FA-Toolbox: On some Hilbert complexes, related compact embeddings, . . . and more

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classical de Rham complex in 3D (∇-rot-div-complex)

$\Omega \subset \mathbb{R}^3$ bounded weak Lipschitz domain, $\partial\Omega = \Gamma = \overline{\Gamma_t \dot\cup \Gamma_n}$

(electro-magnetics, Maxwell's equations)

$$\{0\} \;\underset{\pi_{\{0\}}}{\overset{\iota_{\{0\}}}{\rightleftarrows}}\; \mathsf{L}^2 \;\underset{-\,\mathrm{div}}{\overset{\mathring{\nabla}}{\rightleftarrows}}\; \mathsf{L}^2 \;\underset{\mathrm{rot}}{\overset{\mathring{\mathrm{rot}}}{\rightleftarrows}}\; \mathsf{L}^2 \;\underset{-\nabla}{\overset{\mathring{\mathrm{div}}}{\rightleftarrows}}\; \mathsf{L}^2 \;\underset{\iota_{\mathbb{R}}}{\overset{\pi_{\mathbb{R}}}{\rightleftarrows}}\; \mathbb{R}$$

mixed boundary conditions and inhomogeneous and anisotropic media

$$\{0\} \text{ or } \mathbb{R} \;\underset{\pi}{\overset{\iota}{\rightleftarrows}}\; \mathsf{L}^2 \;\underset{-\,\mathrm{div}_{\Gamma_n}\,\varepsilon}{\overset{\nabla_{\Gamma_t}}{\rightleftarrows}}\; \mathsf{L}^2_{\varepsilon} \;\underset{\varepsilon^{-1}\,\mathrm{rot}_{\Gamma_n}}{\overset{\mu^{-1}\,\mathrm{rot}_{\Gamma_t}}{\rightleftarrows}}\; \mathsf{L}^2_{\mu} \;\underset{-\nabla_{\Gamma_n}}{\overset{\mathrm{div}_{\Gamma_t}\,\mu}{\rightleftarrows}}\; \mathsf{L}^2 \;\underset{\iota}{\overset{\pi}{\rightleftarrows}}\; \mathbb{R} \text{ or } \{0\}$$

for this talk: $\varepsilon = \mu = 1$ (= id) and no mixed boundary conditions
for all appearing complexes

de Rham complex in ND or on Riemannian manifolds (d-complex)

$\Omega \subset \mathbb{R}^N$ bd w. Lip. dom. or Ω Riemannian manifold with cpt cl. and Lip. boundary Γ

(generalized Maxwell equations **the mother of all complexes**)

$$\{0\} \underset{\pi_{\{0\}}}{\overset{\iota_{\{0\}}}{\rightleftarrows}} \mathsf{L}^{2,0} \underset{-\delta}{\overset{\mathring{\mathrm{d}}}{\rightleftarrows}} \mathsf{L}^{2,1} \underset{-\delta}{\overset{\mathring{\mathrm{d}}}{\rightleftarrows}} \cdots \boxed{\mathsf{L}^{2,q} \underset{-\delta}{\overset{\mathring{\mathrm{d}}}{\rightleftarrows}} \mathsf{L}^{2,q+1}} \cdots \mathsf{L}^{2,N-1} \underset{-\delta}{\overset{\mathring{\mathrm{d}}}{\rightleftarrows}} \mathsf{L}^{2,N} \underset{\iota_{\mathbb{R}}}{\overset{\pi_{\mathbb{R}}}{\rightleftarrows}} \mathbb{R}$$

elasticity complex in 3D (sym ∇-Rot $\mathrm{Rot}_{\mathbb{S}}^{\top}$-$\mathrm{Div}_{\mathbb{S}}$-complex)

$\Omega \subset \mathbb{R}^3$ bounded strong Lipschitz domain

$$\{0\} \underset{\pi_{\{0\}}}{\overset{\iota_{\{0\}}}{\rightleftarrows}} \mathsf{L}^2 \underset{-\mathring{\mathrm{Div}}_{\mathbb{S}}}{\overset{\mathrm{sym}\,\mathring{\nabla}}{\rightleftarrows}} \mathsf{L}^2_{\mathbb{S}} \underset{\mathrm{Rot}\,\mathrm{Rot}_{\mathbb{S}}^{\top}}{\overset{\mathring{\mathrm{Rot}}\,\mathring{\mathrm{Rot}}_{\mathbb{S}}^{\top}}{\rightleftarrows}} \mathsf{L}^2_{\mathbb{S}} \underset{-\mathrm{sym}\,\nabla}{\overset{\mathring{\mathrm{Div}}_{\mathbb{S}}}{\rightleftarrows}} \mathsf{L}^2 \underset{\iota_{\mathsf{RM}}}{\overset{\pi_{\mathsf{RM}}}{\rightleftarrows}} \mathsf{RM}$$

biharmonic / general relativity complex in 3D ($\nabla\nabla$-$\mathrm{Rot}_{\mathbb{S}}$-$\mathrm{Div}_{\mathbb{T}}$-complex)

$\Omega \subset \mathbb{R}^3$ bounded strong Lipschitz domain

$$\{0\} \underset{\pi_{\{0\}}}{\overset{\iota_{\{0\}}}{\rightleftarrows}} \mathsf{L}^2 \underset{\operatorname{div}\operatorname{Div}_{\mathbb{S}}}{\overset{\mathring{\nabla\nabla}}{\rightleftarrows}} \mathsf{L}^2_{\mathbb{S}} \underset{\operatorname{sym}\operatorname{Rot}_{\mathbb{T}}}{\overset{\mathring{\operatorname{Rot}}_{\mathbb{S}}}{\rightleftarrows}} \mathsf{L}^2_{\mathbb{T}} \underset{-\operatorname{dev}\nabla}{\overset{\mathring{\operatorname{Div}}_{\mathbb{T}}}{\rightleftarrows}} \mathsf{L}^2 \underset{\iota_{\mathsf{RT}}}{\overset{\pi_{\mathsf{RT}}}{\rightleftarrows}} \mathsf{RT}$$

general complex

$$A_0 : D(A_0) \subset H_0 \to H_1, \qquad A_1 : D(A_1) \subset H_1 \to H_2$$
$$A_0^* : D(A_0^*) \subset H_1 \to H_0, \qquad A_1^* : D(A_1^*) \subset H_2 \to H_1 \qquad \text{(lddc)}$$

general complex property $A_1 A_0 = 0$,

i.e., $R(A_0) \subset N(A_1)$ and/or eq $R(A_1^*) \subset N(A_0^*)$

$$\cdots \quad \underset{\cdots}{\overset{\cdots}{\rightleftarrows}} \quad H_0 \quad \underset{A_0^*}{\overset{A_0}{\rightleftarrows}} \quad H_1 \quad \underset{A_1^*}{\overset{A_1}{\rightleftarrows}} \quad H_2 \quad \underset{\cdots}{\overset{\cdots}{\rightleftarrows}} \quad \cdots$$

general observations

$$Ax = f$$

general theory

- solution theory
- Friedrichs/Poincaré estimates and constants
- Helmholtz/Hodge/Weyl decompositions
- compact embeddings
- continuous and compact inverse operators
- closed ranges
- variational formulations
- functional a posteriori error estimates
- generalized div-curl-lemma
- ...

idea: solve problem with general and simple linear functional analysis

$\Rightarrow$ functional analysis toolbox (fa-toolbox) ...

general observations

$$\mathrm{A}x = f$$

let's say $\mathrm{A} : D(\mathrm{A}) \subset \mathrm{H}_0 \to \mathrm{H}_1$ linear and H_0, H_1 Hilbert spaces

question: How to solve?

general observations

$$\mathrm{A}x = f$$

$\mathrm{A} : D(\mathrm{A}) \subset \mathrm{H}_0 \to \mathrm{H}_1$ linear

solution theory in the sense of Hadamard

- existence $\Leftrightarrow$ $f \in R(\mathrm{A})$
- uniqueness $\Leftrightarrow$ A inj $\Leftrightarrow$ $N(\mathrm{A}) = \{0\}$ $\Leftrightarrow$ A^{-1} exists
- cont dep on f $\Leftrightarrow$ A^{-1} cont

$\Rightarrow$ $x = \mathrm{A}^{-1} f \in D(\mathrm{A})$ and cont estimate (Friedrichs/Poincaré type estimate)

$$|x|_{\mathrm{H}_0} = |\mathrm{A}^{-1} f|_{\mathrm{H}_0} \leq c_{\mathrm{A}} |f|_{\mathrm{H}_1} = c_{\mathrm{A}} |\mathrm{A}x|_{\mathrm{H}_1}$$

$\Rightarrow$ best constant $c_{\mathrm{A}} = |\mathrm{A}^{-1}|_{R(\mathrm{A}),\mathrm{H}_0}$ $\qquad |\mathrm{A}^{-1}|_{R(\mathrm{A}),D(\mathrm{A})} = (c_{\mathrm{A}}^2 + 1)^{1/2}$

general observations

$A : D(A) \subset H_0 \to H_1$

$A^* : D(A^*) \subset H_1 \to H_0$ Hilbert space adjoint

Helmholtz/Hodge/Weyl decompositions (projection theorem)

$$H_1 = \overline{R(A)} \oplus N(A^*) \qquad H_0 = N(A) \oplus \overline{R(A^*)}$$

$$Ax = f$$

solution theory in the sense of Hadamard

- existence $\Leftrightarrow$ $f \in R(A) = N(A^*)^\perp$
- uniqueness $\Leftrightarrow$ A inj $\Leftrightarrow$ $N(A) = \{0\}$ $\Leftrightarrow$ A^{-1} exists
- cont dep on f $\Leftrightarrow$ A^{-1} cont $\Leftrightarrow$ $R(A)$ cl (cl range theo)

fund range cond: $\boxed{R(A) = \overline{R(A)} \text{ closed}}$ (must hold $\rightsquigarrow$ right setting!)

kernel cond: $\boxed{N(A) = \{0\}}$ (fails in gen $\rightsquigarrow$ proj onto $N(A)^\perp = \overline{R(A^*)}$)

general observations

Helmholtz/Hodge/Weyl decompositions (projection theorem)

$$\mathrm{H}_1 = \overline{R(\mathrm{A})} \oplus N(\mathrm{A}^*) \qquad \mathrm{H}_0 = N(\mathrm{A}) \oplus \overline{R(\mathrm{A}^*)}$$

remarkable observations

- time-dependent problems are simple

  in gen $\mathrm{A} : D(\mathrm{A}) \subset \mathrm{H} \to \mathrm{H}$, $\boxed{\mathrm{A} = \partial_t + \mathrm{T}}$ (gen T skew-sa, or alt lsast Re $\mathrm{T} \geq 0$)

  $$N(\mathrm{A}) = \{0\} \qquad N(\mathrm{A}^*) = \{0\} \qquad R(\mathrm{A}) \text{ (cl) } = N(\mathrm{A}^*)^\perp = \mathrm{H}$$

- time-harmonic problems are more complicated

  in gen $\mathrm{A} : D(\mathrm{A}) \subset \mathrm{H} \to \mathrm{H}$, $\boxed{\mathrm{A} = -\omega + \mathrm{T}}$

  $$N(\mathrm{A}),\ N(\mathrm{A}^*) \text{ (fin dim)} \qquad R(\mathrm{A}) \text{ (cl, fin co-dim) } = N(\mathrm{A}^*)^\perp$$

  (Fredholm alternative)

- stat problems are most complicated

  in gen $\mathrm{A} : D(\mathrm{A}) \subset \mathrm{H}_0 \to \mathrm{H}_1$, $\boxed{\mathrm{A} = 0 + \mathrm{T}}$

  $$\dim N(\mathrm{A}) = \dim N(\mathrm{A}^*) = \infty \text{ (possibly)} \qquad R(\mathrm{A}) \text{ (cl, infin co-dim) } = N(\mathrm{A}^*)^\perp$$

fa-toolbox for linear (first order) problems/systems

$$Ax = f$$

general theory

- solution theory
- Friedrichs/Poincaré estimates and constants
- Helmholtz/Hodge/Weyl decompositions
- compact embeddings
- continuous and compact inverse operators
- closed ranges
- variational formulations
- functional a posteriori error estimates
- generalized div-curl-lemma
- ...

idea: solve problem with general and simple linear functional analysis
($\Rightarrow$ fa-toolbox) ...

literature: many parts probably very well known for ages, but hard to find ...

Friedrichs, Weyl, Hörmander, Fredholm, von Neumann, Riesz, Banach, ... ?

Why not rediscover and extend/modify for our purposes?

1st fundamental observations

$\mathrm{A} : D(\mathrm{A}) \subset \mathrm{H}_0 \to \mathrm{H}_1$ lddc, $\mathrm{A}^* : D(\mathrm{A}^*) \subset \mathrm{H}_1 \to \mathrm{H}_0$ Hilbert space adjoint

$(\mathrm{A}, \mathrm{A}^*)$ dual pair as $(\mathrm{A}^*)^* = \overline{\mathrm{A}} = \mathrm{A}$

A, A^* may not be inj

Helmholtz/Hodge/Weyl decompositions (projection theorem)

$$\mathrm{H}_1 = N(\mathrm{A}^*) \oplus \overline{R(\mathrm{A})} \qquad \mathrm{H}_0 = N(\mathrm{A}) \oplus \overline{R(\mathrm{A}^*)}$$

reduced operators restr to $N(\mathrm{A})^\perp$ and $N(\mathrm{A}^*)^\perp$

$$\mathcal{A} := \mathrm{A}|_{N(\mathrm{A})^\perp} = \mathrm{A}|_{\overline{R(\mathrm{A}^*)}} \qquad \mathcal{A}^* := \mathrm{A}^*|_{N(\mathrm{A}^*)^\perp} = \mathrm{A}^*|_{\overline{R(\mathrm{A})}}$$

$\mathcal{A}$, $\mathcal{A}^*$ inj $\quad \Rightarrow \quad \mathcal{A}^{-1}$, $(\mathcal{A}^*)^{-1}$ ex

1st fundamental observations

$\mathrm{A} : D(\mathrm{A}) \subset \mathrm{H}_0 \to \mathrm{H}_1, \quad \mathrm{A}^* : D(\mathrm{A}^*) \subset \mathrm{H}_1 \to \mathrm{H}_0$ lddc $\qquad (\mathrm{A}, \mathrm{A}^*)$ dual pair

$$\mathrm{H}_1 = N(\mathrm{A}^*) \oplus \overline{R(\mathrm{A})} \qquad \mathrm{H}_0 = N(\mathrm{A}) \oplus \overline{R(\mathrm{A}^*)}$$

more precisely

$$\mathcal{A} := \mathrm{A}|_{\overline{R(\mathrm{A}^*)}} : D(\mathcal{A}) \subset \overline{R(\mathrm{A}^*)} \to \overline{R(\mathrm{A})}, \qquad D(\mathcal{A}) := D(\mathrm{A}) \cap N(\mathrm{A})^{\perp} = D(\mathrm{A}) \cap \overline{R(\mathrm{A}^*)}$$
$$\mathcal{A}^* := \mathrm{A}^*|_{\overline{R(\mathrm{A})}} : D(\mathcal{A}^*) \subset \overline{R(\mathrm{A})} \to \overline{R(\mathrm{A}^*)}, \quad D(\mathcal{A}^*) := D(\mathrm{A}^*) \cap N(\mathrm{A}^*)^{\perp} = D(\mathrm{A}^*) \cap \overline{R(\mathrm{A})}$$

$(\mathcal{A}, \mathcal{A}^*)$ dual pair and $\mathcal{A}$, $\mathcal{A}^*$ inj $\Rightarrow$

inverse ops exist (and bij)

$$\mathcal{A}^{-1} : R(\mathrm{A}) \to D(\mathcal{A}) \qquad (\mathcal{A}^*)^{-1} : R(\mathrm{A}^*) \to D(\mathcal{A}^*)$$

refined decompositions

$$D(\mathrm{A}) = N(\mathrm{A}) \oplus D(\mathcal{A}) \qquad D(\mathrm{A}^*) = N(\mathrm{A}^*) \oplus D(\mathcal{A}^*)$$

$\Rightarrow$

$$R(\mathrm{A}) = R(\mathcal{A}) \qquad R(\mathrm{A}^*) = R(\mathcal{A}^*)$$

1st fundamental observations

closed range theorem & closed graph theorem $\Rightarrow$

Lemma (Friedrichs-Poincaré type est/cl range/cont inv)

The following assertions are equivalent:

- **(i)** $\exists\, c_{\mathrm{A}} \in (0,\infty) \quad \forall\, x \in D(\mathcal{A}) \qquad |x|_{\mathrm{H}_0} \le c_{\mathrm{A}} |\mathrm{A}x|_{\mathrm{H}_1}$
- **(i*)** $\exists\, c_{\mathrm{A}^*} \in (0,\infty) \quad \forall\, y \in D(\mathcal{A}^*) \qquad |y|_{\mathrm{H}_1} \le c_{\mathrm{A}^*} |\mathrm{A}^* y|_{\mathrm{H}_0}$
- **(ii)** $R(\mathrm{A}) = R(\mathcal{A})$ *is closed in* H_1.
- **(ii*)** $R(\mathrm{A}^*) = R(\mathcal{A}^*)$ *is closed in* H_0.
- **(iii)** $\mathcal{A}^{-1} : R(\mathrm{A}) \to D(\mathcal{A})$ *is continuous and bijective.*
- **(iii*)** $(\mathcal{A}^*)^{-1} : R(\mathrm{A}^*) \to D(\mathcal{A}^*)$ *is continuous and bijective.*

In case that one of the latter assertions is true, e.g., (ii), $R(\mathrm{A})$ *is closed, we have*

$$\mathrm{H}_0 = N(\mathrm{A}) \oplus R(\mathrm{A}^*) \qquad \mathrm{H}_1 = N(\mathrm{A}^*) \oplus R(\mathrm{A})$$

$$D(\mathrm{A}) = N(\mathrm{A}) \oplus D(\mathcal{A}) \qquad D(\mathrm{A}^*) = N(\mathrm{A}^*) \oplus D(\mathcal{A}^*)$$

$$D(\mathcal{A}) = D(\mathrm{A}) \cap R(\mathrm{A}^*) \qquad D(\mathcal{A}^*) = D(\mathrm{A}^*) \cap R(\mathrm{A})$$

and $\quad \mathcal{A} : D(\mathcal{A}) \subset R(\mathrm{A}^*) \to R(\mathrm{A}), \quad \mathcal{A}^* : D(\mathcal{A}^*) \subset R(\mathrm{A}) \to R(\mathrm{A}^*).$

Note: trivial equivalence to inf-sup condition

1st fundamental observations

recall

(i) $\exists\, c_{\mathrm{A}} \in (0,\infty) \quad \forall\, x \in D(\mathcal{A}) \qquad |x|_{\mathrm{H}_0} \leq c_{\mathrm{A}} |\mathrm{A}x|_{\mathrm{H}_1}$

(i*) $\exists\, c_{\mathrm{A}^*} \in (0,\infty) \quad \forall\, y \in D(\mathcal{A}^*) \qquad |y|_{\mathrm{H}_1} \leq c_{\mathrm{A}^*} |\mathrm{A}^* y|_{\mathrm{H}_0}$

'best' consts in **(i)** and **(i*)** equal norms of the inv ops and Rayleigh quotients

$$c_{\mathrm{A}} = |\mathcal{A}^{-1}|_{R(\mathrm{A}),R(\mathrm{A}^*)} \qquad c_{\mathrm{A}^*} = |(\mathcal{A}^*)^{-1}|_{R(\mathrm{A}^*),R(\mathrm{A})}$$

$$\frac{1}{c_{\mathrm{A}}} = \inf_{0 \neq x \in D(\mathcal{A})} \frac{|\mathrm{A}x|_{\mathrm{H}_1}}{|x|_{\mathrm{H}_0}} \qquad \frac{1}{c_{\mathrm{A}^*}} = \inf_{0 \neq y \in D(\mathcal{A}^*)} \frac{|\mathrm{A}^* y|_{\mathrm{H}_0}}{|y|_{\mathrm{H}_1}}$$

Lemma (Friedrichs-Poincaré type const)

$c_{\mathrm{A}} = c_{\mathrm{A}^*}$

1st fundamental observations

Lemma (cpt emb/cpt inv)

The following assertions are equivalent:

(i) $D(\mathcal{A}) \hookrightarrow\!\!\!\rightarrow \mathrm{H}_0$ *is compact.*

(i*) $D(\mathcal{A}^*) \hookrightarrow\!\!\!\rightarrow \mathrm{H}_1$ *is compact.*

(ii) $\mathcal{A}^{-1} : R(\mathrm{A}) \to R(\mathrm{A}^*)$ *is compact.*

(ii*) $(\mathcal{A}^*)^{-1} : R(\mathrm{A}^*) \to R(\mathrm{A})$ *is compact.*

Lemma (Friedrichs-Poincaré type est/cl range/cont inv)

$\Downarrow$ $\boxed{D(\mathcal{A}) \hookrightarrow\!\!\!\rightarrow \mathrm{H}_0 \text{ compact}}$

(i) $\exists\, c_\mathrm{A} \in (0,\infty) \quad \forall\, x \in D(\mathcal{A}) \qquad |x|_{\mathrm{H}_0} \leq c_\mathrm{A} |\mathrm{A}x|_{\mathrm{H}_1}$

(i*) $\exists\, c_{\mathrm{A}^*} \in (0,\infty) \quad \forall\, y \in D(\mathcal{A}^*) \qquad |y|_{\mathrm{H}_1} \leq c_{\mathrm{A}^*} |\mathrm{A}^* y|_{\mathrm{H}_0}$

(ii) $R(\mathrm{A}) = R(\mathcal{A})$ *is closed in* H_1.

(ii*) $R(\mathrm{A}^*) = R(\mathcal{A}^*)$ *is closed in* H_0.

(iii) $\mathcal{A}^{-1} : R(\mathrm{A}) \to D(\mathcal{A})$ *is continuous and bijective.*

(iii*) $(\mathcal{A}^*)^{-1} : R(\mathrm{A}^*) \to D(\mathcal{A}^*)$ *is continuous and bijective.*

(i)-(iii*) *equi & the resp Helm deco hold &* $|\mathcal{A}^{-1}| = c_\mathrm{A} = c_{\mathrm{A}^*} = |(\mathcal{A}^*)^{-1}|$

2nd fundamental observations

So far no complex...

$$\mathrm{A}_0 : D(\mathrm{A}_0) \subset \mathrm{H}_0 \to \mathrm{H}_1, \quad \mathrm{A}_1 : D(\mathrm{A}_1) \subset \mathrm{H}_1 \to \mathrm{H}_2 \text{ (lddc)}$$
$$\mathrm{A}_0^* : D(\mathrm{A}_0^*) \subset \mathrm{H}_1 \to \mathrm{H}_0, \quad \mathrm{A}_1^* : D(\mathrm{A}_1^*) \subset \mathrm{H}_2 \to \mathrm{H}_1 \text{ (lddc)}$$

general complex ($\mathrm{A}_1\mathrm{A}_0 = 0$, i.e., $R(\mathrm{A}_0) \subset N(\mathrm{A}_1)$ and $R(\mathrm{A}_1^*) \subset N(\mathrm{A}_0^*)$)

$$\cdots \underset{\cdots}{\overset{\cdots}{\rightleftarrows}} \mathrm{H}_0 \underset{\mathrm{A}_0^*}{\overset{\mathrm{A}_0}{\rightleftarrows}} \mathrm{H}_1 \underset{\mathrm{A}_1^*}{\overset{\mathrm{A}_1}{\rightleftarrows}} \mathrm{H}_2 \underset{\cdots}{\overset{\cdots}{\rightleftarrows}} \cdots$$

recall Helmholtz deco

$$\begin{array}{ccccc} \mathrm{H}_1 = & \overline{R(\mathrm{A}_0)} & \oplus & N(\mathrm{A}_0^*) \\ & \cap & & \cup \\ = & N(\mathrm{A}_1) & \oplus & \overline{R(\mathrm{A}_1^*)} \end{array} \qquad \Rightarrow \text{ (e.g.) } N(\mathrm{A}_1) = \overline{R(\mathrm{A}_0)} \oplus \big(\underbrace{N(\mathrm{A}_1) \cap N(\mathrm{A}_0^*)}_{=:K_1}\big)$$

$\Rightarrow$ refined Helmholtz deco

$$\mathrm{H}_1 = \overline{R(\mathrm{A}_0)} \oplus K_1 \oplus \overline{R(\mathrm{A}_1^*)}$$

2nd fundamental observations

recall

$$D(\mathrm{A}_1) = D(\mathcal{A}_1) \cap \overline{R(\mathrm{A}_1^*)} \qquad R(\mathrm{A}_1) = R(\mathcal{A}_1) \qquad R(\mathrm{A}_1^*) = R(\mathcal{A}_1^*)$$

$$D(\mathrm{A}_0^*) = D(\mathcal{A}_0^*) \cap \overline{R(\mathrm{A}_0)} \qquad R(\mathrm{A}_0^*) = R(\mathcal{A}_0^*) \qquad R(\mathrm{A}_0) = R(\mathcal{A}_0)$$

cohomology group $K_1 = N(\mathrm{A}_1) \cap N(\mathrm{A}_0^*)$

Lemma (Helmholtz deco I)

$$\mathrm{H}_1 = \overline{R(\mathrm{A}_0)} \oplus N(\mathrm{A}_0^*) \qquad \mathrm{H}_1 = \overline{R(\mathrm{A}_1^*)} \oplus N(\mathrm{A}_1)$$

$$D(\mathrm{A}_0^*) = D(\mathcal{A}_0^*) \oplus N(\mathrm{A}_0^*) \qquad D(\mathrm{A}_1) = D(\mathcal{A}_1) \oplus N(\mathrm{A}_1)$$

$$N(\mathrm{A}_1) = D(\mathcal{A}_0^*) \oplus K_1 \qquad N(\mathrm{A}_0^*) = D(\mathcal{A}_1) \oplus K_1$$

$$D(\mathrm{A}_1) = \overline{R(\mathrm{A}_0)} \oplus \big(D(\mathrm{A}_1) \cap N(\mathrm{A}_0^*)\big) \qquad D(\mathrm{A}_0^*) = \overline{R(\mathrm{A}_1^*)} \oplus \big(D(\mathrm{A}_0^*) \cap N(\mathrm{A}_1)\big)$$

Lemma (Helmholtz deco II)

$$\mathrm{H}_1 = \overline{R(\mathrm{A}_0)} \oplus K_1 \oplus \overline{R(\mathrm{A}_1^*)}$$

$$D(\mathrm{A}_1) = \overline{R(\mathrm{A}_0)} \oplus K_1 \oplus D(\mathcal{A}_1)$$

$$D(\mathrm{A}_0^*) = D(\mathcal{A}_0^*) \oplus K_1 \oplus \overline{R(\mathrm{A}_1^*)}$$

$$D(\mathrm{A}_1) \cap D(\mathrm{A}_0^*) = D(\mathcal{A}_0^*) \oplus K_1 \oplus D(\mathcal{A}_1)$$

2nd fundamental observations

$$K_1 = N(\mathrm{A}_1) \cap N(\mathrm{A}_0^*) \qquad D(\mathrm{A}_1) = D(\mathcal{A}_1) \cap \overline{R(\mathrm{A}_1^*)} \qquad D(\mathrm{A}_0^*) = D(\mathcal{A}_0^*) \cap \overline{R(\mathrm{A}_0)}$$

Lemma (cpt emb II)

The following assertions are equivalent:

(i) $D(\mathcal{A}_0) \hookrightarrow\!\!\!\!\rightarrow \mathrm{H}_0$, $D(\mathcal{A}_1) \hookrightarrow\!\!\!\!\rightarrow \mathrm{H}_1$, *and* $K_1 \hookrightarrow\!\!\!\!\rightarrow \mathrm{H}_1$ *are compact.*

(ii) $D(\mathrm{A}_1) \cap D(\mathrm{A}_0^*) \hookrightarrow\!\!\!\!\rightarrow \mathrm{H}_1$ *is compact.*

In this case $K_1 < \infty$.

Theorem (fa-toolbox I)

$\Downarrow$ $\boxed{D(\mathrm{A}_1) \cap D(\mathrm{A}_0^*) \hookrightarrow\!\!\!\!\rightarrow \mathrm{H}_1 \textit{ compact}}$

(i) *all emb cpt, i.e.,* $D(\mathcal{A}_0) \hookrightarrow\!\!\!\!\rightarrow \mathrm{H}_0$, $D(\mathcal{A}_1) \hookrightarrow\!\!\!\!\rightarrow \mathrm{H}_1$, $D(\mathcal{A}_0^*) \hookrightarrow\!\!\!\!\rightarrow \mathrm{H}_1$, $D(\mathcal{A}_1^*) \hookrightarrow\!\!\!\!\rightarrow \mathrm{H}_2$ *cpt*

(ii) *cohomology group* K_1 *finite dim*

(iii) *all ranges closed, i.e.,* $R(\mathrm{A}_0)$, $R(\mathrm{A}_0^*)$, $R(\mathrm{A}_1)$, $R(\mathrm{A}_1^*)$ *cl*

(iv) *all Friedrichs-Poincaré type est hold*

(v) *all Hodge-Helmholtz-Weyl type deco I & II hold with closed ranges*

2nd fundamental observations

complex $\cdots \underset{\cdots}{\overset{\cdots}{\rightleftarrows}} \mathrm{H}_0 \underset{\mathrm{A}_0^*}{\overset{\mathrm{A}_0}{\rightleftarrows}} \mathrm{H}_1 \underset{\mathrm{A}_1^*}{\overset{\mathrm{A}_1}{\rightleftarrows}} \mathrm{H}_2 \underset{\cdots}{\overset{\cdots}{\rightleftarrows}} \cdots$

Theorem (fa-toolbox I (Friedrichs-Poincaré type est))

$\Downarrow$ $\boxed{D(\mathrm{A}_1) \cap D(\mathrm{A}_0^*) \hookrightarrow\!\!\!\!\rightarrow \mathrm{H}_1 \text{ compact}}$ $\Rightarrow$ $\exists$ $|\mathcal{A}_i^{-1}| = c_{\mathrm{A}_i} = c_{\mathrm{A}_i^*} = |(\mathcal{A}_i^*)^{-1}| \in (0, \infty)$

(i) $\forall\, x \in D(\mathcal{A}_0)$ $\quad |x|_{\mathrm{H}_0} \le c_{\mathrm{A}_0} |\mathrm{A}_0 x|_{\mathrm{H}_1}$

(i*) $\forall\, y \in D(\mathcal{A}_0^*)$ $\quad |y|_{\mathrm{H}_1} \le c_{\mathrm{A}_0} |\mathrm{A}_0^* y|_{\mathrm{H}_0}$

(ii) $\forall\, y \in D(\mathcal{A}_1)$ $\quad |y|_{\mathrm{H}_1} \le c_{\mathrm{A}_1} |\mathrm{A}_1 y|_{\mathrm{H}_2}$

(ii*) $\forall\, z \in D(\mathcal{A}_1^*)$ $\quad |z|_{\mathrm{H}_2} \le c_{\mathrm{A}_1} |\mathrm{A}_1^* z|_{\mathrm{H}_1}$

(iii) $\forall\, y \in D(\mathrm{A}_1) \cap D(\mathrm{A}_0^*)$ $\quad |(1 - \pi_{K_1})y|_{\mathrm{H}_1} \le c_{\mathrm{A}_1} |\mathrm{A}_1 y|_{\mathrm{H}_2} + c_{\mathrm{A}_0} |\mathrm{A}_0^* y|_{\mathrm{H}_0}$

note $\pi_{K_1} y \in K_1$ and $(1 - \pi_{K_1}) y \in K_1^\perp$

Remark

enough $R(\mathrm{A}_0)$ *and* $R(\mathrm{A}_1)$ *cl*

2nd fundamental observations

complex $\quad \cdots \underset{\cdots}{\overset{\cdots}{\rightleftarrows}} \mathrm{H}_0 \underset{\mathrm{A}_0^*}{\overset{\mathrm{A}_0}{\rightleftarrows}} \mathrm{H}_1 \underset{\mathrm{A}_1^*}{\overset{\mathrm{A}_1}{\rightleftarrows}} \mathrm{H}_2 \underset{\cdots}{\overset{\cdots}{\rightleftarrows}} \cdots$

Theorem (fa-toolbox I (Helmholtz deco))

$\Downarrow$ $\boxed{D(\mathrm{A}_1) \cap D(\mathrm{A}_0^*) \hookrightarrow\!\!\!\rightarrow \mathrm{H}_1 \textit{ compact}}$

$$\begin{aligned} \mathrm{H}_1 &= R(\mathrm{A}_0) \oplus N(\mathrm{A}_0^*) \\ D(\mathrm{A}_0^*) &= D(\mathcal{A}_0^*) \oplus N(\mathrm{A}_0^*) \\ N(\mathrm{A}_1) &= D(\mathcal{A}_0^*) \oplus K_1 \\ D(\mathrm{A}_1) &= R(\mathrm{A}_0) \oplus \big(D(\mathrm{A}_1) \cap N(\mathrm{A}_0^*)\big) \end{aligned}$$

$$\begin{aligned} \mathrm{H}_1 &= R(\mathrm{A}_1^*) \oplus N(\mathrm{A}_1) \\ D(\mathrm{A}_1) &= D(\mathcal{A}_1) \oplus N(\mathrm{A}_1) \\ N(\mathrm{A}_0^*) &= D(\mathcal{A}_1) \oplus K_1 \\ D(\mathrm{A}_0^*) &= R(\mathrm{A}_1^*) \oplus \big(D(\mathrm{A}_0^*) \cap N(\mathrm{A}_1)\big) \end{aligned}$$

$$\begin{aligned} \mathrm{H}_1 &= R(\mathrm{A}_0) \oplus K_1 \oplus R(\mathrm{A}_1^*) \\ D(\mathrm{A}_1) &= R(\mathrm{A}_0) \oplus K_1 \oplus D(\mathcal{A}_1) \\ D(\mathrm{A}_0^*) &= D(\mathcal{A}_0^*) \oplus K_1 \oplus R(\mathrm{A}_1^*) \\ D(\mathrm{A}_1) \cap D(\mathrm{A}_0^*) &= D(\mathcal{A}_0^*) \oplus K_1 \oplus D(\mathcal{A}_1) \end{aligned}$$

Remark

enough $R(\mathrm{A}_0)$ *and* $R(\mathrm{A}_1)$ *cl*

(stat) first order system - solution theory

complex $\cdots \underset{\cdots}{\overset{\cdots}{\rightleftarrows}} \mathrm{H}_0 \underset{\mathrm{A}_0^*}{\overset{\mathrm{A}_0}{\rightleftarrows}} \mathrm{H}_1 \underset{\mathrm{A}_1^*}{\overset{\mathrm{A}_1}{\rightleftarrows}} \mathrm{H}_2 \underset{\cdots}{\overset{\cdots}{\rightleftarrows}} \cdots$

$\boxed{\mathrm{A}_1 x = f}$ $\dim N(\mathrm{A}_1) = \infty$

find $x \in D(\mathrm{A}_1) \cap D(\mathrm{A}_0^*)$ such that the fos

$$\begin{aligned} \mathrm{A}_1 x &= f \\ \mathrm{A}_0^* x &= g \\ \pi_{K_1} x &= k \end{aligned} \qquad \text{think of} \qquad \begin{aligned} (\mathring{\mathrm{rot}} E &= F) \\ (-\operatorname{div} E &= g) \\ (\pi_{\mathrm{D}} E &= K) \end{aligned}$$

kernel = cohomology group = $K_1 = N(\mathrm{A}_1) \cap N(\mathrm{A}_0^*)$

trivially necessary $f \in R(\mathrm{A}_1)$ $g \in R(\mathrm{A}_0^*)$ $k \in K_1$

apply fa-toolbox

(stat) first order system - solution theory

complex $\cdots \underset{\cdots}{\overset{\cdots}{\rightleftarrows}} \mathrm{H}_0 \underset{\mathrm{A}_0^*}{\overset{\mathrm{A}_0}{\rightleftarrows}} \mathrm{H}_1 \underset{\mathrm{A}_1^*}{\overset{\mathrm{A}_1}{\rightleftarrows}} \mathrm{H}_2 \underset{\cdots}{\overset{\cdots}{\rightleftarrows}} \cdots$

find $x \in D(\mathrm{A}_1) \cap D(\mathrm{A}_0^*)$ st fos $\qquad \mathrm{A}_1 x = f \qquad \mathrm{A}_0^* x = g \qquad \pi_{K_1} x = k$

Theorem (fa-toolbox II (solution theory))

$\Downarrow$ $\boxed{D(\mathrm{A}_1) \cap D(\mathrm{A}_0^*) \hookrightarrow\!\!\!\!\rightarrow \mathrm{H}_1 \text{ compact}}$

fos is uniq sol $\Leftrightarrow$ $f \in R(\mathrm{A}_1) \qquad g \in R(\mathrm{A}_0^*) \qquad k \in K_1$

$$x := x_f + x_g + k \in D(\mathcal{A}_1) \oplus D(\mathcal{A}_0^*) \oplus K_1 = D(\mathrm{A}_1) \cap D(\mathrm{A}_0^*)$$

$$\boxed{x_f := \mathcal{A}_1^{-1} f} \in D(\mathcal{A}_1)$$

$$\boxed{x_g := (\mathcal{A}_0^*)^{-1} g} \in D(\mathcal{A}_0^*)$$

dep cont on data $|x|_{\mathrm{H}_1} \le |x_f|_{\mathrm{H}_1} + |x_g|_{\mathrm{H}_1} + |k|_{\mathrm{H}_1} \le c_{\mathrm{A}_1} |f|_{\mathrm{H}_2} + c_{\mathrm{A}_0} |g|_{\mathrm{H}_0} + |k|_{\mathrm{H}_1}$

moreover

$$\pi_{R(\mathrm{A}_1^*)} x = x_f \qquad \pi_{R(\mathrm{A}_0)} x = x_g \qquad \pi_{K_1} x = k \qquad |x|_{\mathrm{H}_1}^2 = |x_f|_{\mathrm{H}_1}^2 + |x_g|_{\mathrm{H}_1}^2 + |k|_{\mathrm{H}_1}^2$$

Remark

enough $R(\mathrm{A}_0)$ *and* $R(\mathrm{A}_1)$ *cl*

(stat) first order system - variational formulations

$$x := x_f + x_g + k \in D(\mathcal{A}_1) \oplus D(\mathcal{A}_0^*) \oplus K_1 = D(\mathrm{A}_1) \cap D(\mathrm{A}_0^*)$$
$$x_f := \mathcal{A}_1^{-1} f \in D(\mathcal{A}_1) = D(\mathrm{A}_1) \cap R(\mathrm{A}_1^*) = D(\mathrm{A}_1) \cap N(\mathrm{A}_0^*) \cap K_1^\perp$$
$$x_g := (\mathcal{A}_0^*)^{-1} g \in D(\mathcal{A}_0^*) = D(\mathrm{A}_0^*) \cap R(\mathrm{A}_0) = D(\mathrm{A}_0^*) \cap N(\mathrm{A}_1) \cap K_1^\perp$$

$$\begin{aligned} \mathrm{A}_1 x &= f \\ \mathrm{A}_0^* x &= g \\ \pi_{K_1} x &= k \end{aligned} \qquad \begin{aligned} \mathrm{A}_1 x_f &= f \\ \mathrm{A}_0^* x_f &= 0 \\ \pi_{K_1} x_f &= 0 \end{aligned} \qquad \begin{aligned} \mathrm{A}_1 x_g &= 0 \\ \mathrm{A}_0^* x_g &= g \\ \pi_{K_1} x_g &= 0 \end{aligned} \qquad \begin{aligned} \mathrm{A}_1 k &= 0 \\ \mathrm{A}_0^* k &= 0 \\ \pi_{K_1} k &= k \end{aligned}$$

- option I: find x_f and x_g separately $\Rightarrow$ $x = x_f + x_g + k$
- option II: find x directly

(stat) first order system - variational formulations I

finding

$$x_f := \mathcal{A}_1^{-1} f \in D(\mathcal{A}_1) = D(\mathrm{A}_1) \cap \underbrace{R(\mathrm{A}_1^*)}_{=R(\mathcal{A}_1^*)} = D(\mathrm{A}_1) \cap N(\mathrm{A}_0^*) \cap K_1^\perp$$

$$\mathrm{A}_1 x_f = f$$

$$\mathrm{A}_0^* x_f = 0$$

$$\pi_{K_1} x_f = 0$$

at least two options

- option Ia: multiply $\mathrm{A}_1 x_f = f$ by $\mathrm{A}_1 \xi$ $\Rightarrow$

$$\forall\, \xi \in D(\mathcal{A}_1) \qquad \langle \mathrm{A}_1 x_f, \mathrm{A}_1 \xi \rangle_{\mathrm{H}_2} = \langle f, \mathrm{A}_1 \xi \rangle_{\mathrm{H}_2}$$

  weak form of $\boxed{\mathrm{A}_1^* \mathrm{A}_1 x_f = \mathrm{A}_1^* f}$

- option Ib: repr $x_f = \mathrm{A}_1^* y_f$ with potential $y_f = (\mathcal{A}_1^*)^{-1} x_f \in D(\mathcal{A}_1^*)$
  and mult by x_f by $\mathrm{A}_1^* \phi$ $\Rightarrow$

$$\forall\, \phi \in D(\mathcal{A}_1^*) \qquad \langle \mathrm{A}_1^* y_f, \mathrm{A}_1^* \phi \rangle_{\mathrm{H}_1} = \langle x_f, \mathrm{A}_1^* \phi \rangle_{\mathrm{H}_1} = \langle \mathrm{A}_1 x_f, \phi \rangle_{\mathrm{H}_2} = \langle f, \phi \rangle_{\mathrm{H}_2}$$

  weak form of $\boxed{\mathrm{A}_1 x_f = f}$ and $\boxed{\mathrm{A}_1 \mathrm{A}_1^* y_f = f}$

analogously for x_g

(stat) first order system - a posteriori error estimates

problem: find $x \in D(\mathrm{A}_1) \cap D(\mathrm{A}_0^*)$ st $\mathrm{A}_1 x = f$ $\mathrm{A}_0^* x = g$ $\pi_{K_1} x = k$

'very' non-conforming 'approximation' of x: $\tilde{x} \in \mathrm{H}_1$

def., dcmp. err. $e = x - \tilde{x} = \pi_{R(\mathrm{A}_0)} e + \pi_{K_1} e + \pi_{R(\mathrm{A}_1^*)} e \in \mathrm{H}_1 = R(\mathrm{A}_0) \oplus K_1 \oplus R(\mathrm{A}_1^*)$

Theorem (sharp upper bounds)

Let $\tilde{x} \in \mathrm{H}_1$ *and* $e = x - \tilde{x}$. *Then*

$$|e|_{\mathrm{H}_1}^2 = |\pi_{R(\mathrm{A}_0)} e|_{\mathrm{H}_1}^2 + |\pi_{K_1} e|_{\mathrm{H}_1}^2 + |\pi_{R(\mathrm{A}_1^*)} e|_{\mathrm{H}_1}^2$$

$$|\pi_{R(\mathrm{A}_0)} e|_{\mathrm{H}_1} = \min_{\phi \in D(\mathrm{A}_0^*)} \big(c_{\mathrm{A}_0} |\mathrm{A}_0^* \phi - g|_{\mathrm{H}_0} + |\phi - \tilde{x}|_{\mathrm{H}_1} \big)$$

reg $(\mathrm{A}_0 \mathrm{A}_0^* + 1)$*-prbl in* $D(\mathrm{A}_0^*)$

$$|\pi_{R(\mathrm{A}_1^*)} e|_{\mathrm{H}_1} = \min_{\varphi \in D(\mathrm{A}_1)} \big(c_{\mathrm{A}_1} |\mathrm{A}_1 \varphi - f|_{\mathrm{H}_2} + |\varphi - \tilde{x}|_{\mathrm{H}_1} \big)$$

reg $(\mathrm{A}_1^* \mathrm{A}_1 + 1)$*-prbl in* $D(\mathrm{A}_1)$

$$|\pi_{K_1} e|_{\mathrm{H}_1} = |\pi_{K_1} \tilde{x} - k|_{\mathrm{H}_1} = \min_{\substack{\xi \in D(\mathrm{A}_0) \\ \zeta \in D(\mathrm{A}_1^*)}} |\mathrm{A}_0 \xi + \mathrm{A}_1^* \zeta + \tilde{x} - k|_{\mathrm{H}_1}$$

cpld $(\mathrm{A}_0^* \mathrm{A}_0)$*-*$(\mathrm{A}_1 \mathrm{A}_1^*)$*-sys in* $D(\mathcal{A}_0)$*-*$D(\mathcal{A}_1^*)$

Remark

Even $\pi_{K_1} e = k - \pi_{K_1} \tilde{x}$ *and the minima are attained at*

$$\hat{\phi} = \pi_{R(\mathrm{A}_0)} e + \tilde{x}, \qquad \hat{\varphi} = \pi_{R(\mathrm{A}_1^*)} e + \tilde{x}, \qquad \mathrm{A}_0 \hat{\xi} + \mathrm{A}_1^* \hat{\zeta} = (\pi_{K_1} - 1) \tilde{x}.$$

A_0^*-A_1-lemma (generalized global div-curl-lemma)

Lemma (A_0^*-A_1-lemma)

Let $D(A_1) \cap D(A_0^*) \hookrightarrow H_1$ be compact, and

(i) (x_n) *bounded in* $D(A_1)$,

(ii) (y_n) *bounded in* $D(A_0^*)$.

$\Rightarrow \exists\ x \in D(A_1)$, $y \in D(A_0^*)$ *and subsequences st*

$x_n \rightharpoonup x$ *in* $D(A_1)$ *and* $y_n \rightharpoonup y$ *in* $D(A_0^*)$ *as well as*

$$\langle x_n, y_n \rangle_{H_1} \to \langle x, y \rangle_{H_1}.$$

A_0^*-A_1-lemma (generalized global div-curl-lemma)

Lemma (generalized A_0^*-A_1-lemma)

Let $R(A_0)$ and $R(A_1$ be closed, and let K_1 be finite dimensional. Moreover, let $(x_n), (y_n) \subset H_1$ be bounded such that

(i) $\widetilde{A}_1(x_n)$ *is relatively compact in* $D(A_1^*)'$,

(ii) $\widetilde{A}_0^*(y_n)$ *is relatively compact in* $D(A_0)'$.

$\Rightarrow \exists\ x, y \in H_1$ *and subsequences st* $x_n \rightharpoonup x$ *in* H_1 *and* $y_n \rightharpoonup y$ *in* H_1 *as well as*

$$\langle x_n, y_n\rangle_{H_1} \to \langle x, y\rangle_{H_1}.$$

proof uses key observation

Lemma

Let $R(A)$ be closed. For $(x_n) \subset H_0$ the following statements are equivalent:

(i) $\widetilde{A}x_n$ *is relatively compact in* $D(A^*)'$.

(ii) $\pi_{R(A^*)}x_n$ *is relatively compact in* $R(A^*)$ *resp.* H_1.

If $x_n \rightharpoonup x$ in H_1, then either of cond. (i) or (ii) implies $\pi_{R(A^*)}x_n \to \pi_{R(A^*)}x$ in H_1.

nice results (and joint work/communication with) Marcus Waurick

classical de Rham complex in 3D (∇-rot-div-complex)

$\Omega \subset \mathbb{R}^3$ bounded weak Lipschitz domain, $\partial\Omega = \Gamma = \overline{\Gamma_t \dot\cup \Gamma_n}$

(electro-magneto dynamics, Maxwell's equations)

$$\{0\} \;\underset{\pi_{\{0\}}}{\overset{\iota_{\{0\}}}{\rightleftarrows}}\; \mathsf{L}^2 \;\underset{-\operatorname{div}}{\overset{\mathring{\nabla}}{\rightleftarrows}}\; \mathsf{L}^2 \;\underset{\operatorname{rot}}{\overset{\mathring{\operatorname{rot}}}{\rightleftarrows}}\; \mathsf{L}^2 \;\underset{-\nabla}{\overset{\mathring{\operatorname{div}}}{\rightleftarrows}}\; \mathsf{L}^2 \;\underset{\iota_{\mathbb{R}}}{\overset{\pi_{\mathbb{R}}}{\rightleftarrows}}\; \mathbb{R}$$

mixed boundary conditions and inhomogeneous and anisotropic media

$$\{0\} \text{ or } \mathbb{R} \;\underset{\pi}{\overset{\iota}{\rightleftarrows}}\; \mathsf{L}^2 \;\underset{-\operatorname{div}_{\Gamma_n}\varepsilon}{\overset{\nabla_{\Gamma_t}}{\rightleftarrows}}\; \mathsf{L}^2_{\varepsilon} \;\underset{\varepsilon^{-1}\operatorname{rot}_{\Gamma_n}}{\overset{\operatorname{rot}_{\Gamma_t}}{\rightleftarrows}}\; \mathsf{L}^2 \;\underset{-\nabla_{\Gamma_n}}{\overset{\operatorname{div}_{\Gamma_t}}{\rightleftarrows}}\; \mathsf{L}^2 \;\underset{\iota}{\overset{\pi}{\rightleftarrows}}\; \mathbb{R} \text{ or } \{0\}$$

classical de Rham complex in 3D (∇-rot-div-complex)

$\Omega \subset \mathbb{R}^3$ bounded weak Lipschitz domain, $\partial\Omega = \Gamma = \overline{\Gamma_t \dot{\cup} \Gamma_n}$

(electro-magneto dynamics, Maxwell's equations with mixed boundary conditions)

$$\{0\} \text{ or } \mathbb{R} \; \underset{\pi}{\overset{\iota}{\rightleftarrows}} \; \mathsf{L}^2 \; \underset{-\operatorname{div}_{\Gamma_n} \varepsilon}{\overset{\nabla_{\Gamma_t}}{\rightleftarrows}} \; \mathsf{L}^2_\varepsilon \; \underset{\varepsilon^{-1}\operatorname{rot}_{\Gamma_n}}{\overset{\operatorname{rot}_{\Gamma_t}}{\rightleftarrows}} \; \mathsf{L}^2 \; \underset{-\nabla_{\Gamma_n}}{\overset{\operatorname{div}_{\Gamma_t}}{\rightleftarrows}} \; \mathsf{L}^2 \; \underset{\iota}{\overset{\pi}{\rightleftarrows}} \; \mathbb{R} \text{ or } \{0\}$$

related fos

$$\begin{array}{rl|rl|rl|rl} \nabla_{\Gamma_t} u = A & \text{in } \Omega & \operatorname{rot}_{\Gamma_t} E = J & \text{in } \Omega & \operatorname{div}_{\Gamma_t} H = k & \text{in } \Omega & \pi v = b & \text{in } \Omega \\ \pi u = a & \text{in } \Omega & -\operatorname{div}_{\Gamma_n} \varepsilon E = j & \text{in } \Omega & \varepsilon^{-1}\operatorname{rot}_{\Gamma_n} H = K & \text{in } \Omega & -\nabla_{\Gamma_n} v = B & \text{in } \Omega \end{array}$$

related sos

$$\begin{array}{rl|rl|rl} -\operatorname{div}_{\Gamma_n} \varepsilon \nabla_{\Gamma_t} u = j & \text{in } \Omega & \varepsilon^{-1}\operatorname{rot}_{\Gamma_n}\operatorname{rot}_{\Gamma_t} E = K & \text{in } \Omega & -\nabla_{\Gamma_n}\operatorname{div}_{\Gamma_t} H = B & \text{in } \Omega \\ \pi u = a & \text{in } \Omega & -\operatorname{div}_{\Gamma_n} \varepsilon E = j & \text{in } \Omega & \varepsilon^{-1}\operatorname{rot}_{\Gamma_n} H = K & \text{in } \Omega \end{array}$$

corresponding compact embeddings:

$$D(\nabla_{\Gamma_t}) \cap D(\pi) = D(\nabla_{\Gamma_t}) = \mathsf{H}^1_{\Gamma_t} \hookrightarrow \mathsf{L}^2 \qquad \text{(Rellich's selection theorem)}$$

$$D(\operatorname{rot}_{\Gamma_t}) \cap D(-\operatorname{div}_{\Gamma_n} \varepsilon) = \mathsf{R}_{\Gamma_t} \cap \varepsilon^{-1}\mathsf{D}_{\Gamma_n} \hookrightarrow \mathsf{L}^2_\varepsilon \qquad \text{(Weck's selection theorem, '72)}$$

$$D(\operatorname{div}_{\Gamma_t}) \cap D(\varepsilon^{-1}\operatorname{rot}_{\Gamma_n}) = \mathsf{D}_{\Gamma_t} \cap \mathsf{R}_{\Gamma_n} \hookrightarrow \mathsf{L}^2 \qquad \text{(Weck's selection theorem, '72)}$$

$$D(\nabla_{\Gamma_n}) \cap D(\pi) = D(\nabla_{\Gamma_n}) = \mathsf{H}^1_{\Gamma_n} \hookrightarrow \mathsf{L}^2 \qquad \text{(Rellich's selection theorem)}$$

Weck's selection theorem for weak Lip. dom. and mixed bc: Bauer/Py/Schomburg ('16)

Weck's selection theorem (Weck '74, (Habil. '72) stimulated by Rolf Leis)

(Weber '80, Picard '84, Costabel '90, Witsch '93, Jochmann '97, Fernandes/Gilardi '97, Kuhn '99, Picard/Weck/Witsch '01, Py '96, '03, '06, '07, '08)

classical de Rham complex in 3D (∇-rot-div-complex)

$$
\begin{aligned}
\operatorname{rot} E &= F && \text{in } \Omega \\
-\operatorname{div} \varepsilon E &= g && \text{in } \Omega \\
\nu \times E &= 0 && \text{at } \Gamma_t \\
\nu \cdot \varepsilon E &= 0 && \text{at } \Gamma_n
\end{aligned}
$$

non-trivial kernel $\mathcal{H}_{\mathrm{D},\varepsilon} = \{H \in \mathrm{L}^2 : \operatorname{rot} H = 0, \operatorname{div} \varepsilon H = 0, \nu \times H|_{\Gamma_t} = 0, \nu \cdot \varepsilon H|_{\Gamma_n} = 0\}$
additional condition on Dirichlet/Neumann fields for uniqueness

$$\pi_{\mathrm{D}} E = K \in \mathcal{H}_{\mathrm{D},\varepsilon}$$

$$\{0\} \text{ or } \mathbb{R} \;\underset{\pi}{\overset{\iota}{\rightleftarrows}}\; \mathrm{L}^2 \;\underset{-\operatorname{div}_{\Gamma_n} \varepsilon}{\overset{\nabla_{\Gamma_t}}{\rightleftarrows}}\; \mathrm{L}^2_\varepsilon \;\underset{\varepsilon^{-1} \operatorname{rot}_{\Gamma_n}}{\overset{\operatorname{rot}_{\Gamma_t}}{\rightleftarrows}}\; \mathrm{L}^2 \;\underset{-\nabla_{\Gamma_n}}{\overset{\operatorname{div}_{\Gamma_t}}{\rightleftarrows}}\; \mathrm{L}^2 \;\underset{\iota}{\overset{\pi}{\rightleftarrows}}\; \mathbb{R} \text{ or } \{0\}$$

$$\cdots \;\underset{\cdots}{\overset{\cdots}{\rightleftarrows}}\; \mathrm{H}_{-1} \;\underset{\mathrm{A}_{-1}^*}{\overset{\mathrm{A}_{-1}}{\rightleftarrows}}\; \mathrm{H}_0 \;\underset{\mathrm{A}_0^*}{\overset{\mathrm{A}_0}{\rightleftarrows}}\; \mathrm{H}_1 \;\underset{\mathrm{A}_1^*}{\overset{\mathrm{A}_1}{\rightleftarrows}}\; \mathrm{H}_2 \;\underset{\mathrm{A}_2^*}{\overset{\mathrm{A}_2}{\rightleftarrows}}\; \mathrm{H}_3 \;\underset{\mathrm{A}_3^*}{\overset{\mathrm{A}_3}{\rightleftarrows}}\; \mathrm{H}_4 \;\underset{\cdots}{\overset{\cdots}{\rightleftarrows}}\; \cdots$$

find $E \in \mathrm{R}_{\Gamma_t}(\Omega) \cap \varepsilon^{-1}\mathrm{D}_{\Gamma_n}(\Omega)$ st (fos) find $x \in D(\mathrm{A}_1) \cap D(\mathrm{A}_0^*)$ st

$$
\begin{aligned}
\operatorname{rot}_{\Gamma_t} E &= F & \qquad & \mathrm{A}_1 x = f \\
-\operatorname{div}_{\Gamma_n} \varepsilon E &= g & \text{translation} \qquad & \mathrm{A}_0^* x = g \\
\pi_{\mathrm{D/N}} E &= K & \qquad & \pi_{K_1} x = k
\end{aligned}
$$

classical de Rham complex in 3D (∇-rot-div-complex)

$c_{A_0} = c_{fp}$ (Friedrichs/Poincaré constant) and $c_{A_1} = c_m$ (Maxwell constant)

Lemma/Theorem $\Downarrow$ $D(A_1) \cap D(A_0^*) \hookrightarrow\!\!\!\!\rightarrow L^2_\varepsilon(\Omega)$ compact

(i) all Friedrichs-Poincaré type est hold

$$\forall\, \varphi \in D(\mathcal{A}_0) \quad |\varphi|_{H_0} \le c_{A_0} |A_0 \varphi|_{H_1} \quad \Leftrightarrow \quad \forall\, \varphi \in H^1_{\Gamma_t} \quad |\varphi|_{L^2} \le c_{fp} |\nabla \varphi|_{L^2_\varepsilon}$$

$$\forall\, \phi \in D(\mathcal{A}_0^*) \quad |\phi|_{H_1} \le c_{A_0} |A_0^* \phi|_{H_0} \quad \Leftrightarrow \quad \forall\, \Phi \in \varepsilon^{-1} D_{\Gamma_n} \cap \nabla H^1_{\Gamma_t} \quad |\Phi|_{L^2_\varepsilon} \le c_{fp} |\operatorname{div} \varepsilon \Phi|_{L^2}$$

$$\forall\, \varphi \in D(\mathcal{A}_1) \quad |\varphi|_{H_1} \le c_{A_1} |A_1 \varphi|_{H_2} \quad \Leftrightarrow \quad \forall\, \Phi \in R_{\Gamma_t} \cap \varepsilon^{-1} \operatorname{rot} R_{\Gamma_n} \quad |\Phi|_{L^2_\varepsilon} \le c_m |\operatorname{rot} \Phi|_{L^2}$$

$$\forall\, \psi \in D(\mathcal{A}_1^*) \quad |\psi|_{H_2} \le c_{A_1} |A_1^* \psi|_{H_1} \quad \Leftrightarrow \quad \forall\, \Psi \in R_{\Gamma_n} \cap \operatorname{rot} R_{\Gamma_t} \quad |\Psi|_{L^2} \le c_m |\operatorname{rot} \Psi|_{L^2_\varepsilon}$$

(ii) all ranges $R(A_0) = \nabla H^1_{\Gamma_t}$, $R(A_1) = \operatorname{rot} R_{\Gamma_t}$, $R(A_0^*) = \operatorname{div} D_{\Gamma_n}$ are cl in L^2

(iii) the inverse ops $(\widetilde{\nabla}_{\Gamma_t})^{-1}$, $(\widetilde{\operatorname{div}_{\Gamma_n} \varepsilon})^{-1}$, $(\widetilde{\operatorname{rot}}_{\Gamma_t})^{-1}$, $(\widetilde{\varepsilon^{-1} \operatorname{rot}_{\Gamma_n}})^{-1}$ are cont, even cpt

(iv) all Helmholtz decomposition hold, e.g.,

$$H_1 = R(A_0) \oplus K_1 \oplus R(A_1^*) \quad \Leftrightarrow \quad L^2_\varepsilon = \nabla H^1_{\Gamma_t} \oplus_{L^2_\varepsilon} \mathcal{H}_{D,\varepsilon} \oplus_{L^2_\varepsilon} \varepsilon^{-1} \operatorname{rot} R_{\Gamma_n}$$

(v) solution theory

(vi) variational formulations

(vii) functional a posteriori error estimates

(viii) div-curl-lemma

(ix) ...

classical de Rham complex in 3D (∇-rot-div-complex)

Theorem (sharp upper bounds)

Let $\boxed{\tilde{E} \in \mathsf{L}^2_\varepsilon}$ *(very non-conforming approximation of* E*!) and* $\boxed{e := E - \tilde{E}}$. *Then*

$$|e|^2_{\mathsf{L}^2_\varepsilon} = |\pi_{R(\nabla_{\Gamma_t})} e|^2_{\mathsf{L}^2_\varepsilon} + |\pi_{R(\varepsilon^{-1}\operatorname{rot}_{\Gamma_n})} e|^2_{\mathsf{L}^2_\varepsilon} + |\pi_{\mathcal{H}_{\mathrm{D},\varepsilon}} e|^2_{\mathsf{L}^2_\varepsilon}$$

$$= \min_{\Phi \in \varepsilon^{-1}\mathsf{D}_{\Gamma_n}} \Big(c_{\mathrm{fp}} |\operatorname{div} \varepsilon\Phi + g|_{\mathsf{L}^2} + |\Phi - \tilde{E}|_{\mathsf{L}^2_\varepsilon} \Big)^2$$

reg $(-\nabla_{\Gamma_t} \operatorname{div}_{\Gamma_n} + 1)$*-prbl in* D_{Γ_n}

$$+ \min_{\Phi \in \mathsf{R}_{\Gamma_t}} \Big(c_{\mathrm{m}} |\operatorname{rot} \Phi - F|_{\mathsf{L}^2} + |\Phi - \tilde{E}|_{\mathsf{L}^2_\varepsilon} \Big)^2$$

reg $(\operatorname{rot}_{\Gamma_n} \operatorname{rot}_{\Gamma_t} + 1)$*-prbl in* R_{Γ_t}

$$+ \min_{\phi \in \mathsf{H}^1_{\Gamma_t}, \Psi \in \mathsf{R}_{\Gamma_n}} |\nabla\phi + \varepsilon^{-1} \operatorname{rot} \Psi + \tilde{E} - K|^2_{\mathsf{L}^2_\varepsilon}$$

cpld $(-\operatorname{div}_{\Gamma_n} \nabla_{\Gamma_t})$-$(\operatorname{rot}_{\Gamma_t} \operatorname{rot}_{\Gamma_n})$*-sys in* $\mathsf{H}^1_{\Gamma_t}$-R_{Γ_n}

Remark

- $(\operatorname{rot}_{\Gamma_t} \operatorname{rot}_{\Gamma_n})$*-prbl needs saddle point formulation*
- Ω *top trv* $\Rightarrow \pi_{\mathrm{D}} = 0$ *and* $\mathsf{R}_{\Gamma_t,0} = \nabla \mathsf{H}^1_{\Gamma_t}$ *and* $\mathsf{D}_{\Gamma_n,0} = \operatorname{rot} \mathsf{R}_{\Gamma_n}$
- $\boxed{\Omega \text{ convex and } \varepsilon = \mu = 1 \text{ and } \Gamma_t = \Gamma \text{ or } \Gamma_n = \Gamma \Rightarrow c_{\mathrm{f}} \leq c_{\mathrm{m}} \leq c_{\mathrm{p}} \leq \frac{\operatorname{diam}_\Omega}{\pi}}$

div-curl-lemma

Lemma (div-curl-lemma (global version))

Assumptions:

(i) (E_n) *bounded in* $\mathrm{L}^2(\Omega)$

(i') (H_n) *bounded in* $\mathrm{L}^2(\Omega)$

(ii) $(\operatorname{rot} E_n)$ *bounded in* $\mathrm{L}^2(\Omega)$

(ii') $(\operatorname{div} \varepsilon H_n)$ *bounded in* $\mathrm{L}^2(\Omega)$

(iii) $\nu \times E_n = 0$ *on* Γ_t, *i.e.,* $E_n \in \mathrm{R}_{\Gamma_t}(\Omega)$

(iii') $\nu \cdot \varepsilon H_n = 0$ *on* Γ_n, *i.e.,* $H_n \in \varepsilon^{-1}\mathrm{D}_{\Gamma_n}(\Omega)$

$\Rightarrow \exists\ E, H$ *and subsequences st*

$E_n \rightharpoonup E$, $\operatorname{rot} E_n \rightharpoonup \operatorname{rot} E$ *and* $H_n \rightharpoonup H$, $\operatorname{div} H_n \rightharpoonup \operatorname{div} H$ *in* $\mathrm{L}^2(\Omega)$ *and*

$$\langle E_n, H_n\rangle_{\mathrm{L}^2_\varepsilon(\Omega)} \to \langle E, H\rangle_{\mathrm{L}^2_\varepsilon(\Omega)}$$

$\Rightarrow$ classical local version

de Rham complex in ND or on Riemannian manifolds (d-complex)

$\Omega \subset \mathbb{R}^N$ bd w. Lip. dom. or Ω Riemannian manifold with cpt cl. and Lip. boundary Γ

(generalized Maxwell equations)

$$\{0\} \overset{\iota_{\{0\}}}{\underset{\pi_{\{0\}}}{\rightleftarrows}} \mathsf{L}^{2,0} \overset{\mathring{\mathrm{d}}}{\underset{-\delta}{\rightleftarrows}} \mathsf{L}^{2,1} \overset{\mathring{\mathrm{d}}}{\underset{-\delta}{\rightleftarrows}} \cdots \mathsf{L}^{2,q} \overset{\mathring{\mathrm{d}}}{\underset{-\delta}{\rightleftarrows}} \mathsf{L}^{2,q+1} \ldots \mathsf{L}^{2,N-1} \overset{\mathring{\mathrm{d}}}{\underset{-\delta}{\rightleftarrows}} \mathsf{L}^{2,N} \overset{\pi_{\mathbb{R}}}{\underset{\iota_{\mathbb{R}}}{\rightleftarrows}} \mathbb{R}$$

de Rham complex in ND or on Riemannian manifolds (d-complex)

$\Omega \subset \mathbb{R}^N$ bd w. Lip. dom. or Ω Riemannian manifold with cpt cl. and Lip. boundary Γ

(generalized Maxwell equations)

$$\{0\} \text{ or } \mathbb{R} \underset{\pi}{\overset{\iota}{\rightleftarrows}} \mathsf{L}^{2,0} \underset{-\delta^1_{\Gamma_n}}{\overset{\mathrm{d}^0_{\Gamma_t}}{\rightleftarrows}} \mathsf{L}^{2,1} \underset{-\delta^2_{\Gamma_n}}{\overset{\mathrm{d}^1_{\Gamma_t}}{\rightleftarrows}} \cdots \mathsf{L}^{2,q} \underset{-\delta^{q+1}_{\Gamma_n}}{\overset{\mathrm{d}^q_{\Gamma_t}}{\rightleftarrows}} \mathsf{L}^{2,q+1} \ldots \mathsf{L}^{2,N-1} \underset{-\delta^N_{\Gamma_n}}{\overset{\mathrm{d}^{N-1}_{\Gamma_t}}{\rightleftarrows}} \mathsf{L}^{2,N} \underset{\iota}{\overset{\pi}{\rightleftarrows}} \mathbb{R} \text{ or } \{0\}$$

related fos

$$\mathrm{d}^q_{\Gamma_t} E = F \quad \text{in } \Omega$$
$$-\delta^q_{\Gamma_n} E = G \quad \text{in } \Omega$$

related sos

$$-\delta^{q+1}_{\Gamma_n} \mathrm{d}^q_{\Gamma_t} E = F \quad \text{in } \Omega$$
$$-\delta^q_{\Gamma_n} E = G \quad \text{in } \Omega$$

includes: EMS rot / div, Laplacian, rot rot, and more...
corresponding compact embeddings:

$$D(\mathrm{d}^q_{\Gamma_t}) \cap D(\delta^q_{\Gamma_n}) \hookrightarrow \mathsf{L}^{2,q} \qquad \text{(Weck's selection theorems, '74)}$$

Weck's selection theorem for Lip. manifolds and mixed bc: Bauer/Py/Schomburg ('17)

elasticity complex in 3D (sym ∇-Rot $\mathrm{Rot}_{\mathbb{S}}^{\top}$-$\mathrm{Div}_{\mathbb{S}}$-complex)

$\Omega \subset \mathbb{R}^3$ bounded strong Lipschitz domain

$$\{0\} \underset{\pi_{\{0\}}}{\overset{\iota_{\{0\}}}{\rightleftarrows}} \mathsf{L}^2 \underset{-\operatorname{Div}_{\mathbb{S}}}{\overset{\mathring{\operatorname{sym}} \nabla}{\rightleftarrows}} \mathsf{L}^2_{\mathbb{S}} \underset{\operatorname{Rot}\operatorname{Rot}_{\mathbb{S}}^{\top}}{\overset{\mathring{\operatorname{Rot}}\operatorname{Rot}_{\mathbb{S}}^{\top}}{\rightleftarrows}} \mathsf{L}^2_{\mathbb{S}} \underset{-\operatorname{sym}\nabla}{\overset{\mathring{\operatorname{Div}}_{\mathbb{S}}}{\rightleftarrows}} \mathsf{L}^2 \underset{\iota_{\mathrm{RM}}}{\overset{\pi_{\mathrm{RM}}}{\rightleftarrows}} \mathrm{RM}$$

elasticity complex in 3D (sym ∇-Rot $\text{Rot}_{\mathbb{S}}^{\top}$-$\text{Div}_{\mathbb{S}}$-complex)

$\Omega \subset \mathbb{R}^3$ bounded strong Lipschitz domain

$$\{0\} \underset{\pi_{\{0\}}}{\overset{\iota_{\{0\}}}{\rightleftarrows}} \mathsf{L}^2 \underset{-\,\text{Div}_{\mathbb{S}}}{\overset{\mathring{\text{sym}}\,\nabla}{\rightleftarrows}} \mathsf{L}^2_{\mathbb{S}} \underset{\text{Rot}\,\text{Rot}_{\mathbb{S}}^{\top}}{\overset{\text{Rot}\,\mathring{\text{Rot}}_{\mathbb{S}}^{\top}}{\rightleftarrows}} \mathsf{L}^2_{\mathbb{S}} \underset{-\,\text{sym}\,\nabla}{\overset{\mathring{\text{Div}}_{\mathbb{S}}}{\rightleftarrows}} \mathsf{L}^2 \underset{\iota_{\text{RM}}}{\overset{\pi_{\text{RM}}}{\rightleftarrows}} \text{RM}$$

related fos ($\text{Rot}\,\mathring{\text{Rot}}_{\mathbb{S}}^{\top}$, $\text{Rot}\,\text{Rot}_{\mathbb{S}}^{\top}$ first order operators!)

$$\begin{array}{rl|rl|rl|rl} \mathring{\text{sym}}\,\nabla v = M & \text{in } \Omega & \text{Rot}\,\mathring{\text{Rot}}_{\mathbb{S}}^{\top} M = F & \text{in } \Omega & \mathring{\text{Div}}_{\mathbb{S}} N = g & \text{in } \Omega & \pi v = r & \text{in } \Omega \\ \pi v = 0 & \text{in } \Omega & -\text{Div}_{\mathbb{S}} M = f & \text{in } \Omega & \text{Rot}\,\text{Rot}_{\mathbb{S}}^{\top} N = G & \text{in } \Omega & -\text{sym}\,\nabla v = M & \text{in } \Omega \end{array}$$

related sos ($\text{Rot}\,\text{Rot}_{\mathbb{S}}^{\top}\,\text{Rot}\,\mathring{\text{Rot}}_{\mathbb{S}}^{\top}$ second order operator!)

$$\begin{array}{rl|rl|rl} -\text{Div}_{\mathbb{S}}\,\mathring{\text{sym}}\,\nabla v = f & \text{in } \Omega & \text{Rot}\,\text{Rot}_{\mathbb{S}}^{\top}\,\text{Rot}\,\mathring{\text{Rot}}_{\mathbb{S}}^{\top} M = G & \text{in } \Omega & -\text{sym}\,\nabla\,\mathring{\text{Div}}_{\mathbb{S}} N = M & \text{in } \Omega \\ \pi v = 0 & \text{in } \Omega & -\text{Div}_{\mathbb{S}} M = f & \text{in } \Omega & \text{Rot}\,\text{Rot}_{\mathbb{S}}^{\top} N = G & \text{in } \Omega \end{array}$$

corresponding compact embeddings:

$$D(\mathring{\text{sym}}\,\nabla) \cap D(\pi) = D(\mathring{\nabla}) = \mathring{\mathsf{H}}^1 \hookrightarrow \mathsf{L}^2$$ (Rellich's selection theorem and Korn ineq.)

$$D(\text{Rot}\,\mathring{\text{Rot}}_{\mathbb{S}}^{\top}) \cap D(\text{Div}_{\mathbb{S}}) \hookrightarrow \mathsf{L}^2_{\mathbb{S}}$$ (new selection theorem)

$$D(\mathring{\text{Div}}_{\mathbb{S}}) \cap D(\text{Rot}\,\text{Rot}_{\mathbb{S}}^{\top}) \hookrightarrow \mathsf{L}^2_{\mathbb{S}}$$ (new selection theorem)

$$D(\pi) \cap D(\text{sym}\,\nabla) = D(\nabla) = \mathsf{H}^1 \hookrightarrow \mathsf{L}^2$$ (Rellich's selection theorem and Korn ineq.)

two new selection theorems for strong Lip. dom.: Py/Schomburg/Zulehner ('18)

elasticity complex in 3D (sym ∇-Rot $\mathrm{Rot}_{\mathbb{S}}^{\top}$-$\mathrm{Div}_{\mathbb{S}}$-complex)

Lemma/Theorem $\Downarrow$ $D(\mathrm{A}_1) \cap D(\mathrm{A}_0^*) \hookrightarrow\!\!\!\rightarrow \mathrm{H}_1, \quad D(\mathrm{A}_2) \cap D(\mathrm{A}_1^*) \hookrightarrow\!\!\!\rightarrow \mathrm{H}_2 \quad \text{cpt}$

(i) all Friedrichs-Poincaré type est hold

$$\text{est for } \mathcal{A}_0 \quad \Leftrightarrow \quad \forall\, \varphi \in D(\operatorname{sym} \mathring{\nabla}) \cap R(\mathrm{Div}_{\mathbb{S}}) = \mathring{\mathrm{H}}^1 \qquad |\varphi|_{\mathrm{L}^2} \le c_0 |\operatorname{sym} \nabla\varphi|_{\mathrm{L}^2}$$

$$\text{est for } \mathcal{A}_0^* \quad \Leftrightarrow \quad \forall\, \Phi \in D(\mathrm{Div}_{\mathbb{S}}) \cap R(\operatorname{sym} \mathring{\nabla}) \qquad |\Phi|_{\mathrm{L}^2} \le c_0 |\operatorname{Div} \Phi|_{\mathrm{L}^2}$$

$$\text{est for } \mathcal{A}_1 \quad \Leftrightarrow \quad \forall\, \Phi \in D(\mathrm{Rot}\,\mathring{\mathrm{Rot}}_{\mathbb{S}}^{\top}) \cap R(\mathrm{Rot}\,\mathrm{Rot}_{\mathbb{S}}^{\top}) \qquad |\Phi|_{\mathrm{L}^2} \le c_1 |\mathrm{Rot}\,\mathrm{Rot}^{\top} \Phi|_{\mathrm{L}^2}$$

$$\text{est for } \mathcal{A}_1^* \quad \Leftrightarrow \quad \forall\, \Phi \in D(\mathrm{Rot}\,\mathrm{Rot}_{\mathbb{S}}^{\top}) \cap R(\mathrm{Rot}\,\mathring{\mathrm{Rot}}_{\mathbb{S}}^{\top}) \qquad |\Phi|_{\mathrm{L}^2} \le c_1 |\mathrm{Rot}\,\mathrm{Rot}^{\top} \Phi|_{\mathrm{L}^2}$$

$$\text{est for } \mathcal{A}_2 \quad \Leftrightarrow \quad \forall\, \Phi \in D(\mathring{\mathrm{Div}}_{\mathbb{S}}) \cap R(\operatorname{sym} \nabla) \qquad |\Phi|_{\mathrm{L}^2} \le c_2 |\operatorname{Div} \Phi|_{\mathrm{L}^2}$$

$$\text{est for } \mathcal{A}_2^* \quad \Leftrightarrow \quad \forall\, \varphi \in D(\operatorname{sym} \nabla) \cap R(\mathring{\mathrm{Div}}_{\mathbb{S}}) = \mathrm{H}^1 \cap \mathrm{RM}^{\perp} \qquad |\varphi|_{\mathrm{L}^2} \le c_2 |\operatorname{sym} \nabla\varphi|_{\mathrm{L}^2}$$

(ii) all ranges $R(\mathrm{A}_n) = R(\mathcal{A}_n)$, $\quad R(\mathrm{A}_n^*) = R(\mathcal{A}_n^*)$ are cl in L^2

(iii) all inverse ops $\mathcal{A}_n^{-1}$, $(\mathcal{A}_n^*)^{-1}$ are cont, even cpt

(iv) all Helmholtz decomposition hold, e.g.,

$$\mathrm{H}_1 = R(\mathrm{A}_0) \oplus K_1 \oplus R(\mathrm{A}_1^*) \quad \Leftrightarrow \quad \mathrm{L}^2 = R(\operatorname{sym} \mathring{\nabla}) \oplus_{\mathrm{L}^2} \mathcal{H}_{\mathrm{D},\mathbb{S}} \oplus_{\mathrm{L}^2} R(\mathrm{Rot}\,\mathrm{Rot}_{\mathbb{S}}^{\top})$$

(v) solution theories

(vi) variational formulations

(vii) functional a posteriori error estimates

(viii) div-curl-lemmas

(ix) . . .

biharmonic / general relativity complex in 3D ($\nabla\nabla$-$\mathrm{Rot}_{\mathbb{S}}$-$\mathrm{Div}_{\mathbb{T}}$-complex)

$\Omega \subset \mathbb{R}^3$ bounded strong Lipschitz domain

$$\{0\} \overset{\iota_{\{0\}}}{\underset{\pi_{\{0\}}}{\rightleftarrows}} \mathsf{L}^2 \overset{\mathring{\nabla\nabla}}{\underset{\operatorname{div}\operatorname{Div}_{\mathbb{S}}}{\rightleftarrows}} \mathsf{L}^2_{\mathbb{S}} \overset{\mathring{\operatorname{Rot}}_{\mathbb{S}}}{\underset{\operatorname{sym}\operatorname{Rot}_{\mathbb{T}}}{\rightleftarrows}} \mathsf{L}^2_{\mathbb{T}} \overset{\mathring{\operatorname{Div}}_{\mathbb{T}}}{\underset{-\operatorname{dev}\nabla}{\rightleftarrows}} \mathsf{L}^2 \overset{\pi_{\mathsf{RT}}}{\underset{\iota_{\mathsf{RT}}}{\rightleftarrows}} \mathsf{RT}$$

biharmonic / general relativity complex in 3D ($\nabla\nabla$-$\mathrm{Rot}_{\mathbb{S}}$-$\mathrm{Div}_{\mathbb{T}}$-complex)

$\Omega \subset \mathbb{R}^3$ bounded strong Lipschitz domain

$$\{0\} \overset{\iota_{\{0\}}}{\underset{\pi_{\{0\}}}{\rightleftarrows}} \mathrm{L}^2 \overset{\mathring{\nabla}\nabla}{\underset{\operatorname{div}\operatorname{Div}_{\mathbb{S}}}{\rightleftarrows}} \mathrm{L}^2_{\mathbb{S}} \overset{\mathring{\mathrm{Rot}}_{\mathbb{S}}}{\underset{\operatorname{sym}\mathrm{Rot}_{\mathbb{T}}}{\rightleftarrows}} \mathrm{L}^2_{\mathbb{T}} \overset{\mathring{\mathrm{Div}}_{\mathbb{T}}}{\underset{-\operatorname{dev}\nabla}{\rightleftarrows}} \mathrm{L}^2 \overset{\pi_{\mathrm{RT}}}{\underset{\iota_{\mathrm{RT}}}{\rightleftarrows}} \mathrm{RT}$$

related fos ($\mathring{\nabla}\nabla$, $\operatorname{div}\operatorname{Div}_{\mathbb{S}}$ first order operators!)

$\mathring{\nabla}\nabla u = M$ in Ω	$\mathring{\mathrm{Rot}}_{\mathbb{S}} M = F$ in Ω	$\mathring{\mathrm{Div}}_{\mathbb{T}} N = g$ in Ω	$\pi v = r$ in Ω
$\pi u = 0$ in Ω	$\operatorname{div}\operatorname{Div}_{\mathbb{S}} M = f$ in Ω	$\operatorname{sym}\mathrm{Rot}_{\mathbb{T}} N = G$ in Ω	$-\operatorname{dev}\nabla v = T$ in Ω

related sos ($\operatorname{div}\operatorname{Div}_{\mathbb{S}} \mathring{\nabla}\nabla = \mathring{\Delta}^2$ second order operator!)

$\operatorname{div}\operatorname{Div}_{\mathbb{S}} \mathring{\nabla}\nabla u = \mathring{\Delta}^2 u = f$ in Ω	$\operatorname{sym}\mathrm{Rot}_{\mathbb{T}} \mathring{\mathrm{Rot}}_{\mathbb{S}} M = G$ in Ω	$-\operatorname{dev}\nabla\mathring{\mathrm{Div}}_{\mathbb{T}} N = T$ in Ω
$\pi u = 0$ in Ω	$\operatorname{div}\operatorname{Div}_{\mathbb{S}} M = f$ in Ω	$\operatorname{sym}\mathrm{Rot}_{\mathbb{T}} N = G$ in Ω

corresponding compact embeddings:

$$D(\mathring{\nabla}\nabla) \cap D(\pi) = D(\mathring{\nabla}\nabla) = \mathring{\mathrm{H}}^2 \hookrightarrow \mathrm{L}^2 \qquad \text{(Rellich's selection theorem)}$$

$$D(\mathring{\mathrm{Rot}}_{\mathbb{S}}) \cap D(\operatorname{div}\operatorname{Div}_{\mathbb{S}}) \hookrightarrow \mathrm{L}^2_{\mathbb{S}} \qquad \text{(new selection theorem)}$$

$$D(\mathring{\mathrm{Div}}_{\mathbb{T}}) \cap D(\operatorname{sym}\mathrm{Rot}_{\mathbb{T}}) \hookrightarrow \mathrm{L}^2_{\mathbb{T}} \qquad \text{(new selection theorem)}$$

$$D(\pi) \cap D(\operatorname{dev}\nabla) = D(\operatorname{dev}\nabla) = D(\nabla) = \mathrm{H}^1 \hookrightarrow \mathrm{L}^2 \qquad \text{(Rellich's selection theorem and Korn type ineq.)}$$

two new selection theorems for strong Lip. dom. and Korn Type ineq.: Py/Zulehner ('16)

biharmonic / general relativity complex in 3D ($\nabla\nabla$-$\mathrm{Rot}_{\mathbb{S}}$-$\mathrm{Div}_{\mathbb{T}}$-complex)

Lemma/Theorem $\Downarrow$ $\boxed{D(\mathrm{A}_1)\cap D(\mathrm{A}_0^*) \hookrightarrow\!\!\!\rightarrow \mathrm{H}_1, \quad D(\mathrm{A}_2)\cap D(\mathrm{A}_1^*) \hookrightarrow\!\!\!\rightarrow \mathrm{H}_2 \quad \text{cpt}}$

(i) all Friedrichs-Poincaré type est hold

est for $\mathcal{A}_0$	$\Leftrightarrow$	$\forall\,\varphi\in D(\mathring{\nabla}\nabla)\cap R(\operatorname{div}\mathrm{Div}_{\mathbb{S}}) = \mathring{\mathrm{H}}^2$	$\lvert\varphi\rvert_{\mathrm{L}^2}\le c_0\lvert\nabla\nabla\varphi\rvert_{\mathrm{L}^2}$
est for $\mathcal{A}_0^*$	$\Leftrightarrow$	$\forall\,\Phi\in D(\operatorname{div}\mathrm{Div}_{\mathbb{S}})\cap R(\mathring{\nabla}\nabla)$	$\lvert\Phi\rvert_{\mathrm{L}^2}\le c_0\lvert\operatorname{div}\mathrm{Div}\,\Phi\rvert_{\mathrm{L}^2}$
est for $\mathcal{A}_1$	$\Leftrightarrow$	$\forall\,\Phi\in D(\mathring{\mathrm{Rot}}_{\mathbb{S}})\cap R(\operatorname{sym}\mathrm{Rot}_{\mathbb{T}})$	$\lvert\Phi\rvert_{\mathrm{L}^2}\le c_1\lvert\mathrm{Rot}\,\Phi\rvert_{\mathrm{L}^2}$
est for $\mathcal{A}_1^*$	$\Leftrightarrow$	$\forall\,\Phi\in D(\operatorname{sym}\mathrm{Rot}_{\mathbb{T}})\cap R(\mathring{\mathrm{Rot}}_{\mathbb{S}})$	$\lvert\Phi\rvert_{\mathrm{L}^2}\le c_1\lvert\operatorname{sym}\mathrm{Rot}\,\Phi\rvert_{\mathrm{L}^2}$
est for $\mathcal{A}_2$	$\Leftrightarrow$	$\forall\,\Phi\in D(\mathring{\mathrm{Div}}_{\mathbb{T}})\cap R(\operatorname{dev}\nabla)$	$\lvert\Phi\rvert_{\mathrm{L}^2}\le c_2\lvert\mathrm{Div}\,\Phi\rvert_{\mathrm{L}^2}$
est for $\mathcal{A}_2^*$	$\Leftrightarrow$	$\forall\,\varphi\in D(\operatorname{dev}\nabla)\cap R(\mathring{\mathrm{Div}}_{\mathbb{T}}) = \mathrm{H}^1\cap\mathrm{RT}^\perp$	$\lvert\varphi\rvert_{\mathrm{L}^2}\le c_2\lvert\operatorname{dev}\nabla\varphi\rvert_{\mathrm{L}^2}$

(ii) all ranges $R(\mathrm{A}_n)=R(\mathcal{A}_n)$, $R(\mathrm{A}_n^*)=R(\mathcal{A}_n^*)$ are cl in L^2

(iii) all inverse ops $\mathcal{A}_n^{-1}$, $(\mathcal{A}_n^*)^{-1}$ are cont, even cpt

(iv) all Helmholtz decomposition hold, e.g.,

$$\mathrm{H}_1 = R(\mathrm{A}_0)\oplus K_1\oplus R(\mathrm{A}_1^*) \quad\Leftrightarrow\quad \mathrm{L}^2_{\mathbb{S}} = R(\mathring{\nabla}\nabla)\oplus_{\mathrm{L}^2_{\mathbb{S}}}\mathcal{H}_{\mathrm{D},\mathbb{S}}\oplus_{\mathrm{L}^2_{\mathbb{S}}} R(\operatorname{sym}\mathrm{Rot}_{\mathbb{T}}),$$

$$\mathrm{H}_2 = R(\mathrm{A}_1)\oplus K_2\oplus R(\mathrm{A}_2^*) \quad\Leftrightarrow\quad \mathrm{L}^2_{\mathbb{T}} = R(\mathring{\mathrm{Rot}}_{\mathbb{S}})\oplus_{\mathrm{L}^2_{\mathbb{T}}}\mathcal{H}_{\mathrm{N},\mathbb{T}}\oplus_{\mathrm{L}^2_{\mathbb{T}}} R(\operatorname{dev}\nabla)$$

(v)-(ix) solution theories, variational formulations, functional a posteriori error estimates, div-curl-lemmas, ...

key tools to prove compact embeddings

- localisation to top triv domains by partition of unity
(sec order ops = problems / regular decompositions in H^{-1} / ...)
- Helmholtz decompositions
- regular potentials
- Rellich's selection theorem

regular potentials

Theorem (regular potentials)

Let (Ω, Γ_t) be a bounded strong Lipschitz pair and $k \geq 0$. Then there exists a continuous linear operator

$$\mathcal{S}^q_{\mathrm{d},k} : \mathring{\mathsf{H}}^{k,q}_{\Gamma_t}(\Omega) \cap \mathring{\mathsf{D}}^q_{\Gamma_t,0}(\Omega) \cap \mathcal{H}^q(\Omega)^\perp \longrightarrow \mathring{\mathsf{H}}^{k+1,q-1}_{\Gamma_t}(\Omega),$$

such that $\mathrm{d}\,\mathcal{S}^q_{\mathrm{d},k} = \mathrm{id}\,|_{\mathring{\mathsf{H}}^{k,q}_{\Gamma_t}(\Omega)\cap\mathring{\mathsf{D}}^q_{\Gamma_t,0}(\Omega)\cap\mathcal{H}^q(\Omega)^\perp}$. *In particular,*

$$\begin{aligned}\mathring{\mathsf{H}}^{k,q}_{\Gamma_t}(\Omega) \cap \mathring{\mathsf{D}}^q_{\Gamma_t,0}(\Omega) \cap \mathcal{H}^q(\Omega)^\perp &= \mathring{\mathsf{H}}^{k,q}_{\Gamma_t}(\Omega) \cap \mathrm{d}\,\mathring{\mathsf{D}}^{q-1}_{\Gamma_t}(\Omega)\\ &= \mathrm{d}\,\mathring{\mathsf{H}}^{k+1,q-1}_{\Gamma_t}(\Omega)\\ &= \mathrm{d}\,\mathring{\mathsf{D}}^{k,q-1}_{\Gamma_t}(\Omega)\end{aligned}$$

and the regular $\mathring{\mathsf{H}}^{k+1,q-1}_{\Gamma_t}(\Omega)$*-potential depends continuously on the data. Especially, these spaces are closed subspaces of* $\mathring{\mathsf{H}}^{k,q}(\Omega)$ *and* $\mathcal{S}^q_{\mathrm{d},k}$ *is a right inverse to* d.

regular docompositions

Theorem (regular decompositions)

Let (Ω, Γ_t) be a bounded strong Lipschitz pair and $k \geq 0$. Then the regular decompositions

$$\mathring{\mathsf{D}}^{k,q}_{\Gamma_t}(\Omega) = \mathring{\mathsf{H}}^{k+1,q}_{\Gamma_t}(\Omega) + \mathrm{d}\,\mathring{\mathsf{H}}^{k+1,q-1}_{\Gamma_t}(\Omega)$$

$$\bigcap \qquad\qquad \bigcup$$

$$= \mathcal{S}^{q+1}_{\mathrm{d},k}\,\mathrm{d}\,\mathring{\mathsf{D}}^{k,q}_{\Gamma_t}(\Omega) \dot{+} \big(\mathring{\mathsf{H}}^{k,q}_{\Gamma_t}(\Omega) \cap \mathring{\mathsf{D}}^{q}_{\Gamma_t,0}(\Omega)\big)$$

hold with linear and continuous regular decomposition resp. potential operators, which can be defined explicitly by the orthonormal Helmholtz projectors and the operators $\mathcal{S}^q_{\mathrm{d},k}$.

joint work with Ralf Hiptmair, Clemens Pechstein, Michael Schomburg, Walter Zulehner

dual regular potentials and decompositions

Dual regular potentials and decompositions involving

$$\mathring{\mathsf{H}}^{-k,q}_{\Gamma_n}(\Omega) = \mathring{\mathsf{H}}^{k,q}_{\Gamma_t}(\Omega)'$$

can be proved by Banach space duality. E.g.:

- $\mathring{\mathsf{D}}^{k,q}_{\Gamma_t}(\Omega)' = \mathring{\Delta}^{-k-1,q}_{\Gamma_n}(\Omega) := \{E' \in \mathring{\mathsf{H}}^{-k-1,q}_{\Gamma_n}(\Omega) \, : \, \delta E' \in \mathring{\mathsf{H}}^{-k-1,q-1}_{\Gamma_n}(\Omega)\}$
- dual ranges are closed
- dual Friedrichs/Poincaré typ estimates, inf-sup condition, i.e.,

$$\delta^{-1} : \delta \, \mathring{\mathsf{H}}^{-k,q}_{\Gamma_n}(\Omega) \longrightarrow \big(\mathrm{d}\, \mathring{\mathsf{H}}^{k+1,q-1}_{\Gamma_t}(\Omega)\big)' \qquad \text{cont}$$

$$\Updownarrow$$

$$\forall\, H' \in \big(\mathrm{d}\, \mathring{\mathsf{H}}^{k+1,q-1}_{\Gamma_t}(\Omega)\big)' \qquad \frac{1}{c}|H'|_{\mathring{\mathsf{H}}^{-k,q}_{\Gamma_n}(\Omega)} \le |\,\delta\, H'|_{\mathring{\mathsf{H}}^{-k-1,q-1}_{\Gamma_n}(\Omega)} \le c|H'|_{\mathring{\mathsf{H}}^{-k,q}_{\Gamma_n}(\Omega)}$$

$$\Updownarrow$$

$$0 < \inf_{0 \neq H \in \mathrm{d}\, \mathring{\mathsf{H}}^{k+1,q-1}_{\Gamma_t}(\Omega)} \; \sup_{0 \neq E \in \mathring{\mathsf{H}}^{k+1,q-1}_{\Gamma_t}(\Omega)} \frac{\langle H, \mathrm{d}\, E\rangle_{\mathring{\mathsf{H}}^{k,q}_{\Gamma_t}(\Omega)}}{|H|_{\mathring{\mathsf{H}}^{k,q}_{\Gamma_t}(\Omega)} |E|_{\mathring{\mathsf{H}}^{k+1,q-1}_{\Gamma_t}(\Omega)}}$$

dual regular potentials and decompositions

Ω top triv $\quad\Rightarrow$

$$\mathrm{d}\,\mathring{\mathsf{H}}^{k+1,q-1}_{\Gamma_t}(\Omega) = \mathring{\mathsf{H}}^{k,q}_{\Gamma_t}(\Omega) \cap \mathring{\mathsf{D}}^{q}_{\Gamma_t,0}(\Omega)$$

$$\delta\,\mathring{\mathsf{H}}^{-k,q}_{\Gamma_n}(\Omega) = \mathring{\Delta}^{-k-1,q-1}_{\Gamma_n,0}(\Omega) = \{H' \in \mathring{\mathsf{H}}^{-k-1,q-1}_{\Gamma_n}(\Omega) \,:\, \delta\,H' = 0\}$$

literature (fa-toolbox, complexes, a posteriori error estimates, ...)

some results of this talk:

- Py: *Solution Theory, Variational Formulations, and Functional a Posteriori Error Estimates for General First Order Systems with Applications to Electro-Magneto-Statics and More*,
  (NFAO) Numerical Functional Analysis and Optimization, 2019

literature (complexes, Friedrichs type constants, Maxwell constants)

results of this talk:

- Py: *On Constants in Maxwell Inequalities for Bounded and Convex Domains*, Zapiski POMI/ (JMS)Journal of Mathematical Sciences (Springer New York), 2015
- Py: *On Maxwell's and Poincare's Constants*, (DCDS) Discrete and Continuous Dynamical Systems - Series S, 2015
- Py: *On the Maxwell Constants in 3D*, (M2AS) Mathematical Methods in the Applied Sciences, 2017
- Py: *On the Maxwell and Friedrichs/Poincaré Constants in ND*, (MZ) Mathematische Zeitschrift, 2019

- Py: *. . . some (so far) unpublished results*

literature (complexes, Friedrichs type constants, compact embeddings)

- Weck, N.: *Maxwell's boundary value problems on Riemannian manifolds with nonsmooth boundaries*,
  (JMA2) Journal of Mathematical Analysis and Applications, 1974 (1972)
- Picard, R.: *An elementary proof for a compact imbedding result in generalized electromagnetic theory*,
  (MZ) Mathematische Zeitschrift, 1984
- Witsch, K.-J.: *A remark on a compactness result in electromagnetic theory*,
  (M2AS) Mathematical Methods in the Applied Sciences, 1993

results of this talk:

- Bauer, S., Py, Schomburg, M.: *The Maxwell Compactness Property in Bounded Weak Lipschitz Domains with Mixed Boundary Conditions*,
  (SIMA) SIAM Journal on Mathematical Analysis, 2016
- Py, Zulehner, W.: *The divDiv-Complex and Applications to Biharmonic Equations*,
  (AA) Applicable Analysis, 2019
- Hiptmair, R., Pechstein, C. Py, Schomburg, M., Zulehner, W.: *Regular Potentials and Regular Decompositions for Bounded Strong Lipschitz Domains with Mixed Boundary Conditions in Arbitrary Dimensions*,
  almost submitted
- Py, Schomburg, M., Zulehner, W.: *The Elasticity Complex*,
  almost submitted

literature (div-curl-lemma)

original papers (local div-curl-lemma):

- Murat, F.: *Compacité par compensation*,
  Annali della Scuola Normale Superiore di Pisa-Classe di Scienze, 1978
- Tartar, L.: *Compensated compactness and applications to partial differential equations*,
  Nonlinear analysis and mechanics, Heriot-Watt symposium, 1979

literature (div-curl-lemma)

recent papers (global div-curl-lemma, H^1-detour):

- Gloria, A., Neukamm, S., Otto, F.: *Quantification of ergodicity in stochastic homogenization: optimal bounds via spectral gap on Glauber dynamics*, (IM) Invent. Math., 2015
- Kozono, H., Yanagisawa, T.: *Global compensated compactness theorem for general differential operators of first order*, (ARMA) Arch. Ration. Mech. Anal., 2013
- Schweizer, B.: *On Friedrichs inequality, Helmholtz decomposition, vector potentials, and the div-curl lemma*, accepted preprint, 2018

recent papers (global div-curl-lemma, general results/this talk):

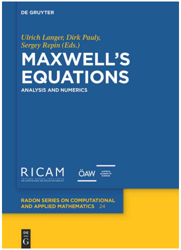
- Waurick, M.: *A Functional Analytic Perspective to the div-curl Lemma*, (JOP) J. Operator Theory, 2018
- Py: *A Global div-curl-Lemma for Mixed Boundary Conditions in Weak Lipschitz Domains and a Corresponding Generalized* A_0^*-A_1-*Lemma in Hilbert Spaces*, (ANA) Analysis (Munich), 2019

literature (full time-dependent Maxwell equations)

- Py, Picard, R.: *A Note on the Justification of the Eddy Current Model in Electrodynamics*, (M2AS) Mathematical Methods in the Applied Sciences, 2017
- Py, Picard, R., Trostorff, S., Waurick, M.: *On a Class of Degenerate Abstract Parabolic Problems and Applications to Some Eddy Current Models*, submitted, 2019

literature (Maxwell's equations and more...)

upcoming book (Monday!)



- Langer, U., Py, Repin, S. (Eds): *Maxwell's equations. Analysis and numerics*, Radon Series on Applied Mathematics, De Gruyter, July 2019

. . . the world is full of complexes . . . ;)

⇒ relaxing at (and you're all invited!)

AANMPDE 13

13th Workshop on Analysis and Advanced Numerical Methods
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