C4.3 Functional Analytic Methods for PDEs
Lecture 13

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In the last lecture

- First existence theorem: Direct method of the calculus of variation.
- Second existence theorem: Fredholm alternative.

This lecture

- Second existence theorem: Fredholm alternative.
- The compactness of the embedding $L^2(\Omega) \hookrightarrow H^{-1}(\Omega)$.
- Third existence theorem: Spectral theory.

The Fredholm alternative for $I - K$

Definition

Let H be a Hilbert space. An bounded linear operator $K : H \to H$ is said to be *compact* if K maps bounded subset of H into pre-compact subsets of H.

Theorem (Fredholm alternative)

Let H be a Hilbert space and $K : H \to H$ be a compact bounded linear operator. Then we have the dichotomy that either $I - K$ is invertible or $\mathrm{Ker}\,(I - K)$ is non-trivial.

The Fredholm alternative for $I - K$

Proof

- Suppose by contradiction that $Ker\,(I - K) = 0$ but $Im\,(I - K)$ is a proper subspace of H.
- Let $V_0 = H$ and define inductively $V_{m+1} = (I - K)(V_m)$. We claim that V_{m+1} is a closed and proper subspace of V_m.

Lemma

Let H be a Hilbert space and $K : H \to H$ be compact. If $Ker\,(I - K) = 0$, then $V = Im\,(I - K)$ is a closed subspace of H.

- ⋆ By the lemma and the contradiction hypothesis, V_1 is a closed proper subspace of V_0.
- ⋆ We have $(I - K)V_1 \subset (I - K)V_0 = V_1$. It follows that $KV_1 \subset V_1$. By the lemma again, $V_2 = (I - K)V_1$ is a closed subspace of V_1.

The Fredholm alternative for $I - K$

Proof

- We are proving the claim that V_{m+1} is a closed and proper subspace of V_m.
  - ⋆ V_1 is a closed proper subspace of V_0.
  - ⋆ V_2 is a closed subspace of V_1.
  - ⋆ As V_1 is a proper subspace of V_0, we can take $u \in V_0 \setminus V_1$.
  - ⋆ It is clear that $(I - K)u \in V_1$.
  - ⋆ If $(I - K)u \in V_2$, then there is some $(I - K)u = (I - K)w$ for some $w \in V_1$, contradicting the fact that $Ker\,(I - K) = 0$.
  - ⋆ We thus have $(I - K)u \in V_1 \setminus V_2$. Hence V_2 is a closed proper subspace of V_1.
  - ⋆ The claim follows by induction.

The Fredholm alternative for $I - K$

Proof

- $H = V_0 \supsetneq V_1 \supsetneq V_2 \supsetneq \dots$ is a strict nested sequence of closed spaces.
- We now use the projection theorem to write $V_m = V_{m+1} \oplus W_{m+1}$ where W_{m+1} is the orthogonal complement of V_{m+1} within V_m.
- Take some $w_m \in W_{m+1} \subset V_m$ with $\|w_m\| = 1$. By the compactness of K, (Kw_m) has a convergent subsequence. To reach a contradiction, we show that $\|Kw_l - Kw_m\| \geq 1$ for $m > l$.

The Fredholm alternative for $I - K$

Proof

- ... To reach a contradiction, we show that $\|Kw_l - Kw_m\| \geq 1$ for $m > l$.
  - ⋆ We write
  $$Kw_l - Kw_m = \Big\{(I-K)w_m - (I-K)w_l - w_m\Big\} + w_l,$$
  and consider the terms in curly braces.
  - ⋆ $w_l \in W_{l+1} \subset V_l$ and so $(I-K)w_l \subset V_{l+1}$.
  - ⋆ $w_m \in W_{m+1} \subset V_m \subset V_{l+1}$.
  - ⋆ $(I-K)w_m \in (I-K)(V_m) = V_{m+1} \subset V_{l+1}$.
  - ⋆ So the terms in the curly braces belong to V_{l+1}.
  - ⋆ As $w_l \in W_{l+1}$, we thus have by Pythagoras' theorem that $\|Kw_l - Kw_m\| \geq \|w_l\| = 1$.

  As explained earlier, this gives a contradiction to the compactness of K and thus concludes the proof.

The Fredholm alternative

Theorem (Fredholm alternative)

Suppose that Ω is a bounded Lipschitz domain. Suppose that $a, b, c \in L^\infty(\Omega)$, a is uniformly elliptic, and $L = -\partial_i(a_{ij}\partial_j) + b_i\partial_i + c$.

1. *The boundary value problem*

$$\begin{cases} Lu = f + \partial_i g_i & \text{in } \Omega, \\ u = u_0 & \text{on } \partial\Omega \end{cases} \tag{BVP}$$

   is uniquely solvable for each $f \in L^2(\Omega), g \in L^2(\Omega)$ and $u_0 \in H^1(\Omega)$ if and only if $L|_{H_0^1(\Omega)}$ is injective.

2. *The kernels N of $L|_{H_0^1(\Omega)}$ and N^* of $L^*|_{H_0^1(\Omega)}$ are finite dimensional, and their dimensions are equal.*

3. *If N is non-trivial, (BVP) has a solution if and only if $B(u_0, v) = \langle f, v\rangle - \langle g_i, \partial_i v\rangle$ for all $v \in N^*$.*

The Fredholm alternative

Theorem (Uniqueness implies existence)

Suppose that Ω is a bounded Lipschitz domain. Suppose that $a, b, c \in L^\infty(\Omega)$, a is uniformly elliptic, and $L = -\partial_i(a_{ij}\partial_j) + b_i\partial_i + c$. Then $L : H_0^1(\Omega) \to H^{-1}(\Omega)$ is bijective if and only if it is injective.

Proof

- Step 1: Consideration of the top order operator L_{top} defined by $L_{top}u = -\partial_i(a_{ij}\partial_j u)$.
    - ⋆ We know from our first existence theorem that L_{top} is a bijection from $X = H_0^1(\Omega)$ in to X^*.
    - ⋆ Let $A : X^* \to X$ be the inverse of L_{top}. By the inverse mapping theorem, A is bounded linear.
    - ⋆ Let us give a direct proof for the boundedness of A. Suppose that $AT = u$, i.e. $L_{top}u = T$. Then $B_{top}(u, \varphi) = T\varphi$ where B_{top} is the bilinear form associated with L_{top}.

Proof

- Step 1: Consideration of the top order operator L_{top} defined by $L_{top} u = -\partial_i(a_{ij}\partial_j u)$.
  - ⋆ Using $\varphi = u$ and the ellipticity we have

$$\lambda \|\nabla u\|^2_{L^2(\Omega)} \leq \int_\Omega a_{ij}\partial_j u \partial_i u \, dx = B_{top}(u, u) = Tu \leq \|T\| \|u\|_X.$$

  - ⋆ Thus, by Friedrichs' inequality, we have

$$\|u\|_X^2 \leq C\|Du\|^2_{L^2(\Omega)} \leq C\|T\|\|u\|_X,$$

    and so $\|AT\|_X \leq C\|T\|$, i.e. A is bounded.

The Fredholm alternative

Proof

- Step 2: We recast the equation $Lu = T$ as an equation in the form $(I - K)u = AT$ where K is a linear operator from X into itself.
  - ⋆ We have

$$\begin{aligned} Lu = T &\Leftrightarrow L_{top}u + b_i\partial_i u + cu = T \\ &\Leftrightarrow A(L_{top}u + b_i\partial_i u + cu) = AT \\ &\Leftrightarrow u - A(-b_i\partial_i u - cu) = AT. \end{aligned}$$

  - ⋆ Hence $Lu = T$ is equivalent to $(I - K)u = AT$ with $Ku = A(-b_i\partial_i u - cu)$.
  - ⋆ We saw earlier in Lecture 11 that the map $u \mapsto -b_i\partial_i u - cu$ is a bounded linear map from X into X^*. Hence $K : X \to X$ is bounded linear.

The Fredholm alternative

Proof

- Step 3: We conclude using the Fredholm alternative for operators of the form $I - Compact$.
  - ⋆ To conclude, we need to show that $I - K$ is a bijection.
  - ⋆ Since $L : X \to X^*$ is injective, so is $I - K$. Hence, by the Fredholm alternative for operators of the form $I - Compact$, it suffices to show that K is compact, i.e. every bounded sequence $(u_m) \subset X$ has a subsequence u_{m_j} such that (Ku_{m_j}) is convergent.
  - ⋆ Suppose $(u_m) \subset X$ is bounded. As K is bounded, (Ku_m) is also bounded.
  - ⋆ As X is reflexive, we may assume after passing to a subsequence that $u_m \rightharpoonup u$ and $Ku_m \rightharpoonup w$ in $X = H_0^1(\Omega)$.
  - ⋆ In addition, by Rellich-Kondrachov's theorem, we may also assume that $u_m \to u$ and $Ku_m \to w$ in $L^2(\Omega)$.

The Fredholm alternative

Proof

- Step 3: We conclude using the Fredholm alternative...
  - ⋆ Claim: $w = Ku$.
    - ▷ We have $Ku_m = A(-b_i\partial_i u_m - cu_m)$ and so $L_{top}(Ku_m) = -b_i\partial_i u_m - cu_m$.
    - ▷ This means

$$\int_\Omega a_{ij}\partial_j(Ku_m)\partial_i\varphi\,dx = \int_\Omega(-b_i\partial_i u_m - cu_m)\varphi\,dx \text{ for all } \varphi \in H_0^1(\Omega).$$

    - ▷ Sending $m \to \infty$ using the fact that $u_m \rightharpoonup u$ and $Ku_m \rightharpoonup w$ in H^1 we get

$$\int_\Omega a_{ij}\partial_j w\partial_i\varphi\,dx = \int_\Omega(-b_i\partial_i u - cu)\varphi\,dx \text{ for all } \varphi \in H_0^1(\Omega).$$

    - ▷ This means $L_{top}w = -b_i\partial_i u - cu$, i.e. $w = L_{top}^{-1}(-b_i\partial_i u - cu) = Ku$.

The Fredholm alternative

Proof

- Step 3: We conclude using the Fredholm alternative...
  - ⋆ We thus have u_m converges weakly in H^1 and strongly in L^2 to u, and Ku_m converges weakly in H^1 and strongly in L^2 to Ku.
  - ⋆ We need to upgrade the weak convergence of Ku_m in H^1 to strong convergence. By working instead with the sequence $u_m - u$, we may assume at this point that $u = 0$.
  - ⋆ Recall that $L_{top}(Ku_m) = -b_i \partial_i u_m - cu_m$ and so

$$\int_\Omega a_{ij} \partial_j (Ku_m) \partial_i \varphi \, dx = \int_\Omega (-b_i \partial_i u_m - cu_m) \varphi \, dx \text{ for all } \varphi \in H_0^1(\Omega).$$

  - ⋆ Taking $\varphi = Ku_m$, and using ellipticity we thus find

$$\lambda \|\nabla Ku_m\|_{L^2(\Omega)}^2 \leq \|b_i \partial_i u_m + cu_m\|_{L^2(\Omega)} \|Ku_m\|_{L^2(\Omega)}$$

The first factor is bounded and the second factor goes to 0.

The Fredholm alternative

Proof

- Step 3: We conclude using the Fredholm alternative...
  - So we have proven that $\nabla K u_m \to 0$ in L^2. Together with the fact that $K u_m \to 0$ in L^2, we have that $K u_m \to 0$ in H^1.
  - We conclude that K is compact.
  - As $I - K$ is injective, we conclude that $I - K$ is invertible, and so is L.

Compactness of $L^2(\Omega) \hookrightarrow H^{-1}(\Omega)$

Let us make a couple of remarks on the proof.

- One of the ideas in the proof is to write $Lu = T$ in the form $(I - K)u = L_{top}^{-1} \circ T$ where $K : H_0^1(\Omega) \to H_0^1(\Omega)$ is compact.
- The operator K is given by $Ku = L_{top}^{-1}(-b_i \partial_i u - cu)$. Hence $K = L_{top}^{-1} \circ B$ where $B : H_0^1(\Omega) \to H^{-1}(\Omega)$ is given by

$$Bu = -b_i \partial_i u - cu,$$

$$\text{i.e. } Bu(\varphi) = \int_\Omega (-b_i \partial_i u - cu)\varphi \, dx \text{ for } \varphi \in H_0^1(\Omega).$$

- The operator B can be decompose further as $B = J \circ B_0$ where $B_0 : H_0^1(\Omega) \to L^2(\Omega)$ is given by $B_0 u = -b_i \partial_i u - cu$ and $J : L^2(\Omega) \to H^{-1}(\Omega)$ is the natural injection given by

$$Jv(\varphi) = \int_\Omega v\varphi \, dx \text{ for } v \in L^2(\Omega), \varphi \in H_0^1(\Omega).$$

Compactness of $L^2(\Omega) \hookrightarrow H^{-1}(\Omega)$

- Altogether we have the chain $K = L_{top}^{-1} \circ J \circ B_0$:

$$K : H_0^1(\Omega) \stackrel{B_0}{\to} L^2(\Omega) \stackrel{J}{\to} H^{-1}(\Omega) \stackrel{L_{top}^{-1}}{\to} H_0^1(\Omega).$$

- We have the following compactness result for J, which also implies the compactness of K.

Theorem

Suppose that Ω is a bounded Lipschitz domain. Then the natural injection $J : L^2(\Omega) \to H^{-1}(\Omega)$ defined by

$$Jv(\varphi) = \int_\Omega v\varphi\, dx \text{ for } v \in L^2(\Omega) \text{ and } \varphi \in H_0^1(\Omega)$$

is compact, i.e. if (v_m) is bounded in $L^2(\Omega)$, then there is a subsequence (v_{m_j}) such that (Jv_{m_j}) is convergent in $H^{-1}(\Omega)$.

Compactness of $L^2(\Omega) \hookrightarrow H^{-1}(\Omega)$

Proof

- Suppose (v_m) is bounded in $L^2(\Omega)$.
  Then there is a subsequence (v_{m_j}) which converges weakly in L^2 to some limit $v \in L^2(\Omega)$.
- We aim to show that (Jv_{m_j}) converges in H^{-1} to Jv.
- By working with $v_{m_j} - v$ instead of v_{m_j}, we may assume that $v = 0$.
- Suppose by contradiction that $Jv_{m_j} \not\to 0$. Passing to a subsequence, we may assume that

$$\|Jv_{m_j}\|_{H^{-1}} > \delta > 0.$$

- Let w_j be the solution to

$$\begin{cases} -\Delta w_j + w_j &= v_{m_j} \quad \text{in } \Omega, \\ w_j &= 0 \quad \text{on } \partial\Omega. \end{cases}$$

Compactness of $L^2(\Omega) \hookrightarrow H^{-1}(\Omega)$

Proof

- As $Jv_{m_j} \neq 0$, we have that $w_j \neq 0$. Also, by definition of weak solution, we have

$$\int_\Omega v_{m_j} \varphi \, dx = \int_\Omega [\nabla w_j \cdot \nabla \varphi + w_j \varphi] \, dx \text{ for all } \varphi \in H_0^1(\Omega).$$

  This means

$$Jv_{m_j}(\varphi) = \langle w_j, \varphi \rangle_{H^1} \text{ for all } \varphi \in H_0^1(\Omega).$$

- Observe that if we take supremum over $\varphi \in H_0^1(\Omega)$ with $\|\varphi\|_{H_0^1(\Omega)} \leq 1$, then the supremum of the right hand side is attained exactly at $\varphi_j := \frac{w_j}{\|w_j\|_{H^1}}$.

Compactness of $L^2(\Omega) \hookrightarrow H^{-1}(\Omega)$

Proof

- We thus have, for $\varphi_j = \frac{w_j}{\|w_j\|_{H^1}}$,

$$\|Jv_{m_j}\|_{H^{-1}} = Jv_{m_j}(\varphi_j) = \int_\Omega v_{m_j}\varphi_j\,dx.$$

- The sequence (φ_j) is bounded in $H^1(\Omega)$. By Rellich-Kondrachov's theorem, we may assume after passing to a subsequence, that φ_j converges strongly in L^2 to some $\varphi_* \in L^2(\Omega)$.
- Now as v_{m_j} converges weakly to $v = 0$ in $L^2(\Omega)$, we arrive at

$$\lim_{j\to\infty} \|Jv_{m_j}\|_{H^{-1}} = \lim_{j\to\infty} \int_\Omega v_{m_j}\varphi_j\,dx = \int_\Omega 0\varphi_*\,dx = 0,$$

contradicting the statement that $\|Jv_{m_j}\|_{H^{-1}} > \delta > 0$.

Spectra of elliptic operators

Theorem (Spectrum of an elliptic operator)

Suppose that Ω is a bounded Lipschitz domain. Suppose that $a, b, c \in L^\infty(\Omega)$, a is uniformly elliptic, and $L = -\partial_i(a_{ij}\partial_j) + b_i\partial_i + c$. Then there exists an at most countable set $\Sigma \subset \mathbb{R}$ such that the boundary value problem

$$\begin{cases} Lu = \lambda u + f & \text{in } \Omega, \\ u = 0 & \text{on } \partial\Omega \end{cases} \tag{EBVP}$$

has a unique solution if and only if $\lambda \notin \Sigma$. Furthermore, if Σ is infinite then $\Sigma = \{\lambda_k\}_{k=1}^\infty$ with

$$\lambda_1 \leq \lambda_2 \leq \ldots \to \infty.$$

The set Σ is called the real spectrum of the operator L.

Proof

- Let B be the bilinear form associated with L. Recall the energy estimate: There exists $\mu > 0$ depending on the L^∞ bounds for a, b, c and the ellipticity constant λ such that

$$\frac{\lambda}{2}\|u\|^2_{H^1(\Omega)} \leq B(u,u) + \mu\|u\|^2_{L^2(\Omega)}.$$

- If we define $L_\mu u = Lu + \mu u$ and let B_μ be the bilinear form associated with L_μ, then the right hand side above is exactly $B_\mu(u,u)$.
- So B_μ is coercive. By the Fredholm alternative, the operator $L_\mu : H^1_0(\Omega) \to H^{-1}(\Omega)$ is invertible. Denote its inverse by S_μ.

Spectra of elliptic operators

Proof

- Define an operator $K : L^2(\Omega) \to L^2(\Omega)$ by:

$$K : L^2(\Omega) \overset{J}{\hookrightarrow} H^{-1}(\Omega) \overset{S_\mu}{\to} H_0^1(\Omega) \overset{Id}{\hookrightarrow} L^2(\Omega).$$

  The last leg is compact by Rellich-Kondrachov's theorem, hence K is compact.
  (We also know that J is compact, but that is a harder statement.)

- Let Σ be the set of $\lambda \in \mathbb{R}$ such that (EBVP) is not always uniquely solvable. By the Fredholm alternative,

$$\begin{aligned}\lambda \in \Sigma &\Leftrightarrow (L - \lambda Id) \text{ is not injective}\\ &\Leftrightarrow (L_\mu - (\lambda + \mu)Id) \text{ is not injective}\\ &\Leftrightarrow I - (\lambda + \mu)K \text{ is not injective}\\ &\Leftrightarrow \lambda + \mu \neq 0 \text{ and } (\lambda + \mu)^{-1} \in \sigma_p(K).\end{aligned}$$

Spectra of elliptic operators

Proof

- ... $\lambda \in \Sigma$ if and only if $\lambda + \mu \neq 0$ and $(\lambda + \mu)^{-1} \in \sigma_p(K)$. The conclusion follows from a general result for spectra of compact operators, which we take for granted.

Theorem (Spectra of compact operators)

Let H be a Hilbert space of infinite dimension, $K : H \to H$ be a compact bounded linear operator and $\sigma(K)$ be its spectrum (i.e. the set of $\lambda \in \mathbb{C}$ such that $\lambda I - K$ is not invertible). Then

1. 0 *belongs to* $\sigma(K)$.
2. $\sigma(K) \setminus \{0\} = \sigma_p(K) \setminus \{0\}$, *i.e.* $\lambda I - K$ *has non-trivial kernel for* $\lambda \in \sigma(K) \setminus \{0\}$.
3. $\sigma(K) \setminus \{0\}$ *is either finite or an infinite sequence tending to* 0.