}) := 1 - \hat{x} \quad \text{for all } \hat{x} \in \hat{\kappa}, \]
\[ \hat{\varphi}_1(\hat{x}) := \hat{x} \quad \text{for all } \hat{x} \in \kappa. \]

These functions form a basis of $P_1(\hat{\kappa})$. Then

\[ \varphi_i(x) = \begin{cases} (\hat{\varphi}_1 \circ T_{i-1}^{-1})(x) & x \in [x_{i-1}, x_i], \\ (\hat{\varphi}_0 \circ T_{i-1}^{-1})(x) & x \in [x_i, x_{i+1}]. \end{cases} \]
Demo: Developing FEM in 1D [cleared]
Going Higher Order

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

Possible extension:

\[
P_h^k := \{ v_h \in C^0(\bar{\Omega}) : \text{for all } i \in \{1, \ldots, N\}, v_h|_{I_i} \in \mathbb{P}_k \}.
\]

Higher Order Approximation

Let \( 0 \leq \ell \leq k \). Then for \( v \in H^{\ell+1}(\Omega) \),

\[
\| v - I_h^k v \|_{L^2} + h \| (v - I_h^k v) \|_{H^1} \leq Ch^{\ell+1} |v|_{H^{\ell+1}}.
\]
Define some degrees of freedom (or DoFs) for high-order 1D FEM.

Let \( \{ \gamma_j \}_{j=0}^{N+1} \in (V_h^1)' \) be the linear functionals so that
\[
\gamma_j(v_h) = v_h(x_j) \quad \text{for all } v_h \in V_h^1.
\]

Using terminology from classical mechanics, these functions are called (global) degrees of freedom. The functions \( \{ \phi_i \}_{i=0}^{N+1} \) that are defined so that
\[
\gamma_j(\phi_i) = \delta_{i,j} \quad (i,j \in \{0, \ldots, N+1\}, \phi_i \in V_h^1)
\]
holds are called (global) shape functions. One can also define local shape functions on the reference element.
Define local form functions for high-order 1D FEM.

The local form functions are typically chosen to be Lagrange polynomials:

\[ \hat{\phi}_i^k(\hat{x}) = \frac{\prod_{j=0, j \neq i}^k (\hat{x} - \hat{x}_j)}{\prod_{j=0, j \neq i}^k (\hat{x}_i - \hat{x}_j)}, \]

where \( \hat{x}_j = j/k \) for \( i = 0, \ldots, k \).

\[ x_{i,j} := x_i + (j/k)h_i \quad \text{for} \quad i = 0, \ldots, N \quad \text{and} \quad j = 0, \ldots, k - 1, \]

further \( x_{N+1,0} = 0 \). Then

\[ \dim(V_h^k) = k(N + 1) + 1. \]
Obtain the global shape functions for high-order 1D FEM.

Define

\[
\varphi_{i,0}(x) := \begin{cases} 
\hat{\varphi}_k \circ T_{i-1}^{-1}(x) & x \in [x_{i-1}, x_i], \\
\hat{\varphi}_0 \circ T_i^{-1}(x) & x \in [x_i, x_{i+1}], \\
0 & \text{otherwise,}
\end{cases}
\]

and

\[
\varphi_{i,j}(x) := \begin{cases} 
\hat{\varphi}_k \circ T_{i-1}^{-1}(x) & x \in [x_i, x_{i+1}], \\
0 & \text{otherwise.}
\end{cases}
\]

for \( j = 0, \ldots, k - 1 \) und \( i = 0, \ldots, N \).
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Discontinuous Galerkin Methods for Hyperbolic Problems
A Boundary Value Problem

Consider the following elliptic PDE

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

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

Weak form?

Multiply by a test function \(v \in H^1_0(\Omega)\) and integrate by parts:

\[
\int_{\Omega} \left[ -\nabla \cdot (\kappa(x) \nabla u) - f(x) \right] v \, dx = 0
\]

\[
\Leftrightarrow -\int_{\partial \Omega} v \left[ \kappa \hat{n} \cdot \nabla u \right] \, d\Gamma + \int_{\Omega} \left[ \kappa(x) \nabla u \cdot \nabla v - f(x) v \right] \, dx = 0.
\]

The boundary integral vanishes since \(v \in H^1_0\) and we find

\[
\int_{\Omega} \kappa(x) \nabla u \cdot \nabla v \, dx = \int_{\Omega} f(x) v \, dx.
\]
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...

\[
a(u, v) := \int_\Omega \kappa(x) \nabla u \cdot \nabla v \, dx,
\]
\[
g(v) := \int_\Omega f(x) v \, dx,
\]

Is this symmetric, coercive, and continuous?

- **Symmetric**: yes.
- **Coercive**: When there exists \( c \) so that \( 0 < c \leq \kappa(x) \) for all \( x \).
- **Continuous**: When there exists \( C \) so that \( \kappa(x) \leq C < \infty \) for all \( x \).
Triangulation: 2D

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

\[ \overline{\Omega} = \bigcup_{i=1}^{M} E_m. \]
Elements and the Bilinear Form

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

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

what happens to $a$ and $g$?

$$a(u, v) = \sum_{m=1}^{M} \int_{E_m} \kappa(x) \nabla u \cdot \nabla v \, dx,$$

$$g(v) = \sum_{m=1}^{M} \int_{E_m} q(x) v \, dx.$$
Basis Functions

Expand

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

and plug into the weak form.

\[ \sum_{j=1}^{N_p} u_j a(\varphi_j, \varphi_i) = g(\varphi_i), \quad \text{for } i = 1 \ldots N_p. \]
Global Lagrange Basis

Approximate solution $u_h$: Piecewise linear on $\Omega$

$$u_h$$

$$\Omega$$

The Lagrange basis for $V_h$ consists of piecewise linear $\varphi_i$, with...

$$\varphi_i(x_i) = 1 \quad \text{and} \quad \varphi_i(x_j) = 0, \quad \text{for} \quad i \neq j.$$
Features of the basis?

- For the piecewise linear Lagrange basis, each $\varphi_i$ is continuous on $\Omega$.
- Restricted to $E_m$, each $\varphi_i$ is linear.
Local Basis

What basis functions exist on each triangle?

On each triangle, $E_m$, we have three non-zero basis functions, one for each vertex of the triangle:

In the Figure, $\varphi_1(x_1) = 1$, $\varphi_1(x_2) = 0$, and $\varphi_1(x_3) = 0$. 
Local Basis Expressions

Write expressions for the nodal linear basis in 2D.

\[ \varphi_1(r, s) = 1 - r - s \]
\[ \varphi_2(r, s) = r \]
\[ \varphi_3(r, s) = s \]
Higher-Order, Higher-Dimensional Simplex Bases

What’s an $n$-simplex?

$r_i \geq 0$, $\sum r_i \leq 1$. ($\rightarrow$ barycentric) Interval, $\triangle$, tetrahedron, ...

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

$$P^N := \text{span} \left\{ \prod_{i=1}^{d} x_i^{n_i} : \sum n_i \leq N \right\}$$

Give nodal sets (on the $\triangle$) for $P^N$ and $\text{dim } P^N$ in general.

$$\text{dim } P^N = N_p = \frac{(N + 1)(N + 2)}{2}$$

Avoiding Runge: e.g. Warburton ‘06
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.

Set up a Vandermonde matrix:

\[
V := \begin{bmatrix}
\varphi_1(\xi_1) & \cdots & \varphi_{N_p}(\xi_1) \\
\vdots & \ddots & \vdots \\
\varphi_1(\xi_{N_p}) & \cdots & \varphi_{N_p}(\xi_{N_p}) 
\end{bmatrix}.
\]

Then \(\ell_i := \sum_{j=1}^{N_p} (V^{-T})_{i,j} \varphi_j\) is a Lagrange basis.
Higher-Order, Higher-Dimensional Tensor Product Bases

What’s a tensor product element?

\[ [0, 1]^n \subset \mathbb{R}^n. \text{ Interval, quad, hexahedron.} \]

Give a higher-order polynomial space on the \( n \)-simplex:

\[ Q^N := \text{span}\left\{ \prod_{i=1}^{d} x_i^{n_i} : \max n_i \leq N \right\} \]

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

Can use tensor product of one-dimensional basis ⇒ Lower complexity for this and many other operations.
Construct a mapping $T_m : \hat{E} \rightarrow E_m$. Reference element $\hat{E}$, global $\triangle E_m$.

$$T_m(r, s) = (x_2 - x_1)r + (x_3 - x_1)s + x_1.$$ 

What is the Jacobian of $T_m$?

$$J_T = \begin{bmatrix} \frac{\partial x}{\partial r} & \frac{\partial x}{\partial s} \\ \frac{\partial y}{\partial r} & \frac{\partial y}{\partial s} \end{bmatrix} = \begin{bmatrix} \frac{\partial T}{\partial r} & \frac{\partial T}{\partial s} \\ \frac{\partial T}{\partial r} & \frac{\partial T}{\partial s} \end{bmatrix}$$

$$= \begin{bmatrix} (x_2 - x_1) & (x_3 - x_1) \end{bmatrix} \in \mathbb{R}^{2 \times 2}.$$
More on Mappings

Is an affine mapping sufficient for a tensor product element?

No, because affine mappings preserve parallel lines: Global elements could only be parallelograms.

Idea: Consider a mapping $T_m \in (Q^1)^n$.

How might we accomplish curvilinear elements using the same idea?

- Use isoparametric mappings $T_m \in (P^N)^n$ (if FEM basis is $P^N$)
- Use subparametric mappings $T_m \in (P^M)^n$
  ($M < N$ if FEM basis is $P^N$)
- Use superparametric mappings $T_m \in (P^M)^n$
  ($M > N$ if FEM basis is $P^N$)
Constructing the Global Basis

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

$$\phi_{i,j}(\mathbf{x}) = \hat{\phi}_j(T_m^{-1}(\mathbf{x})).$$

What's the gradient of this basis?

$$\nabla_x \phi_j(T^{-1}(\mathbf{x})) = \left[ \frac{d}{dx} \phi_j(T^{-1}(\mathbf{x})) \right]^T = \left[ \left( \frac{d\phi_j}{dr} \right) T^{-1}(\mathbf{x}) J_T^{-1}(\mathbf{x}) \right]^T = J_T^{-T}(\mathbf{x}) \nabla_r \phi_j(T^{-1}(\mathbf{x})).$$
Assembling a Linear System

Express the matrix and vector elements in

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

\[
a(\varphi_i, \varphi_j) = \sum_{m=1}^{M} \int_{E_m} \kappa(x) \nabla \varphi_i \cdot \nabla \varphi_j \, dx,
\]

\[
g(\varphi_i) = \sum_{m=1}^{M} \int_{E_m} f(x) \varphi_i \, dx.
\]
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.

\[
\int_E f(x) \varphi_i(x) \, dx = |J_T| \int_{\hat{E}} f(T(r)) \varphi_i(r) \, dr.
\]
Inhomogeneous Dirichlet BCs

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

- Find a function \( u^0 \in H^1(\Omega) \) with boundary values \( u^0(x) = \eta(x) \) on \( \partial \Omega \). ("lifted" from boundary to volume)
- Define \( \hat{u} := u - u^0 \in H^1_0(\Omega) \).
- Insert \( u = \hat{u} + u^0 \) into the weak form:

\[
\begin{align*}
  a(\hat{u} + u^0, v) &= a(\hat{u}, v) + a(u^0, v) = g(v), \\
  a(\hat{u}, v) &= g(v) - a(u^0, v), \\
  \hat{g}(v) &:=
\end{align*}
\]

where still \( \hat{u} \in H^1_0 \).

Altogether:
- Inhomogeneous BC just leads to extra term on RHS.
- No change in function spaces.
Demo

- **Demo:** Developing FEM in 2D [cleared]
- **Demo:** 2D FEM Using Firedrake [cleared]
- **Demo:** Rates of Convergence [cleared]
Outline

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Finite Volume Methods for Hyperbolic Conservation Laws

Finite Element Methods for Elliptic Problems
  tl;dr: Functional Analysis
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  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:

- $\bar{\Omega} = \bigcup_{i=1}^{M} E_i$.
- If $E_i \cap E_j$ consists of exactly one point, then it is a common vertex of $E_i$ and $E_j$.
- If $E_i \cap E_j$ consists of more than one point for $i \neq j$, then $E_i \cap E_j$ is a common edge of $E_i$ and $E_j$.

Give an example of a non-admissible partition.

One with a hanging node.
Mesh Resolution, Shape Regularity

**Definition (Diameter)**

A bounded set $\Omega$ has diameter $d(\Omega) = \sup \{|x - y| : x, y \in \Omega\}$.

**Mesh Resolution**

When every element of a partition has diameter at most $2h$, we write $T_h$ instead of $T$.

**Definition (Shape Regularity (Braess, Def. II.5.1))**

A family of partitions $\{T_h\}$ is called shape regular if there exists a number $\kappa > 0$ so that every $E \in T_h$ contains a circle of radius $\rho_T$ with $\rho_E \geq h_E/\kappa$, where $h_T$ is half the diameter of $E$. 


Cone Conditions

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

for every $x \in \partial \Omega$ there exists a neighborhood of $x$ within which $\partial \Omega$ can be represented as the graph of a Lipschitz function.

Lipschitz domains satisfy a cone condition:
The interior angles at vertices are positive, so that a cone can be placed in $\Omega$ with its tip at the vertex.

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 $s := t(t + 1)/2$ 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 $u \in H^t(\Omega)$

$$\|u - Iu\|_{H^t} \leq c(\Omega, (z_i)) |u|_{H^t}.$$

**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

$$\|u - Iu\|_{H^m(E_h)} \leq Ch^{t-m} |u|_{H^t(E_h)}.$$
Approximation for Congruent Triangles: Proof (1/2)

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

Let $u \in H^t(E_h)$. Define $v \in H^t(\hat{E})$ by $v(y) := u(hy)$. Then $D_w^\alpha v = h^{\lvert \alpha \rvert} D_w^\alpha u$ for $\lvert \alpha \rvert \leq t$.

Work out the scaling for the Sobolev seminorm.

$$\lvert v \rvert_{H^\ell(\hat{E})}^2 = \sum_{\lvert \alpha \rvert = \ell} \int_{\hat{E}} (D_w^\alpha v)^2 = \sum_{\lvert \alpha \rvert = \ell} \int_{E_h} h^{2\ell} (D_w^\alpha u)^2 h^{-2} = h^{2\ell-2} \lvert u \rvert_{H^\ell(E_h)}^2.$$

Work out the scaling for the Sobolev norm. Recall $h \leq 1$.

$$\lVert u \rVert_{H^m(E_h)}^2 = \sum_{\ell \leq m} \lvert u \rvert_{H^\ell(E_h)}^2 = \sum_{\ell \leq m} h^{-2\ell+2} \lvert v \rvert_{H^\ell(E_h)}^2 \leq C' h^{-2m+2} \lVert v \rVert_{H^m(\hat{E})}^2.$$
Approximation for Congruent Triangles: Proof (1/2)

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

\[ \begin{align*}
\|v\|^2_{H^\ell(\hat{E})} &= |u|^2_{H^\ell(E_h)} \\
\|u\|^2_{H^m(E_h)} &\leq C'h^{-2m+2} \|v\|^2_{H^m(\hat{E})}
\end{align*} \]

Prove the estimate.

Inserting \( u - lu \) into this estimate in place of \( u \):

\[ \begin{align*}
\|u - lu\|_{H^m(E_h)} &\leq C'h^{-m+1} \|v - lv\|_{H^m(\hat{E})} \\
&\leq C'ch^{-m+1} |v|_{H^t(\hat{E})} \leq C'ch^{t-m} |u|_{H^t(E_h)}.
\end{align*} \]
**Definition (Broken Norm)**

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

$$ \| u \|_{H^m,h} := \sqrt{\sum_{i=1}^M \| u \|_{H^m(E_i)}^2}. $$

**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 $u \in H^t(\Omega)$,

$$ \| u - l_h u \|_{H^m,h} \leq c(\Omega, \kappa, t) h^{t-m} \| u \|_{H^t(\Omega)}, $$

where $l_h$ denotes interpolation by a piecewise polynomial of degree $t - 1$. 
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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

\[
J(v) := \frac{1}{2} a(v, v) - g(v)
\]

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

\[
J(u + tv) = \frac{1}{2} a(u + tv, u + tv) - g(u + tv)
\]

\[
= J(u) + t[a(u, v) - g(v)] + \frac{t^2}{2} a(v, v).
\]

for \( u, v \in V \) and \( t \in \mathbb{R} \).

If \( u \) satisfies \( a(u, v) = g(v) \), \( J(u + v) > J(u) \).

If \( J \) has a min at \( u \), derivative of \( t \mapsto J(u + tv) \) must vanish at \( t = 0 \).
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.

\[ \mathcal{L}(x, y, \lambda) = f(x, y) + \lambda g(x, y) = x^2 + y^2 + \lambda(x + y - 2). \]

Write down a necessary condition for a constrained minimum.

\[ 0 = \nabla \mathcal{L} = \begin{bmatrix} \nabla f + \lambda \nabla g \\ g \end{bmatrix}. \]
Saddle Point Problems

\( X, M \) Hilbert spaces. \( a : X \times X \rightarrow \mathbb{R} \) and \( b : X \times M \rightarrow \mathbb{R} \) 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.

\[
\mathcal{L}(u, \lambda) = J(u) + [b(u, \lambda) - \langle g, \lambda \rangle] \quad (\lambda \in M).
\]

\( J \) and \( \mathcal{L} (\cdot, \lambda) \) agree when constraint is satisfied.

Ideas: Select \( \lambda \in M \) to ‘tweak’ \( \mathcal{L} \) so that minimizer of \( \mathcal{L}(\cdot, \lambda) \) satisfies the constraints. (Finite-dim: \( -\nabla f = J_g^T \lambda \))

Yields saddle point problem: find \( (u, \lambda) \in X \times M \) so that

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

\[
b(u, \mu) = \langle g, \mu \rangle \quad (\mu \in M).
\]
Example: Saddle Point Problem in $\mathbb{R}^2$

$$f(x, y) = x^2 + y^2 \rightarrow \min!$$
$$g(x, y) = x + y = 2$$

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.

The Hessian has the form

$$\mathcal{H}_\mathcal{L} = \begin{bmatrix} H_f & \nabla g \\ \nabla g^T & 0 \end{bmatrix}. $$

$$\mathcal{H}_\mathcal{L} = \begin{bmatrix} A & B^T \\ B & 0 \end{bmatrix} = M \begin{bmatrix} A \\ -BA^{-1}B^T \end{bmatrix} M^T,$$

demonstrating indefiniteness using Sylvester’s Law of Inertia. (cf. Benzi et al. ‘05, Section 3.4)
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?

- \( u \) is the velocity field,
- \( p \) is the pressure,
- \( f \) is an externally applied force field,
- Pressure gradient gives rise to an additional force that prevents a density change.
- \( \nabla \cdot u = 0 \) is the incompressibility constraint:
  Pressure falls/rises where a source/sink would be created.
Stokes: Properties

\[ \Delta \mathbf{u} + \nabla p = -\mathbf{f} \quad (x \in \Omega), \]
\[ \nabla \cdot \mathbf{u} = 0 \quad (x \in \Omega), \]
\[ \mathbf{u} = \mathbf{u}_0 \quad (x \in \partial \Omega). \]

Can we choose any \( \mathbf{u}_0 \)?

\[ \int_{\partial \Omega} \mathbf{u}_0 \cdot \hat{n} dS_x = \int_{\partial \Omega} \mathbf{u} \cdot \hat{n} dS_x = \int_{\Omega} \nabla \cdot \mathbf{u} dx = 0 \]

is a compatibility condition. Satisfied e.g. for \( \mathbf{u}_0 \equiv 0 \).

Does Stokes fully determine the pressure?

Only up to an additive constant. Additionally demand \( \int_{\Omega} p dx = 0 \).
Stokes: Variational Formulation

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

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

\[ X = H^1_0(\Omega)^n, \quad M = L^2_0(\Omega) := \left\{ q \in L^2(\Omega) : \int_\Omega q dx = 0 \right\} \]

Derive a weak form.

\[ a(u, v) = \int_\Omega J_u : J_v, \quad b(v, q) = \int_\Omega \nabla \cdot v q, \]

\[ A : B = \text{tr}(AB^T) = \sum_{i,j} A_{i,j} B_{i,j}. \quad \text{Find } (u, p) \in X \times M \text{ so that} \]

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

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

where in reusing \( b \), we used that \((- \text{div})^* = \text{grad}\) are adjoint.
The Stokes weak form is clearly in saddle-point form. Do all saddle point problems have unique solutions?

\[ f(x, y) = x^2 + y^2 \rightarrow \min!, \]
\[ x + y = 2, \]
\[ 3x + 3y = 6. \]

\[ L(x, y, \lambda) = x^2 + y^2 + \lambda(x + y - 2) + \mu(3x + 3y - 6). \text{ (}\lambda, \mu\text{) no longer uniquely determined.} \]

\[ \rightarrow \text{Need a criterion.} \]
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

\[
  a(v, v) \geq c_0 \| v \|_X^2 \quad (v \in V).
\]

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

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

No! E.g. for Stokes, the \(B\) block is short-and-fat \(\Rightarrow\) \(\exists\) nullspace.

What is the inf-sup condition saying?

"\(b\) has no \(\mu\)-nullspace."

Why does it suffice for \(a\) to be \(V\)-elliptic?

True in the linear algebra, too! (Think Schur complements.) ([Benzi et al. ‘05, Thm. 3.2])
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 [cleared] \((P^1-P^1)\)

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

The differential operators being applied to \(u\) and \(p\) in the Stokes system are of different order.

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

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

Fortin’s Criterion ([Fortin 1977])

Suppose there exists a bounded projector $\Pi_h : X \rightarrow X_h$ so that

$$b(v - \Pi_h v, \mu_h) = 0 \quad (\mu_h \in M_h).$$

If $\|\Pi_h\| \leq c$ for some constant $c$ independent of $h$, then $b$ satisfies the inf-sup-condition on $X_h \times M_h$.

Let $\mu_h \in M_h$. By assumption, $b(v, \mu_h) = b(\Pi_h v, \mu_h)$ for $v \in X$.

$$\sup_{v_h \in X_h} \frac{b(v_h, \mu_h)}{\|v_h\|} \geq \sup_{v_h \in \Pi_h X} \frac{b(v_h, \mu_h)}{\|v_h\|} = \sup_{v \in X} \frac{b(\Pi_h v, \mu_h)}{\|\Pi_h v\|} \geq \frac{1}{c} \sup_{v \in X} \frac{b(v, \mu_h)}{\|v\|} \geq c_2 \|\mu_h\|. $$

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$H^1$-Boundedness of the $L^2$-Projector

Assume $H^2$-regularity and a uniform triangulations $T_h$. (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 $c$,

$$\|\pi^0_h v\|_{H^1} \leq c \|v\|_{H^1}.$$

Ingredients?

- Regularity
- Aubin-Nitsche
- Inverse estimates (For affine, pw. polynomial family $V_h$:
  $$\|v_h\|_{H^t,h} \leq Ch^{m-t} \|v_h\|_{H^m,h} \text{ with } 0 \leq m \leq t,$$
  $$\|v_h\|_{H^1,h} \leq Ch^{-1} \|v_h\|_{L^2,h}.$$
Does $H^1$ boundedness of the $H^1$ projector hold?

Yes, any Hilbert space projection is bounded. (Pythagoras)

How would this break down without the uniformity assumption?

On a graded mesh, where $L^2$ projection introduces $O(1/h)$ growth in the $H^1$ seminorm (which measures oscillation, in a way).
Bubbles and the MINI Element

What is a bubble function?

\[ \varphi_b(r, s) = rs(1 - r - s). \] (see figure on next slide)

Let \( B^3 \) be the span of the bubble function and \( T_h \) the triangulation.

Define the MINI variational space \( X_h \times M_h \).

\[ X_h := \{ v_h \in C(\Omega)^2 \cap H^1_0(\Omega)^2 : v_h|_E \in (P^1 \oplus B^3)^2 \text{ for } E \in T_h \} \]

\[ M_h := \{ q_h \in C(\Omega) \cap L^2_0(\Omega) : v_h|_E \in P^1 \text{ for } E \in T_h \} \]

Computational impact of the bubble DOF?

Not coupled to DOFs outside the element; can use static condensation to eliminate.
The Bubble in Pictures

\[ r + s \leq 1? r \times s \times (1 - r - s) : 1/0 \]
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.

Assume uniform meshes (can generalize). Let

$$M_h := \{ v_h \in C(\bar{\Omega}) \cap H^1_0(\Omega) : v_h|_E \in P^1 \text{ for } E \in T_h \}.$$

Let $\pi^0_h : H^1_0 \to M_h$ be the $L^2$ projector.

Then $\|\pi^0_h v\|_{H^1} \leq c_1 \|v\|_{H^1}$ from its $H^1$-boundedness and, from the interpolation estimate,

$$\|v - \pi^0_h v\|_{L^2} \leq \|v - I v\|_{L^2} + \|I v - \pi^0_h v\|_{L^2} = \|v - I v\|_{L^2} + \|\pi^0_h (I v - v)\|_{L^2} \leq c_2 h \|v\|_{H^1}.$$
MINI Satisifies an inf-sup Condition (2/4)

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

Let $\pi_h^1 : L^2 \to B^3$ be linear so that

$$\int_E (\pi_h^1 v - v) dx = 0 \quad \text{for } E \in T_h.$$ 

What does this bubble projector do?

- Project onto piecewise constant functions.
- Replace the constant by a bubble with the same integral.

Do we have an estimate for the bubble projector?

$$\|\pi_h^1 v\|_{L^2} \leq c_3 \|v\|_{L^2}.$$
MINI Satisfies an inf-sup Condition (3/4)

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

Define $\Pi_h \nu := \pi^0_h \nu + \pi^1_h (\nu - \pi^0_h \nu)$. By construction, $\Pi_h$ preserves the constant mode, i.e. $\int (\Pi_h \nu - \nu) dx = 0$.

Show Fortin’s criterion for $\Pi_h$.

Extend $\Pi_h$ to vector-valued component-by-component.

$q_h \in M_h$ is continuous, so we may apply Gauss’s theorem.

\[
b(\mathbf{v} - \Pi_h \mathbf{v}, q_h)
\]
\[
= \int \nabla \cdot (\mathbf{v} - \Pi_h \mathbf{v}) q_h dx
\]
\[
= \int_{\partial \Omega} (\mathbf{v} - \Pi_h \mathbf{v}) \cdot \hat{n} q_h dS_x - \int_{\Omega} (\mathbf{v} - \Pi_h \mathbf{v}) \cdot \nabla q_h dx = 0.
\]
MINI Satisfies an inf-sup Condition (4/4)

- \|\pi_h^0 v\|_{H^1} \leq c_1 \|v\|_{H^1} \text{ for } L^2 \text{ 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 $\Pi_h$.

\[
\|\Pi_h v\|_{H^1} \leq \|\pi_h^0 v\|_{H^1} + \|\pi_h^1(v - \pi_h^0 v)\|_{H^1}
\leq c_1 \|v\|_{H^1} + c_4 h^{-1} \|\pi_h^1(v - \pi_h^0 v)\|_{L^2}
\leq \text{ inv.est. } c_1 \|v\|_{H^1} + c_4 h^{-1} c_3 \|v - \pi_h^0 v\|_{L^2}
\leq c_1 \|v\|_{H^1} + c_4 c_3 c_2 \|v\|_{H^1}.
\]
Demo: 2D Stokes Using Firedrake [cleared] (MINI and Taylor-Hood)
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  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 $v \in V$.

Let $u \in V$ and observe $a_u(v) := a(u, v)$ is a bounded linear functional (due to continuity of $a$). Let $t_u \in V$ be the Riesz representer of $a_u$ with $a_u(v) = \langle v, t_u \rangle$ for all $v \in V$. Consider the mapping defined by that:

$$T : V \rightarrow V, \quad u \mapsto Tu := t_u.$$  

We show that $T$ is linear, bounded, has closed range, and is onto $V$. 
Lax-Milgram Proof (2/5)

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

For \( u, v, w \in V \) and \( \alpha \in \mathbb{R} \):

\[ \langle v, T(\alpha u + w) \rangle = a(\alpha u + w, v) = \alpha \langle v, Tu \rangle + \langle v, Tw \rangle. \]

Show boundedness \( \Leftrightarrow \) continuity of \( T \).

\[ \| Tu \|^2 = \langle Tu, Tu \rangle = a_u(Tu) = a(u, Tu) \leq c_1 \| Tu \| \| u \| \quad \text{(continuity).} \]
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.)

Let \( z_n = Tu_n \) be a sequence in \( \text{range}(T) \). By definition, \( a(u_n, v) = \langle v, Tu_n \rangle = \langle v, z_n \rangle \) for all \( v \in V \), so that

\[
  a(u_n - u_m, v) = \langle v, z_n - z_m \rangle \\
  \Rightarrow a(u_n - u_m, u_n - u_m) = \langle u_n - u_m, z_n - z_m \rangle \\
  \Rightarrow c_0 \|u_n - u_m\|^2 \leq \|u_n - u_m\| \|z_n - z_m\| \quad \text{(coercivity)} \\
  \Rightarrow c_0 \|u_n - u_m\| \leq \|z_n - z_m\|.
\]

If \( z_n \to z \), \((u_n)\) must be Cauchy, so has a limit (because \( V \) is Hilbert). Let \( u \) be the limit. Next: Show \( z = Tu \).

Let \( v \in V \) be arbitrary. \( a(u_n, v) \to a(u, v) \) by continuity. Also:

\[ |\langle Tu_n - z, v \rangle| \to 0, \] so that \( \langle v, Tu_n \rangle \to \langle v, z \rangle \), so \( a(u, v) = \langle v, z \rangle \), and by definition of \( T \), \( z = Tu \).
a(u, v) = \langle v, Tu \rangle. Show that \( T \) is onto \( V \).

Suppose not. By the Hilbert projection theorem, there exists \( w \in \text{range}(T)\perp \setminus \{0\} \). Therefore \( \langle w, Tu \rangle = 0 \) for all \( u \in V \). Choosing \( u = w \) gives \( 0 = \langle w, Tw \rangle = a(w, w) \), a contradiction.
Lax-Milgram Proof (5/5)

Show existence of the solution \( u \).

Let \( z \) be the Riesz representer of \( g \): \( g(v) = \langle v, z \rangle \) for all \( v \in V \). Since \( T : V \to V \) is onto, there exists a \( u \in V \) so that \( z = Tu \), i.e. \( g(v) = \langle v, Tu \rangle = a(u, v) \) for all \( v \in V \).

Show uniqueness of the solution \( u \).

Suppose we have a second \( \hat{u} \) with \( z = T\hat{u} \). Then \( a(u - \hat{u}, v) = 0 \) for all \( v \in V \), particularly \( a(u - \hat{u}, u - \hat{u}) = 0 \), i.e. \( u = \hat{u} \).
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Conservation laws

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

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

<table>
<thead>
<tr>
<th>Example: Maxwell’s Equations</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\partial_t D - \nabla \times H = -j$,</td>
</tr>
<tr>
<td>$\nabla \cdot D = \rho$,</td>
</tr>
<tr>
<td>$\partial_t B + \nabla \times E = 0$,</td>
</tr>
<tr>
<td>$\nabla \cdot B = 0$.</td>
</tr>
</tbody>
</table>

What do we do with the divergence constraints?

Ignore them. If satisfied at initial condition, they continue to be satisfied.
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 \( \mathbf{q} = (E_x, E_y, E_z, H_x, H_y, H_z)^T \)?

No: coeff. on the wrong side of the \( \nabla \cdot \). Only OK for constant-coeff.
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Solving $q_t + aq_x = 0$: Finite Differences

- Simple to implement
- High-order
- Local and explicit in time
- Theory available
- High-order/geometry: pick one.
  - Upwind/downwind differencing?
  - How about in a system?
  - Boundaries?
  - Discontinuities?

\[
D^-_t + aD^-_x = 0
\]

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

Robust, fast, good for c.laws
Local and explicit in time
Solid theory
High-order/geometry: pick one.

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

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

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

\[ \int_{\Omega} q_t^N \phi + aq_x^N \phi \, dx = 0 \]

for $\phi$ in a test space.

- High-order
- geom. flexible
- Non-local and implicit in time
- Solid theory
- Not nonlinearly robust
- Not fast: Mass matrix solve
Do we really want high order?

Any advantage to 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?

Spectral expansion of solution decays quickly (i.e. solution smooth)

Figure from talk by Jan Hesthaven
Summarizing

Want flexibility of finite elements \textit{without} the drawbacks.

Let’s redevelop finite elements, with a bit more care.

Strategy:

- Use $n$-dimensional POV for a while to expose geometric issues more clearly.
- Reduce to 1D when necessary.
- Mop up remaining issues later.
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Developing the Scheme

What do do about unbounded domains?

Need to truncate domain, e.g.:
- Special boundary conditions (e.g. Engquist/Majda '77, Hagstrom/Warburton '04)
- Perfectly Matched Layers (PMLs, Berenger '94)
Dealing with the Mesh, Part I

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

$$T_k: \hat{E} \rightarrow E_k$$

$$x = (x, y, z) = T_k(r, s, t) = T_k(r)$$

- $T_k$ affine for straight-sided simplices: $T_k(r) = Ar + b$
- 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 integrate on $\Omega$:

$$\int_{\Omega} f dx = \sum_{E_k} \int_{E_k} f dx = \sum_{E_k} \int_{\hat{E}} f \left| \frac{dx}{dr} \right| dr$$

and differentiate on $\Omega$:

$$\frac{\partial f}{\partial x} = \frac{\partial r}{\partial x} \frac{\partial f}{\partial r}$$

Jacobian of $T_k^{-1}$?

$$\frac{dx}{dr} \frac{dr}{dx} = Id \iff \left( \frac{dx}{dr} \right)^{-1} = \frac{dr}{dx}$$
Dealing with the Mesh, Part III

Approximation basis set on $E_k$?

Use the one we have on $\hat{E}$:

$$\phi_i^k(x) := \phi_i(T_k^{-1}(x))$$

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

- A basis of rational functions.
- Approximation results nontrivial.
Going Galerkin

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

Integrate by parts:

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

Problem?

- **Problem:** Two values to choose from on boundary.
- Don’t choose (for now).
- Call chosen answer **numerical flux** \((F^k \cdot n)^*\)
- Feel vaguely reminded of finite volume
Strong-Form DG

Weak form:

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

Integrate by parts again:

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

- Strong-form DG
- Same solution as weak for linear, constant-coefficient problems.
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Accuracy and Stability

In DG: what provides accuracy? what provides stability?

- Local approximation space provides *accuracy*
- Fluxes provide *stability*

**Lax equivalence:** Accuracy + Stability = Convergence

→ Let flux choice be guided by stability.

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

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

Trick: Set \( \phi = q \). Specialize \( F(u) := (au, 0, 0)^T = ae_x u \).

\[ 0 = \int_{E_k} q_t^k q_k \, dx - \int_{E_k} aq_k e_x \cdot \nabla q_k \, dx + \int_{\partial E_k} (aq_k e_x \cdot \hat{n})^* q_k \, dS_x \]
\[ = \int_{E_k} q_t^k q_k \, dx - \int_{E_k} aq_k \partial_x q_k \, dx + \int_{\partial E_k} (aq_k n_x)^* q_k \, dS_x \]
\[ = \frac{\partial_t}{2} \int_{E_k} q_k q_k \, dx - \int_{E_k} aq_k \partial_x q_k \, dx + \int_{\partial E_k} (aq_k n_x)^* q_k \, dS_x \]

\[ \Rightarrow \frac{\partial_t \| q_k \|_{2,E_k}^2}{2} = \int_{E_k} aq_k \partial_x q_k \, dx - \int_{\partial E_k} (aq_k n_x)^* q_k \, dS_x \leq 0 \]
Stability: Basic Setup (2/2)

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

Integrate by parts:

\[ \int f \partial_x f = - \int f \partial_x f + \int f^2 n_x \]

to see:

\[ \frac{\partial_t \|q_k\|_{2,E_k}^2}{2} = \int_{E_k} a(q_k)^2 n_x \, dx - \frac{1}{2} \frac{\|a q_k n_x\|^2}{2} - (a q_k n_x)^* q_k \, dS_x \]

This depends on neighbors—end of element-local analysis!
Stability: Going Global

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

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

\[
= \sum \left( \int_{f} \frac{a(q_k^+)^2 n_x^+}{2} - (aq_k n_x)^* q_k^+ dS_x + \int_{f} \frac{a(q_k^-)^2 n_x^-}{2} - (aq_k n_x)^* q_k^- dS_x \right)
\]

- Assumption: \((aq_k n_x)^*_+ + (aq_k n_x)^*_- = 0\) ("no accumulation on interface")
- \(a\) is constant
Gather up

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

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

\[
= \sum_{f \in \text{faces}} \int_f \left( a n_x^- q_k^- + q_k^+ \right) - (aq_k n_x)^*_- (q_k^- - q_k^+ dS_x \right)
\]

Want all that non-positive. So demand:

\[
\left( a n_x^- q_k^- + q_k^+ \right) - (aq_k n_x)^*_- (q_k^- - q_k^+ \right) \leq 0
\]
Picking a Flux

Want:

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

Ideas?

One possible choice:

\[(aq_k n_x)^*_2 := an_x \frac{q_k^- + q_k^+}{2} \]

- Called the central flux.
- Observe: \((*) = 0 \Rightarrow L^2\)-norm exactly conserved!
- The lazy man’s flux.
- Works.
- Problematic! Why?
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?

\[
(aq_k n_x)^* := an_x \frac{q_k^- + q_k^+}{2} + \alpha \frac{q_k^- - q_k^+}{2}
\]

(with \( \alpha \geq 0 \))

Unit considerations suggest: \( \alpha = \pm an_x^- \geq 0. \)

Called the upwind flux (aka local L-F)

- Observe: \( (*) < 0 \Rightarrow \) dissipative!
- Quite good in practice.
Comparing Fluxes (1/3)

Central

Upwind penalizes jumps!

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

Central fluxes v. Upwind fluxes

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
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?

‘Pick the average’ or ‘pick the upwind value’

Swept under the rug: Boundary conditions

Also important for stability!

Element coupling (and BCs) done weakly

- Numerical solution really is discontinuous
- Hence “discontinuous Galerkin”
Accuracy

Stability: (preliminary version) done!
Accuracy: Depends on approximation properties!

Need approximation space: polynomials of (total) degree at most $N$ on the reference element.

So, expect $h^{N+1}$ residual.

Practically often true. Theoretically:
- Lesaint, Raviart ‘74:
  - $h^N$ in the general case
  - $h^{N+1}$ for special grids
- Johnson ‘86: $h^{N+1/2}$
What to do about systems?

- Consider Riemann (jump) problem
  - Obtain ‘fan’ of different wave speeds
- *Rankine-Hugoniot condition*:

  $$[F(q)] = \text{(wave speed)} \cdot [q]$$

- Number states across fan $q_0, q_{-1}, q_1, \ldots$
- Set up Rankine-Hugoniot at each state boundary
- Solve for rest-state flux $F(q_0)$
- Just like Finite Volume
What about multiple dimensions?

We’ve dealt with 1D systems.

How about the move to multiple dimensions?

*In principle* there is (almost) nothing to see.

Recipe:

- Reduce $nD$ c.law to $1D$ c.law across boundary
- Diagonalize
- Play Rankine-Hugoniot game as before
- Transform back
Simultaneous Diagonalization

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

$$q_t + \begin{pmatrix} 0 & -c_nx & -c_ny \\ -c_nx & 0 & 0 \\ -c_ny & 0 & 0 \end{pmatrix} \partial_n q = 0$$

Must simultaneously diagonalize for all $(n_x, n_y)^T$ to obtain generic expression!

More symbolically:

$$q_t + (An_x)\partial_x q + (Bn_y)\partial_y q$$

Need to find matrix $S$ that simultaneously diagonalizes $An_x$ and $Bn_y$!

Jumps and Averages

Jump and average of a scalar quantity:

\[
\{q\} := \frac{q^- + q^+}{2} \\
[q] := q^+ n^+ + q^- n^-
\]

Jump and average of a vector quantity:

\[
\{q\} := \frac{q^- + q^+}{2} \\
[q] := q^+ \cdot n^+ + q^- \cdot n^-
\]
A Flux for Maxwell’s

Wanted to solve Maxwell’s equation in the time domain. Numerical flux?
Either look in the literature:

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

or derive yourself: **Demo: Finding Numerical Fluxes for DG** [cleared] (Part 2)

**Good news:** Scheme mathematically complete.
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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?

Two main choices:

- **Modal DG** (expansion coefficients)
- **Nodal DG** (point values at nodal locations)

We choose to use nodal DG here.

Need: set of basis functions, set of nodes
Function spaces same as for FEM: $P^N, Q^N$.

Numerically: better to use orthogonal polynomials with

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

- 1D: Legendre polys
- $n$D: Proriol ‘57/Koornwinder ‘75/Dubiner ‘93

Notation: $(\phi_i)^{N_p}_{i=1}$. 
Nodes

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

\[ V_{ij} := \phi_j(\xi_i) \]

\[ V \text{(modal coeff.)} = (\text{nodal coeff.}) \]

\(\xi_i\) determine \(\text{cond}(V)\)!

- Equispaced nodes: \(\text{cond. exponential in } N\)
- 1D: Gauß-Lobatto or Chebyshev
- \(nD\): cottage industry
  (e.g. [Warburton ‘06])
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:

\[ \mathcal{M}^k_{ij} := \int_{E_k} \ell_i \ell_j dx = |A_k| \mathcal{M} := |A_k| \int_{\hat{E}} \ell_i \ell_j dx = |A_k| V^{-T} V^{-1} \]

\[ S^{k,\partial \nu}_{ij} := \int_{E_k} \ell_i \partial_{x^\nu} \ell_j dx, \]

\[ \mathcal{M}^{k,\Lambda}_{ij} := \int_{A \subset \partial E_k} \ell_i \ell_j dS_x. \]

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

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

How can we do time integration on this weak form?

Goal: Dig out $\partial_t u$! Must invert $M$.

- In ‘normal’ finite elements: large, unstructured, sparse matrix
- In DG: Block-diagonal
- In simplicial DG: Templated block-diagonal
- In curvilinear DG: Still templated block-diagonal
  e.g.: [Warburton ‘08], [Chan, Hewett, Warburton ‘17]
Trick: Multiple face mass matrices

Applying multiple face mass matrices at once:

\[
\int_{\partial E_k} \hat{n} \cdot (F^*) \phi dS =
\begin{pmatrix}
M^{A_1} \\
M^{A_2} \\
M^{A_3}
\end{pmatrix} \cdot 
\begin{pmatrix}
J_1 \hat{n} \cdot (F^*)|_{A_1} \\
\cdots\\nJ_3 \hat{n} \cdot (F^*)|_{A_3}
\end{pmatrix}.
\]
DG and Modern Computers: Possible Advantages

DG on modern processor architectures: Why?

- On-chip parallelism
  - DG inherently parallel.
- Deepening Memory Hierarchy
  - The majority of DG is local.
- Compute Bandwidth $\gg$ Memory Bandwidth
  - DG is arithmetically intense.
- Processors favor dense data.
  - Local parts of the DG operator are dense.
- Penalty on scattered access.
  - DG’s cell connectivity is sparser than CG’s
  - and more regular.