Isogeometric Representation and Analysis
MS7 and MS9

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Presentations

MS 7 (Wednesday)

- **3:00-3:25 Challenges of Isogeometric Representation for CAD**
  - *Tor Dokken*, SINTEF, Norway
- **3:30-3:55 NURBS Volume Parameterizations for Blades**
  - *Elisabeth Pilgerstorfer,* Johannes Kepler University, Austria
- **4:00-4:25 Analysis-aware Modeling: Model Quality**
  - *Tom Lyche*, University of Oslo, Norway
- **4:30-4:55 Analysis-aware Modeling: Representing Shape and Volume**
  - *Elaine Cohen*, University of Utah

MS 9 (Thursday)

- **3:00-3:25 Isogeometric Analysis: Toward Integration of CAD and FEA**
  - Tom Hughes, *Scott Lipton*, and Mike Scott, University of Texas, Austin
- **Cancelled 3:30-3:55**
- **4:00-4:25 Advances in the Error Analysis for Isogeometric Discretization Techniques**
  - *Annalisa Buffa*, Consiglio Nazionale delle Ricerche, Italy;
- **4:30-4:55 Towards an Isogeometric Toolkit**
  - *Vibeke Skytt*, SINTEF, Norway

Challenges of Isogeometric Representation for CAD

Tor Dokken, SINTEF, Norway

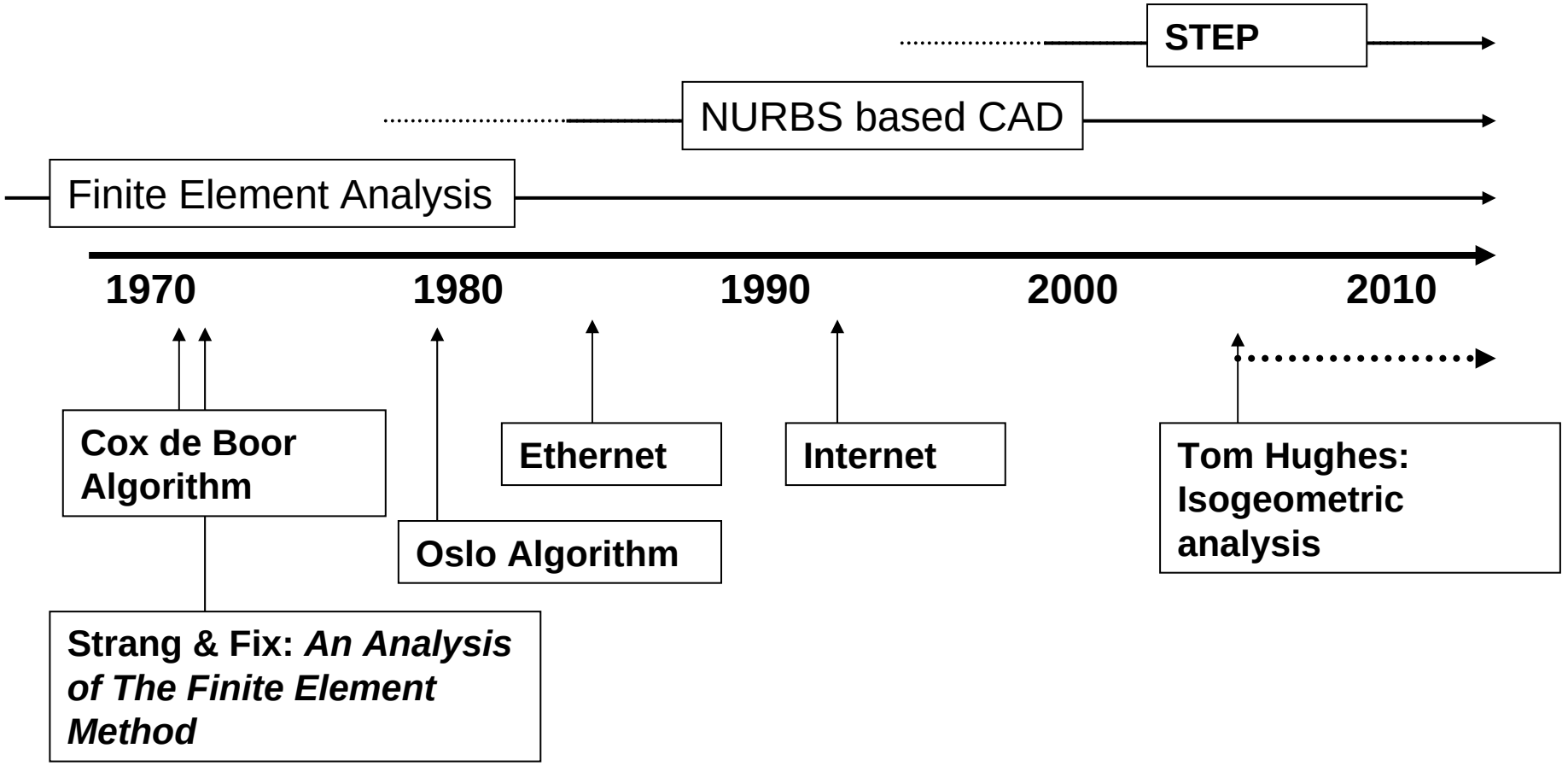
Independent evolution of CAD and FEM

- CAD (NURBS) and Finite Elements evolved in different communities before electronic data exchange
  - FEM developed to improve analysis in Engineering
  - CAD developed to improve the design process
  - Information exchange was drawing based, consequently the mathematical representation used posed no problems
    - Manual modelling of the element grid
  - Implementations used approaches that best exploited the limited computational resources and memory available.
- FEA was developed before the NURBS theory
  - FEA evolution started in the 1940s and was given a rigorous mathematical foundation in 1973 in Strang and Fix's *An Analysis of The Finite Element Method*
  - B-splines: 1972: DeBoor-Cox Calculation, 1980: Oslo Algorithm

From stand alone computers and systems to integrated information flows

- As long as communication between computers was hard, information exchange remained paper based
  - The Ethernet invented by Xerox Parc in 1973-1975,
  - ISO/IEEE 802/3 standard in 1984
  - Deployment in industry started, simple communication between computers
- CAD Data Exchange introduced
  - IGES Version 1.0 in 1980
  - STEP started in 1984 as a successor of IGES, SET and VDA-FS, Initial Release in 1994/1995, deployment started
- The Internet opened to all 1991
  - Start of deployment of data exchange between processes over the Internet

Timeline important events



What is isogeometric analysis?

- Introduced by Prof. Tom Hughes, University of Texas at Austin in 2005
  - Replace traditional Finite Elements by NURBS Elements
  - NURBS (NonUniform Rational B-splines) is used in CAD for representing free form curves and sculptured surfaces.
  - NURBS elements can represent the CAD-geometry exactly
  - Claim: NURBS elements have many advantages compared to traditional Finite Elements
  - Claim: Removes the bottleneck between CAD and analysis
  - Examples published show superior performance of isogeometric analysis compared to traditional FEA

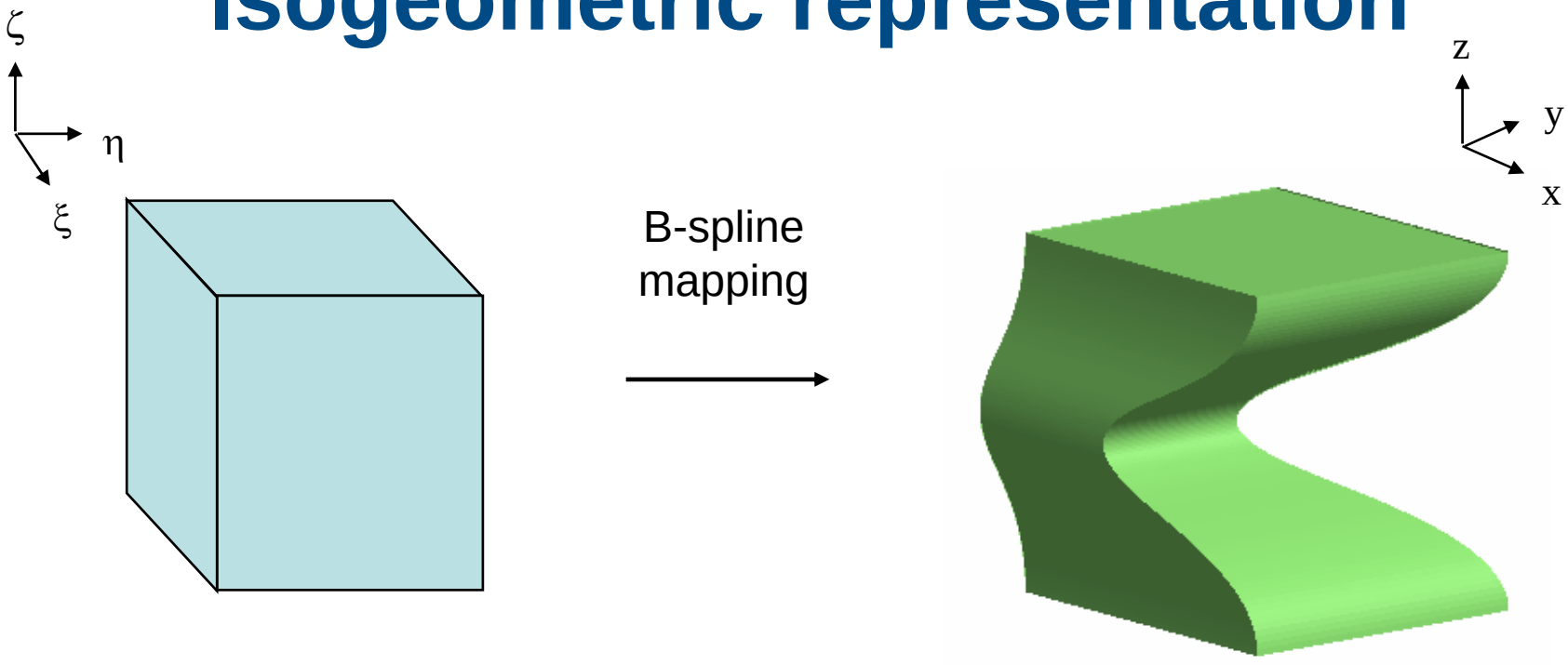
Why are splines important to isogeometric analysis?

- B-Splines are polynomial, same as Finite Elements
- B-Splines are very stable numerically
- B-splines represent regular piecewise polynomial structure in a more compact way than Finite Elements
- NonUniform rational B-splines can represent degree 2 algebraic curves and surfaces exactly. (circle, ellipse, cylinder, cone…)
- Efficient and stable methods exist for refining the piecewise polynomials represented by splines
  - Knot insertion (Oslo Algorithm, 1980)
  - B-spline has a rich set of refinement methods

Why have NURBS not been used in FEA?

- FEA was developed before the NURBS theory
- NURBS and Finite Elements evolved in different communities before electronic data exchange
- Current computers have extreme performance compared to earlier computers. Allows more generic solutions.
  - Mathematical representation chosen based on what was computationally feasible.
- Heterogeneous multi-core processors require new algorithms and changes of existing codes
  - Most existing (CAD) program codes are sequential
  - Combine the introduction of NURBS in FEA and exploiting the performance of heterogeneous multi-core processors

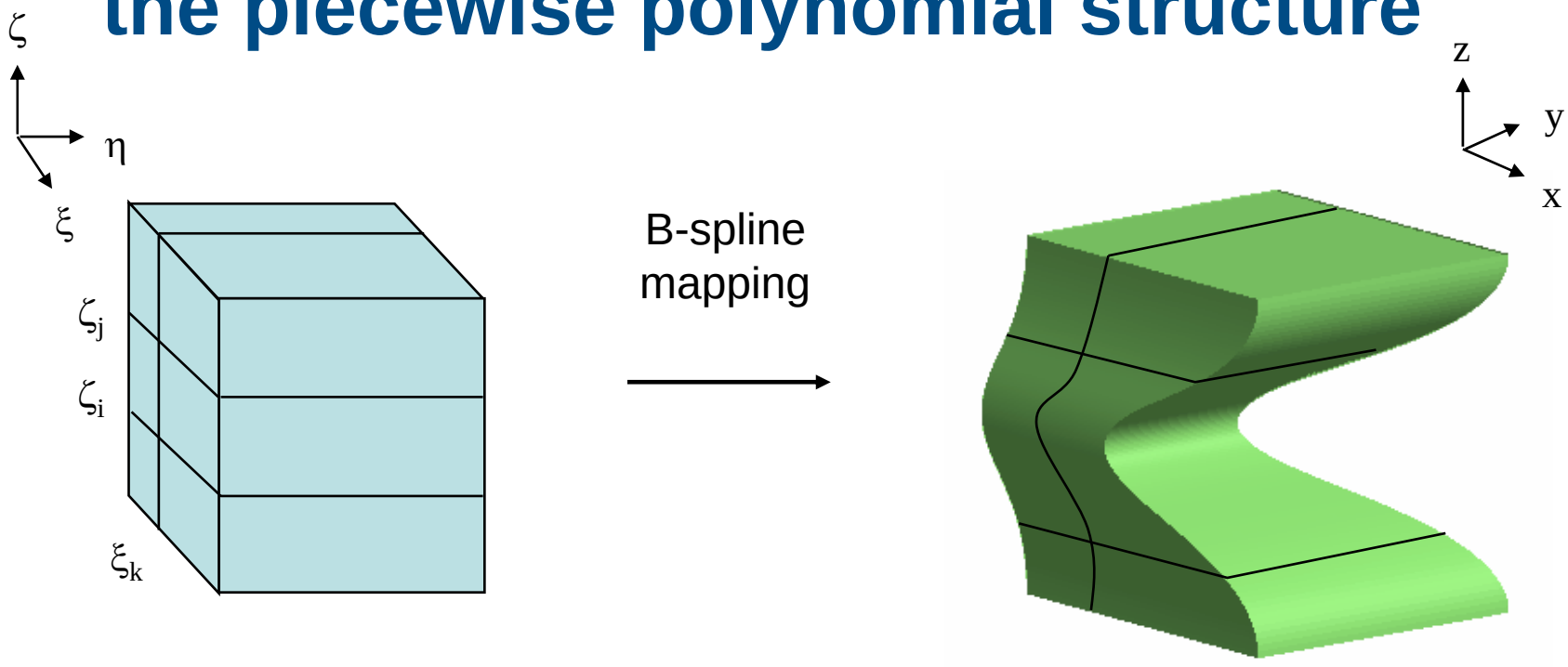
Isogeometric representation



Example by :
Tom Hughes

- The faces of the block reproduce the CAD-shape exactly

The description is refined by knots defining the piecewise polynomial structure

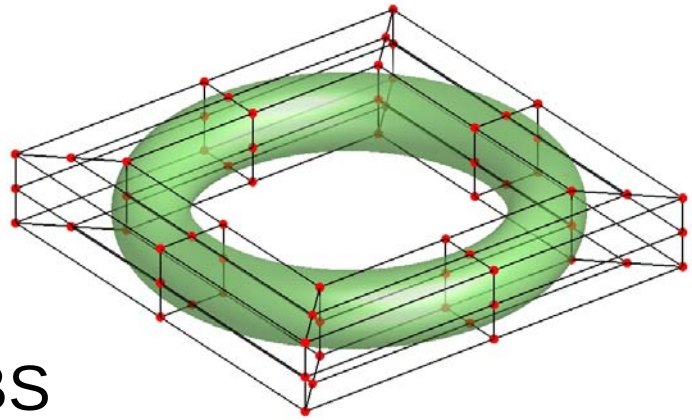


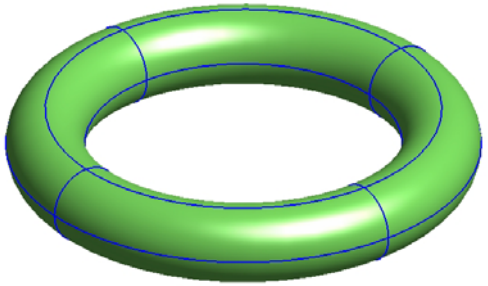
Example by :
Tom Hughes

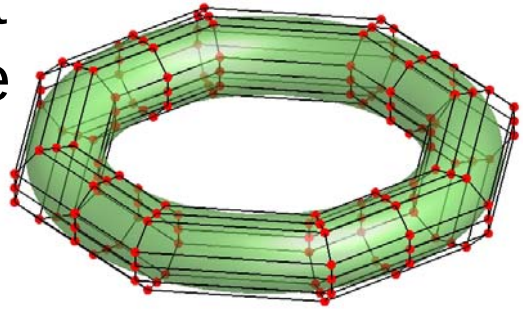
- Knot insertion do not change the geometry, only the “element structure”

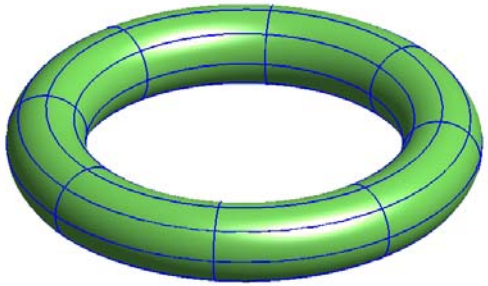
Knot insertion (h-refinement)

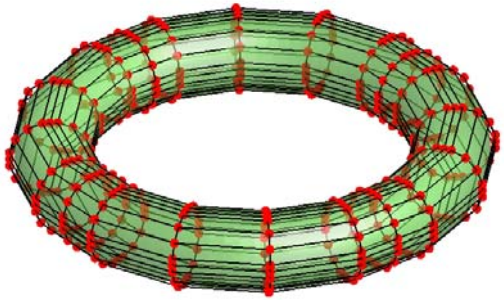
NURBS control net around the shape

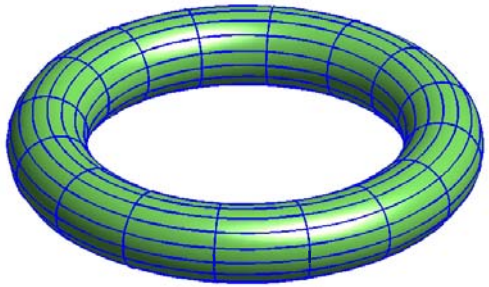












Mesh on the shape

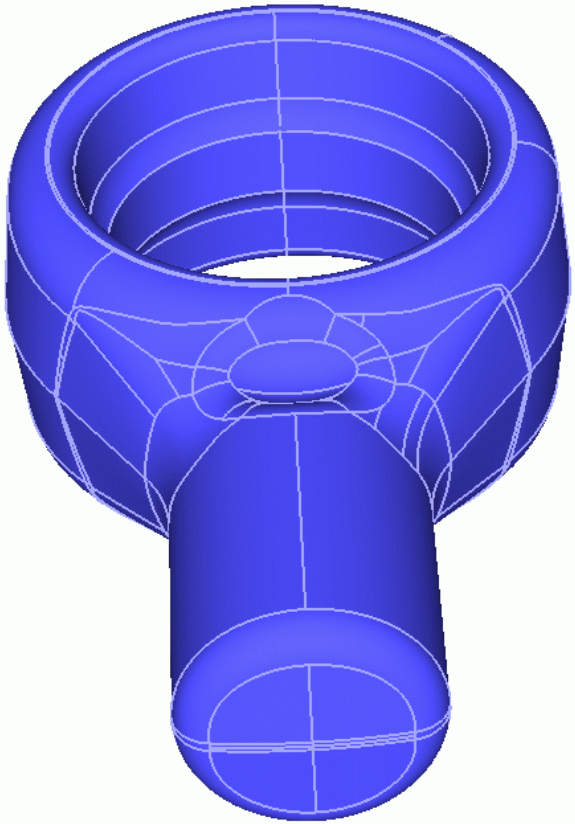
Example by : Tom Hughes

CAD has to change to support isogeometric analysis

- Example: Patch structure of a fairly simple CAD-object
  - Object designed patch by patch to match the desired shape
  - Shape designed for production

CAD patch structure not an obvious guide to NURBS block structure

- We would like considerably fewer NURBS blocks than the number of surfaces patches
- The object has three main parts
  - The “torus” like part
  - The “cylindrical” handle
  - The transition between these
- Not obvious how this can be represented as a composition of NURBS blocks
  - Acute angles
  - Extraordinary points
  - Singular points



Current CAD technology is here to stay

- The major part of revenue of CAD vendors comes from industries that don't suffer from the CAD to analysis bottleneck.
- Current CAD is standardized in ISO STEP (ISO 10303)
- The driving force for isogeometric CAD has to be industries that has the most to gain from the novel approach, e.g.,
  - aeronautics, defense, space and automotive industries
- Iso geometric CAD: A next natural step in CAD evolution?
- ISO STEP should also encompass isogeometric CAD

Two approaches to isogeometric CAD

1. Build the block structure one block at the time
   - User responsible for block interfaces and interfaces to outer and inner hulls.
   - Similar to surface modeling without trimming
2. Design the trivariate block structure in an already existing ISO STEP type CAD model
   - The user controls the block structure. The blocks snap together and to outer and inner hulls.
   - Similar to designing surfaces into a point cloud in reverse engineering

- We believe that starting with approach 2 and then gradually introduce approach 1 is the best approach

Tensor product NURBS lacks local refinement

- The regular structure of tensor product NURBS does not allow local refinement
- Local refinement is the aim of hierarchal B-splines
  - Isogeometric analysis needs to have a one-level coding
- T-splines has a one level coding of hierarchal B-splines
  - However, T-spline theory is developed only? for surfaces,
- Alternative: **L**ocally **R**efined **Splines**, where selected tensor product B-spline basis functions are refined.
  - The splines space is be a space of tensor product B-spline basis functions with refinement at different levels.
  - The spline space will be globally linearly independent, but in refined interval there will be linear dependencies.
  - SINTEF is now addressing the potential of LR-Splines

SINTEF Activities with isogeometric representation and analysis

- Isogeometry. Norwegian project for improving the mathematics used in the processes between CAD and FEM. (2008-2011) (SINTEF + 2 industrial partners).
- ICADA. Norwegian project looking at the use of splines elements (mathematics of CAD) in FEM. (2008-2013) (SINTEF + 3 industrial partners).
- Exciting. EU-project looking at the use of isogeometric analysis within the transport sector. (2008-2011) (3 Universities, 2 R&D Institutes, 4 industrial partners)
  - Coordinator: Prof. Bert Jüttler

Work so far at SINTEF

- ***Isogeometry***: Focus on CAD-model qualities necessary for modeling of NURBS-volumes into CAD-structures
  - Preparatory work within quality control and repair of CAD-models
- ***ICADA***: Focus on direct modeling of NURBS volumes by basic operations such as generating NURBS volumes:
  - Surface sweeping
  - Surface rotation
  - Lofting through surface

  Provide good NURBS volumes for isogeometric analysis
- ***Exciting:*** The **Isogeometric Toolkit** with NURBS functionality for curves, surfaces and volumes, and provide complementary software, e.g., quadratur formulas
  - For information see *http://www.sintef.no/math_software.*

Conclusion

- Isogeometric representation has the potential of introducing close integration of CAD and FEA, and to improve the quality of FEA
  - FEA has to be changed
  - CAD has to be changed
  - ISO STEP has to be extended
  - More exact models will improve the quality of long term archival
- The driving force for isogeometric CAD has to be research and industries in need of removing the bottlenecks between CAD and FEA
- Growing interest for the approach in US and Europe
  - An isogeometric toolkit is under development
- Heterogeneous multi-core processors demands changes of many software codes
  - This is an opportunity also to readdress established solutions