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Design for IGA-type discretization workflows

Funded by the European Union

1st Technical Workshop

DC4: “Co-simulation strategies involving IBRA for the solution of multi-field problems”

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DC4 Personal Project
Introduction

Doctoral Candidate in the field of Co-simulation strategies involving IBRA for solution of multi-field problems

Supervisor: Prof. Dr. Ing. habil. Roland Wüchner

Objectives:

- Development and assessment of mapping operators between different discretizations
- Combination of different field solvers (e.g. fluid, structure, acoustic, …) by suitable coupling algorithms and effective data transfer approaches to enable efficient and also robust multi-field simulations
- Assessment of IBRA-solver-benefits in surface-coupled problems (like FSI)

Start Date: November 6, 2023

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First Steps into this topic…

Main Focus during this period of time

- ❑ Establish a robust foundation on IGA, IBRA and Coupled Problems
- ❑ Familiarize myself with the Kratos Multi-Physics framework and and gain a brief understanding of Co-simulation strategies

First Steps:

1. Introduction to NURBS Geometrical Modelling
2. Development of strong foundations in Isogeometric Analysis (IGA) and Isogeometric B-Rep Analysis (IBRA)
3. Introduction to Coupled Problems, with a particular focus on Fluid-Structure Interaction (FSI) simulations
4. Introduction to Kratos Multi-Physics

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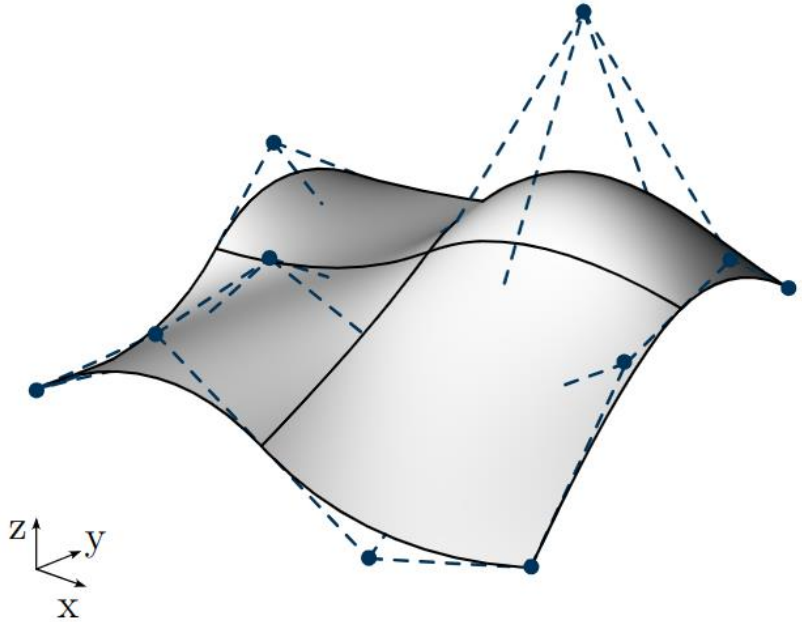
Introduction to NURBS Geometrical Modelling – Geometric Fundamentals

Key References

- ❑ Piegl, L., & Tiller, W. (2012). *The NURBS book*. Springer Science & Business Media.
- ❑ Cottrell, J. A., Hughes, T. J., & Bazilevs, Y. (2009). *Isogeometric analysis: toward integration of CAD and FEA*. John Wiley & Sons.

Learning Path:

1. Bézier Curves & Surfaces
2. B-Splines Curves, Surfaces & Solids
   - Knot Vector and Cox-de Boor Recursion formula for the computation of B-Splines basis functions
   - Main mathematical properties of B-Splines
3. NURBS Curves, Surfaces & Solids as a generalization of B-Splines
   - Trimmed NURBS Surfaces



NURBS surface with $w_{i,j} = cte$
(B-Spline surface)

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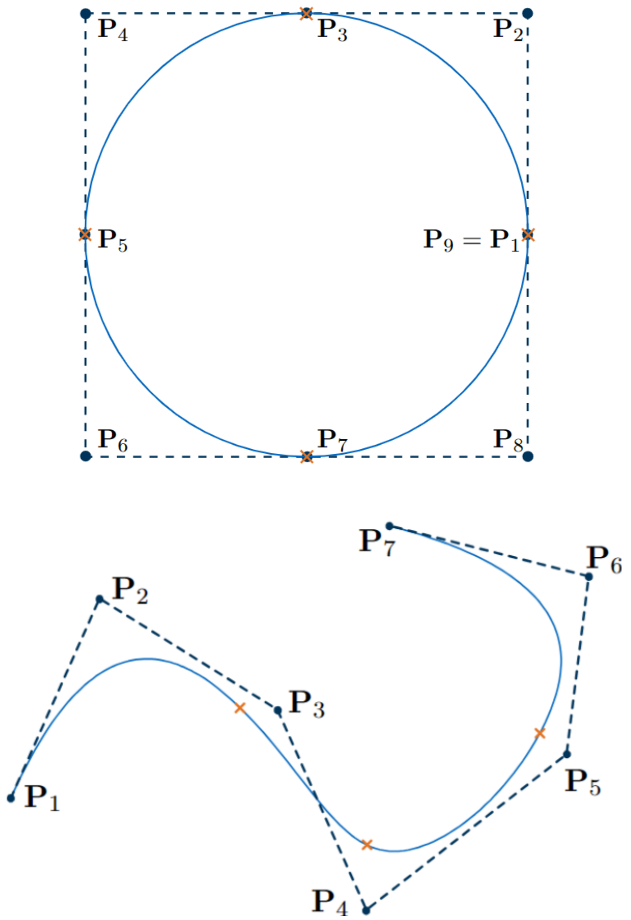
Introduction to NURBS Geometrical Modelling – Geometric Fundamentals

Key Points & Advantajes of NURBS

- NURBS-based-B-Rep models are the **standard model description within CAD** because of their smooth and accurate representations in 3D modelling
- Offers superior **flexibility and control** over the shape of curves and surfaces
- They fulfill the necessary conditions in order to be basis functions
- Enables **seamless integration between geometric design and analysis** processes (adopt the geometry description from design for analysis)
- **Excellent mathematical properties** of the basis functions, especially their higher interelement continuity (C^{∞}continuous between two knots and C^{p-k} continuous at a knot of multiplicity k) and their local support ($N_{i,p}(\xi) \neq 0$ only in the interval $[\xi_i, \xi_{i+p+1}]$)
- The rational aspect of NURBS basis functions allows for **exact representation of conic sections** and other complex shapes



NURBS curves

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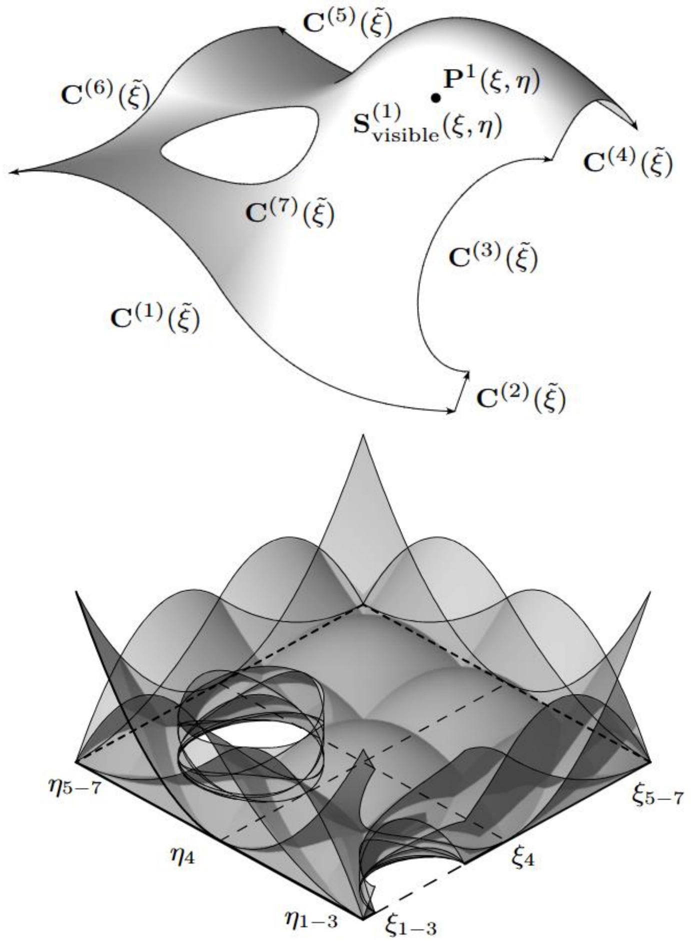
Introduction to NURBS Geometrical Modelling – Geometric Fundamentals

Drawbacks associated with NURBS

- NURBS do **not necessarily interpolate the control points**
- The computation of NURBS curves & surfaces **could be computationally expensive**, particularly when dealing with high degrees or a large number of control points
- **Pure local refinement** in NURBS patches is **not possible**
- **Trimming introduces challenges**, including changes to the support domain of basis functions, potential loss of global continuity, and difficulties in achieving precise modifications in the trimmed region
- The introduction of trimming lines breaks the continuity of the basis functions, especially at the boundaries of the trimmed region



Trimmed NURBS Surface and corresponding basis functions

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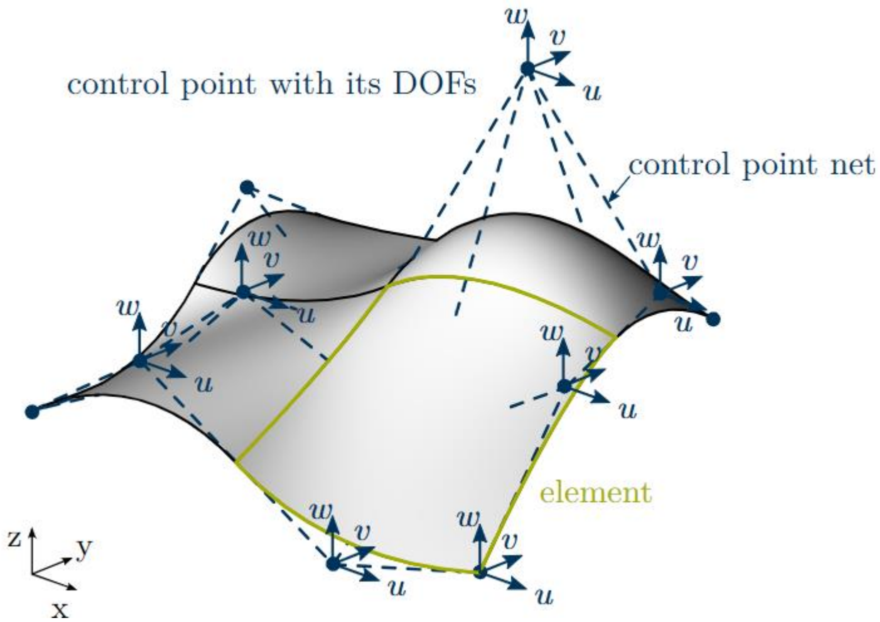
Introduction to IGA with focus on the main differences with classical FEA

Key References

- Cottrell, J. A., Hughes, T. J., & Bazilevs, Y. (2009). *Isogeometric analysis: toward integration of CAD and FEA*. John Wiley & Sons.

Learning Path:

1. Elements definition in IGA
2. Nodes and DOF definition in IGA
3. Mesh refinement strategies
   - Order elevation (p-refinement)
   - Knot insertion (h-refinement)
   - k-refinement (combination of order elevation and knot insertion)
4. Elemental numerical integration techniques



Elements, nodes and DOF´s in Isogeometric Analysis

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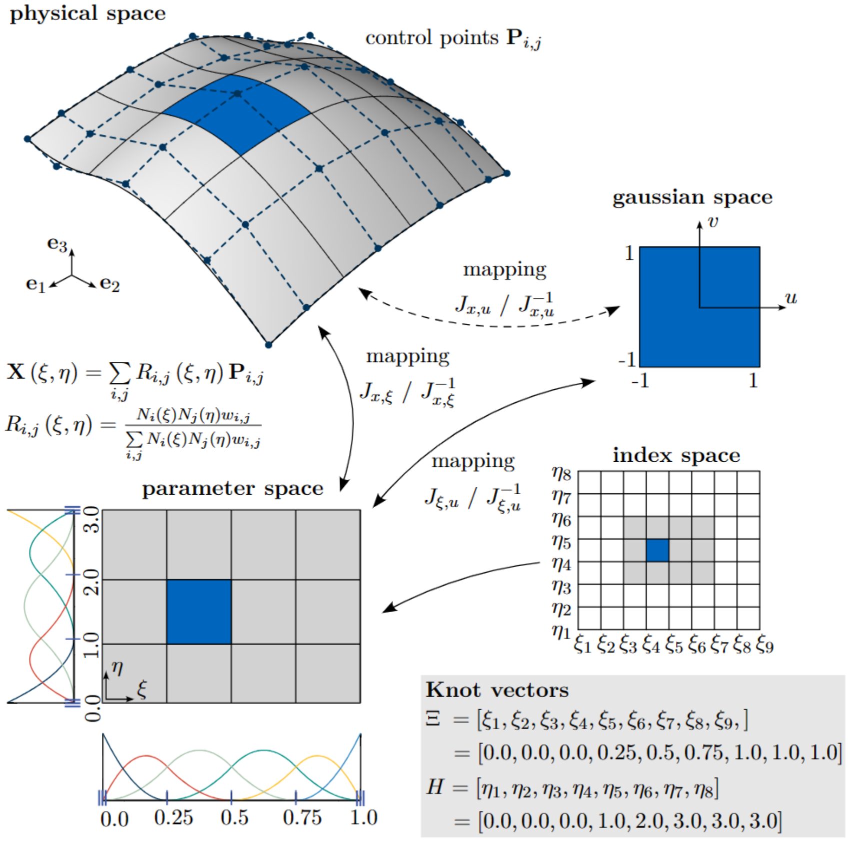
Introduction to IGA with focus on the main differences with classical FEA

Peculiarities of IGA with respect to classical FEA

- IGA uses the **same basis functions** to represent both the geometry and the solution field, thus bridging the gap between CAD and CAE
- **No** need for **mesh generation** and no **geometrical error**
- The **control points carry the degrees of freedom**, but they are not necessarily placed on the NURBS curve, surface or solid

$$\boldsymbol{u_{cp}} \neq \boldsymbol{u_{st}}$$

- In IGA, an **element** is defined by a **nonzero knot span**
- IGA basis functions possess **higher order interelement continuity**, leading to smoother solutions and continuous stress fields
- Gauss quadrature integration: an **additional mapping** from parameter space to gaussian space is required
- In IGA, Dirichlet BC´s inside a patch must be weakly enforced



Elements, nodes and DOF´s in Isogeometric Analysis

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Introduction to Isogeometric B-Rep Analysis (IBRA)

Key References

- Breitenberger, M., Apostolatos, A., Philipp, B., Wüchner, R., & Bletzinger, K. U. (2015). *Analysis in computer aided design: Nonlinear isogeometric B-Rep analysis of shell structures. Computer Methods in Applied Mechanics and Engineering, 284, 401-457.*
- Teschemacher, T., Bauer, A. M., Oberbichler, T., Breitenberger, M., Rossi, R., Wüchner, R., & Bletzinger, K. U. (2018). *Realization of CAD-integrated shell simulation based on isogeometric B-Rep analysis. Advanced Modeling and Simulation in Engineering Sciences, 5, 1-54.*

Learning Path:

1. B-Rep of a model: geometry (shape) and topology (F, E and V)
2. Concept of Isogeometric B-Rep elements for enforcing different types of BC´s (Dirichlet, Neumann and Coupling between patches)
3. Numerical integration techniques for trimmed elements (NEJA) and IBRA workflow

Surface B-Rep model

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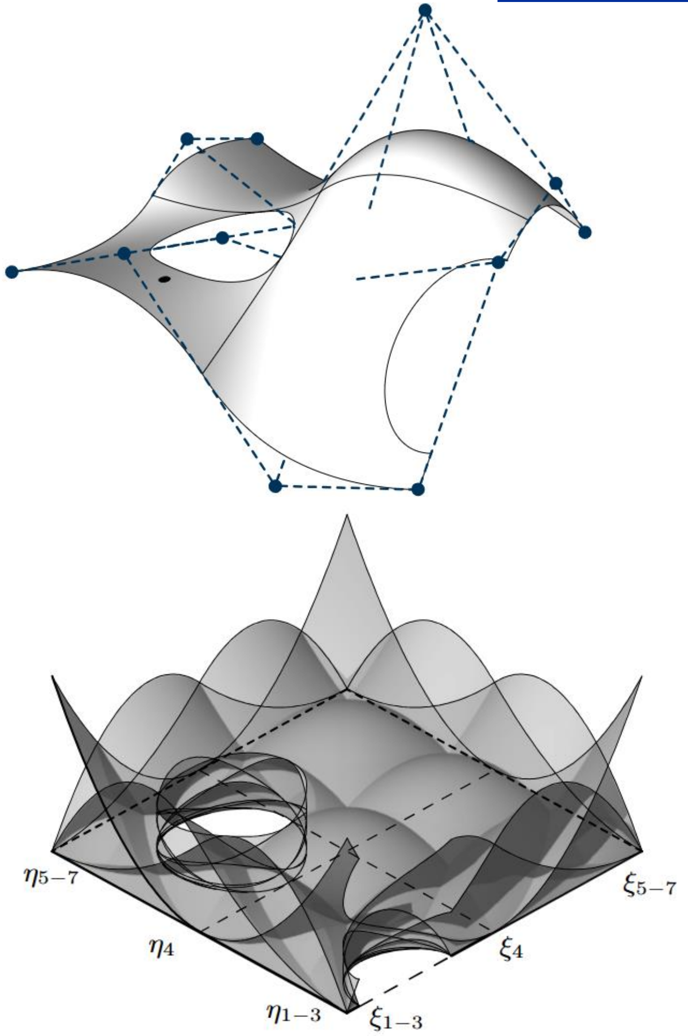
Introduction to Isogeometric B-Rep Analysis (IBRA)

Key Points related to IBRA

- Classical IGA works effectively until the point at which trimming operations are introduced
- IBRA can be considered as a generalization of isogeometric analysis (IGA) that uses the boundary representation (B-Rep) of the design model in addition to the same basis functions as in IGA for approximating the solution fields
- IBRA provided a novel approach to address trimming. The basic idea is to keep using all CP´s included in the model, considering however that only a portion of the domain, the one enclosed by trimming lines, is actually considered in the integration process
- B-Rep edge elements are used for patch coupling or imposition of Neumann and Dirichlet BC´s (in a weak sense): Penalty approach, Lagrange Multiplier Method or Nitsche Method



Trimmed NURBS Surface and its basis functions

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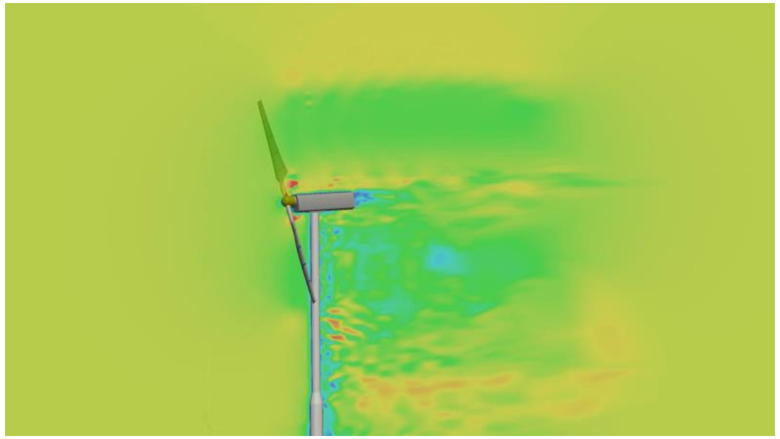
Introduction to Coupled Problems with a particular focus on FSI

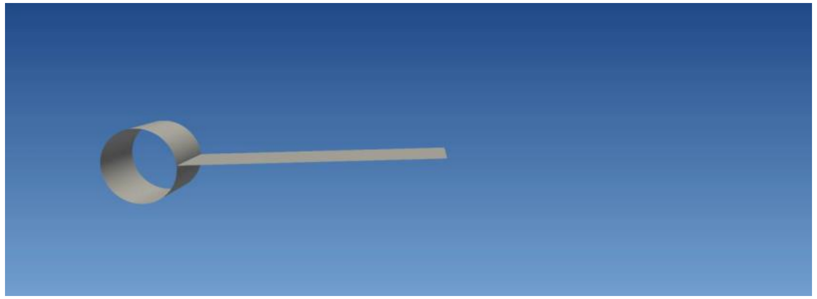
Key References

- *The finite element method for fluid-structure interaction with open-source software.* Joint course between TUM and CIMNE (2023)
- Bazilevs, Y., Takizawa, K., & Tezduyar, T. E. (2013). *Computational fluid-structure interaction: methods and applications.* John Wiley & Sons.

Contents covered in the course:

1. Introduction to Multiphysics: Coupled Problems and Coupling strategies (Monolithic and Partitioned for the case of strongly coupled problems)
2. Balance equations for the incompressible fluid and their discretization with FEM
3. Problems of Galerkin FE formulations of N-S Equations and stabilization
4. Arbitrary Lagrangian-Eulerian Formulation for mesh movement and deformation
5. Krylov methods for solving large linear systems





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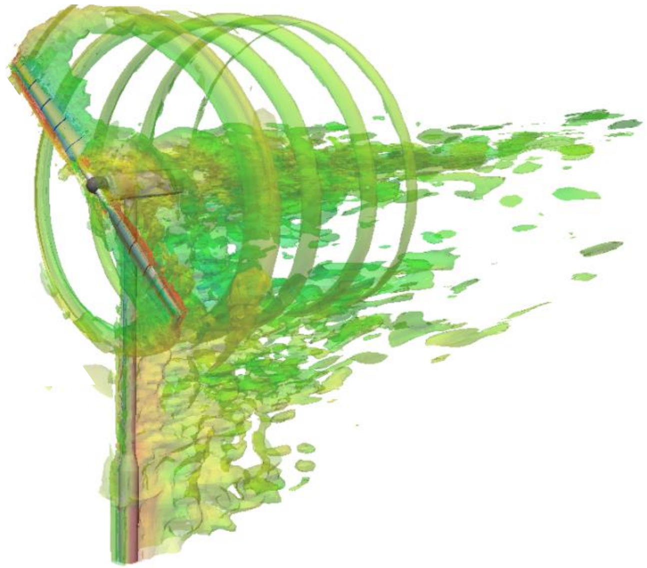
Brief Introduction to Kratos Multiphysics

Key References

- Dadvand, P., Rossi, R., & Oñate, E. (2010). *An object-oriented environment for developing finite element codes for multi-disciplinary applications.* Archives of computational methods in engineering, 17, 253-297.
- Introduction to Kratos Multiphysics course offered at ISD TU Braunschweig

Learning Path:

1. General Structure of Kratos: Kernel and Applications
2. OOP: Main Classes defined in Kratos
3. Kratos Data Structures
4. GitHub and developing in Kratos (Master, Branches, Pull requests, merge,etc)
5. Kratos Installation, Python interface and running some test cases



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KRATOS MULTI-PHYSICS

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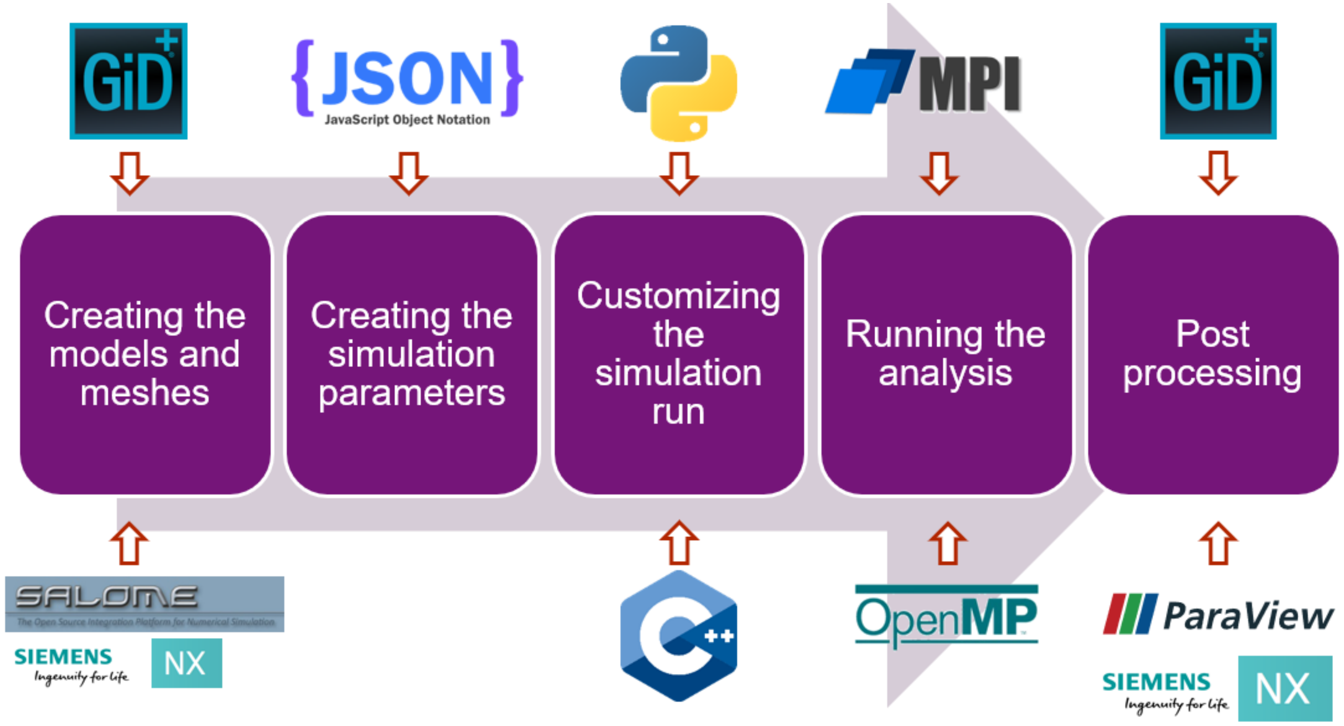
Brief Introduction to Kratos Multiphysics – Main Features & Working Pipeline

Kratos Main Features

1. Framework for parallel Multi-physics programs development
2. Object Oriented C++ code base
3. Python Interface
4. Open source and free
5. Flexibility and extensibility are the Kratos keywords
6. Modular structure of Kratos

- Kernel
- Applications: Fluid Mechanics Application, Structural Mechanics Application, ALE application, meshing application, Co-Simulation application, etc.



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Future Work & Research

Next Steps...

- Delve into co-simulation strategies, beginning with a comprehensive literature review and subsequent analysis of the CoSimulation application within Kratos Multiphysics
- Acquire hands-on experience and proficiency in Kratos Multiphysics
- Develop a deeper comprehension of the IGA application within Kratos Multiphysics
- Broaden my understanding of the mapping operators utilized between various discretizations
- Implement benchmark problems for co-simulation within Kratos Multiphysics and rigorously evaluate the performance of various co-simulation strategies

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Thank you!

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