Beyond FEA:
Arbitrary-Lagrangean-Eulerian (ALE) Method

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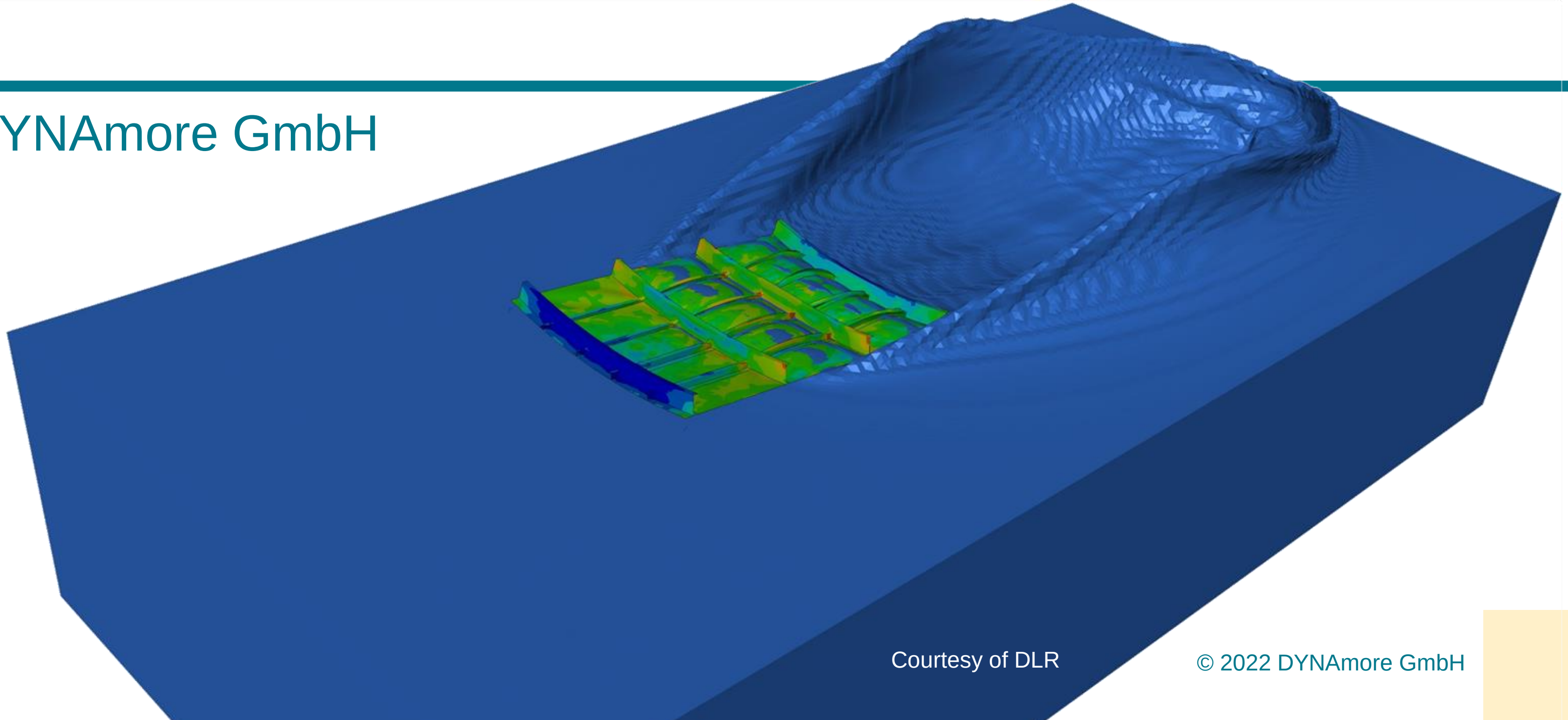


Courtesy of DLR

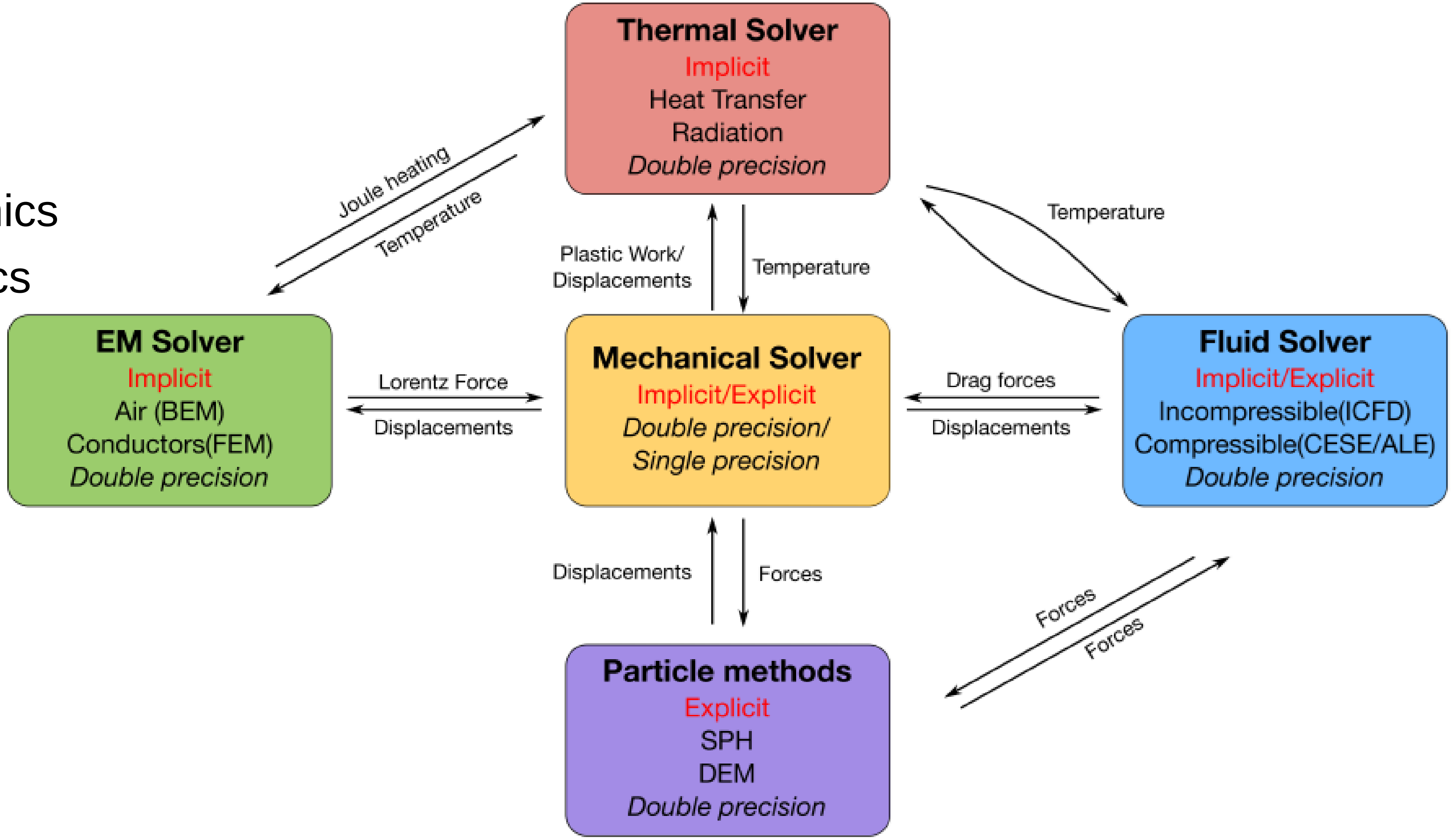
Introduction

First things first

Introduction

LS-DYNA Multi-Physic Solver

- **One Code for all**
  - Structural mechanics
  - Heat transfer
  - Incompressible fluid dynamics
  - Compressible fluid dynamics
  - Electromagnetics
  - Particle methods



Introduction

Overview

- ALE Fundamentals
- ALE in LS-DYNA
- Lagrangean-Structure Interaction
- Moving Reference Frame
- Output
- Structured ALE (S-ALE)
- Summary

ALE Fundamentals

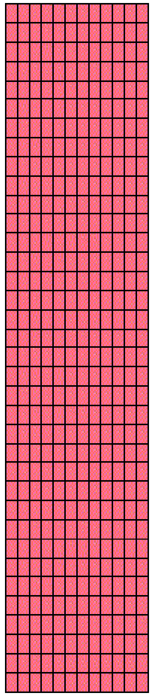
Under the hood

ALE Fundamentals

Overcoming Element Degration

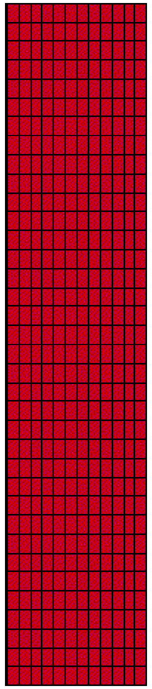
Problem

- Large deformations/distortions
- Element performance degration



Solution

- Mesh-adaptivity (re-meshing)
- ALE approach

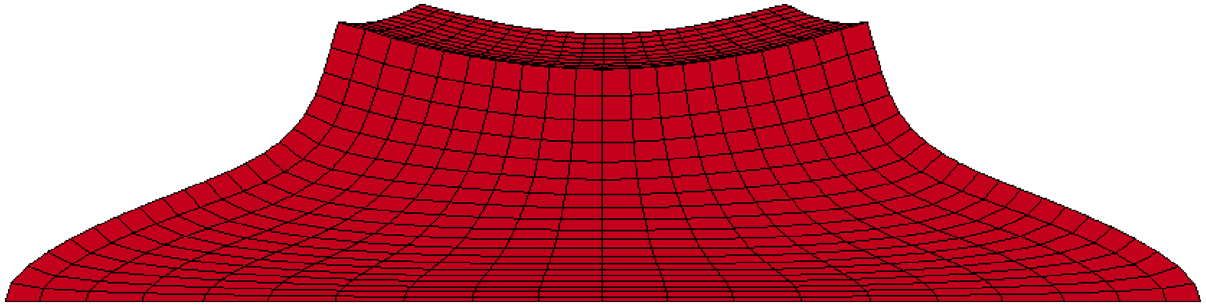


ALE Fundamentals

Lagrangean vs ALE forumulation

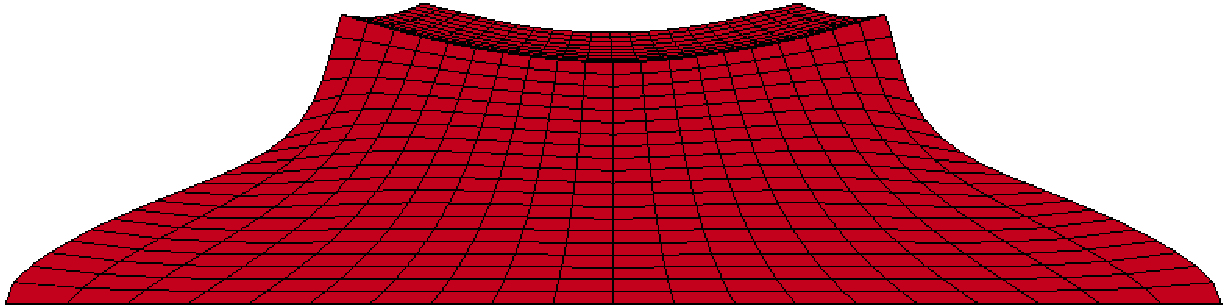
Lagrangeian Formulation

- **Nodes are tied to material**
- Mesh deforms with the material
- Not suitable for very large deformations, e. g. forging, extrusion, material flow



ALE formulation

- **Nodes are not tied to material**
- Nodes are repositioned to avoid exessive mesh distortion
- Relative motion between material and mesh



ALE Fundamentals

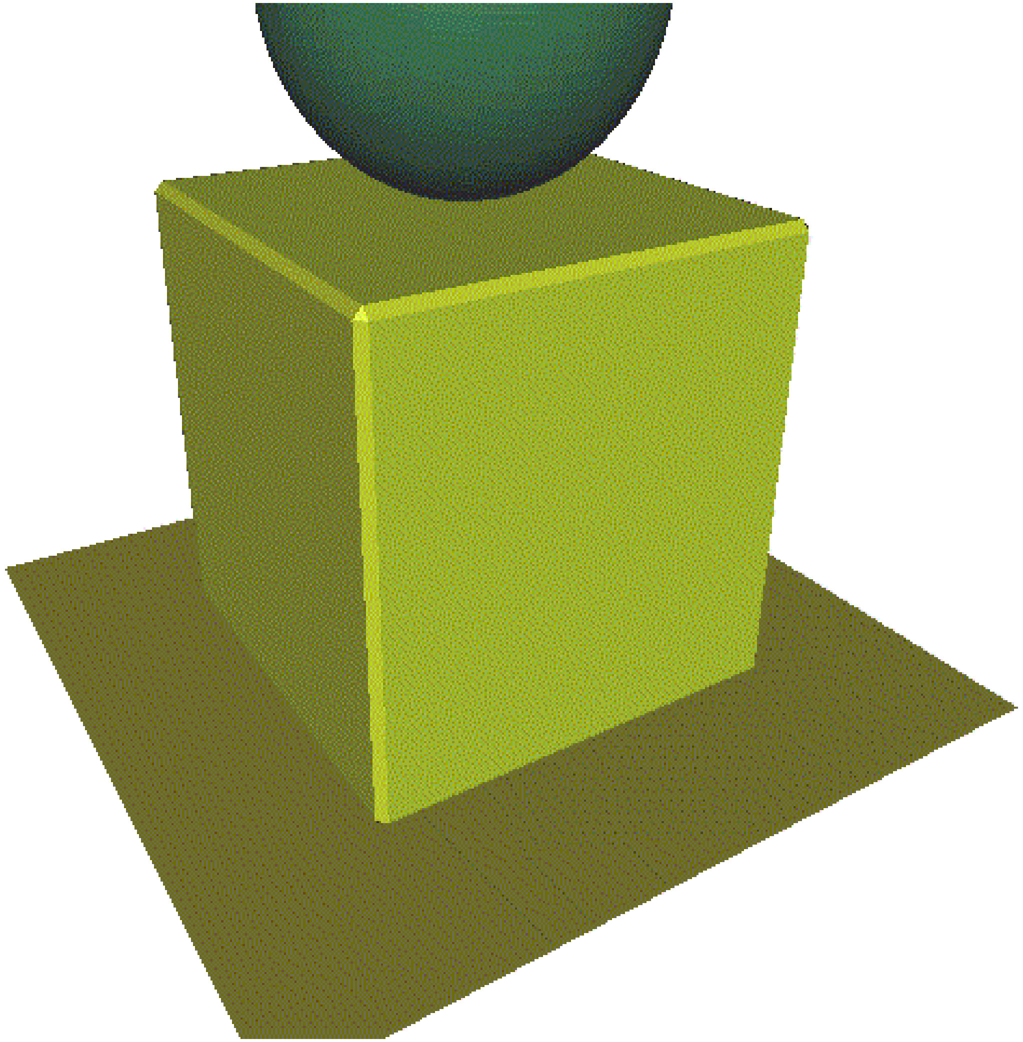
Solving complex PDE

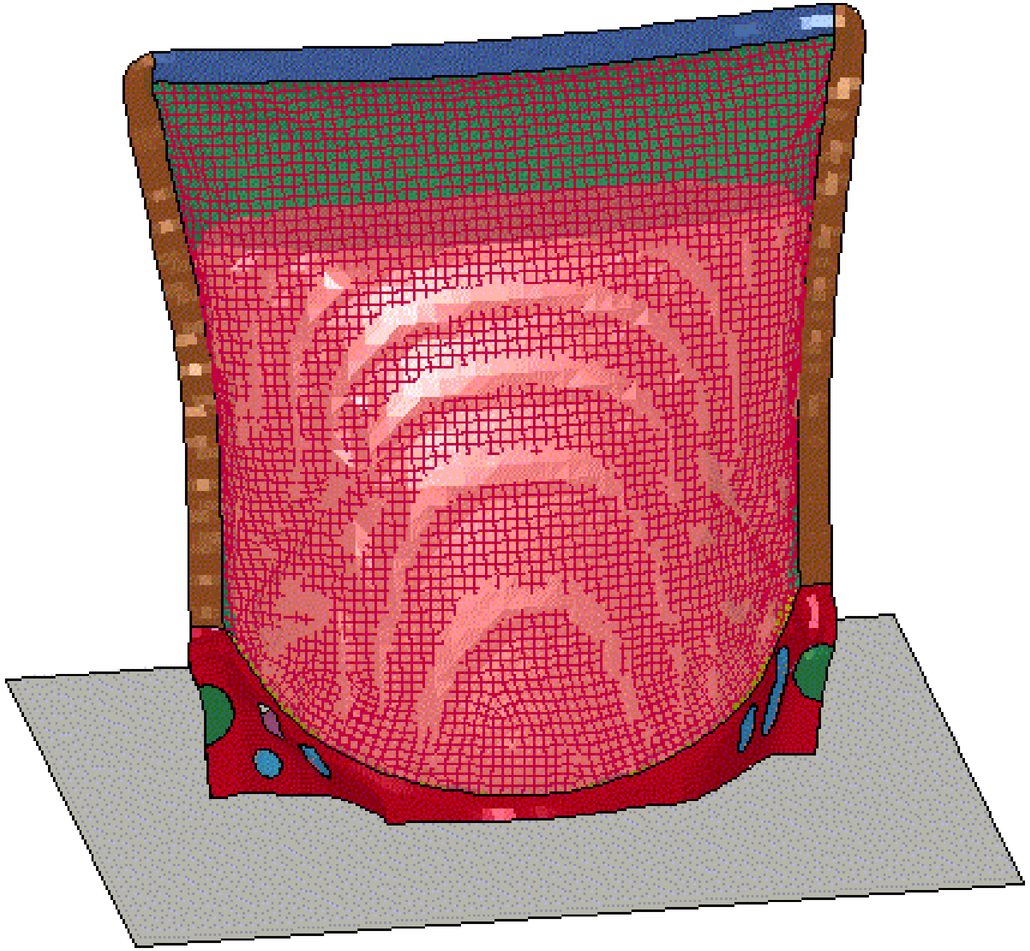
- Numerical methods to solve partial differential equations (PDE), e. g.
  - **Mass balance**
  - **Momentum balance**
  - **Energy balance**
- Numerical solution procedure comprises
  - **Space discretization**, e. g. Finite-Element Analysis (FEA), Smoothed Particle Hydrodynamics (SPH)
  - **Time discretization**, e. g. Backward Euler (BE), Central Difference (CD) scheme

ALE (Arbirary Lagrangean Eulerian)

- Is neither one of these
- In particular, it still **exploits FEA and CD for space and time discretrization**, respectively
- However, tweaks the update of the solutions state **using Lagrangean and Eulerian formulation**

ALE Fundamentals
Application examples



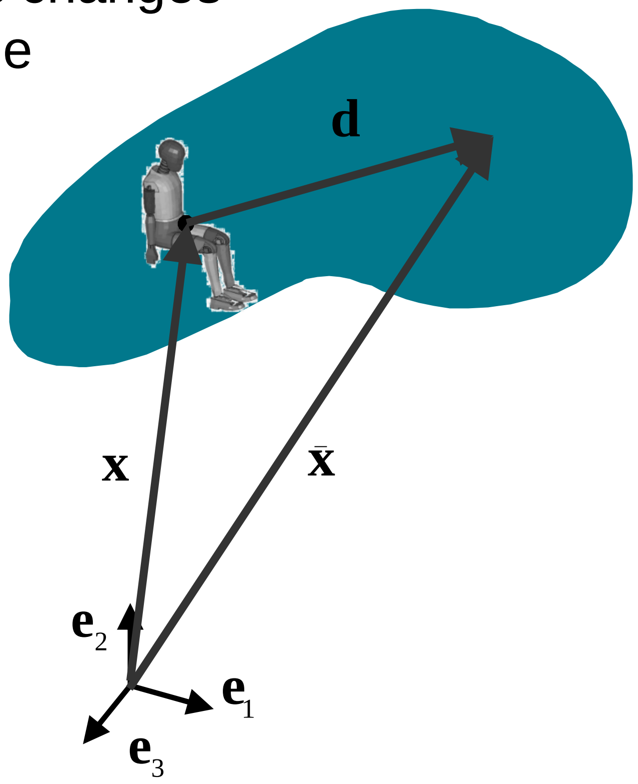


ALE Fundamentals

Lagrangean vs Eulerian Formulation

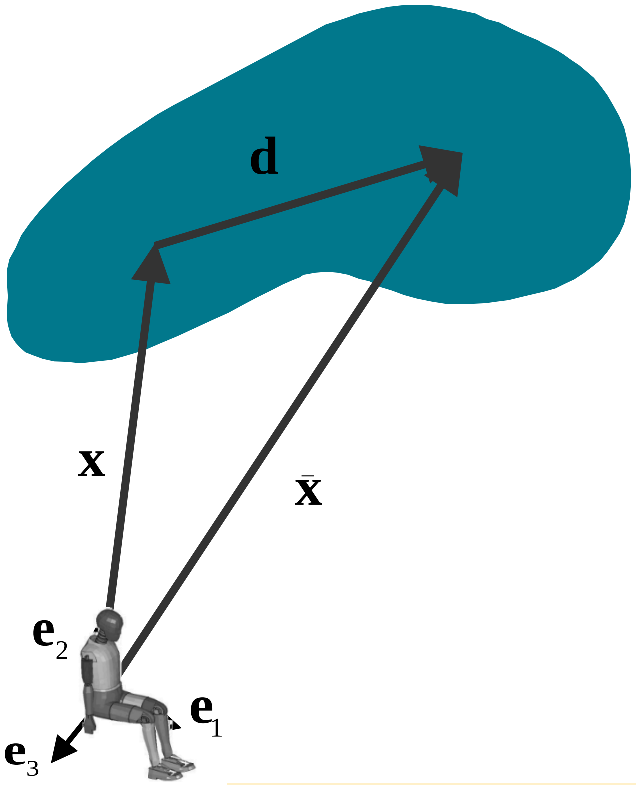
Lagrangean

- Material description
- Follows material motion and observes changes in variable



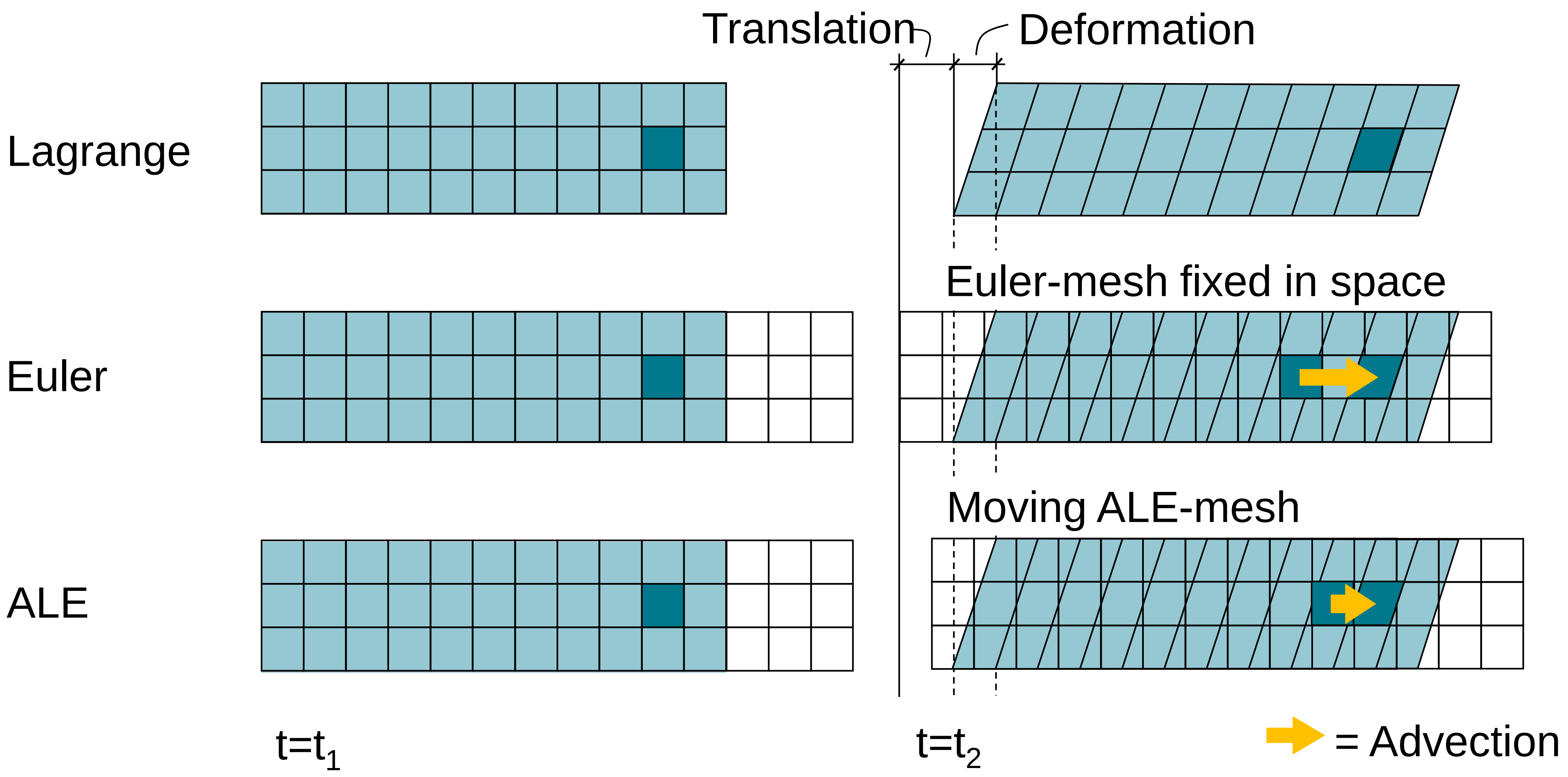
Eulerian

- Spatial description
- Observation of material-point attached variables pass by a fixed point



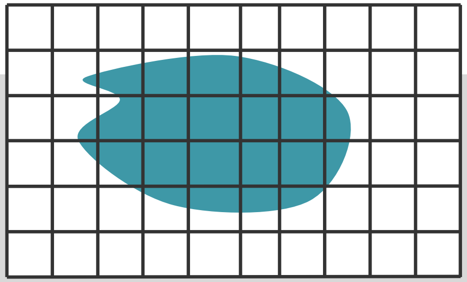
ALE Fundamentals

Lagrangean vs Eulerian Formulation vs ALE



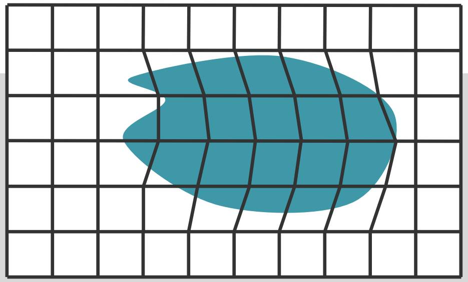
ALE Fundamentals

ALE time advancement



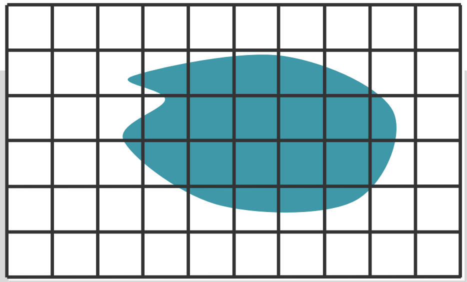
FEA Step

- Lagrangean



Intermediate ALE Steps

- Mesh smoothing
- Advection



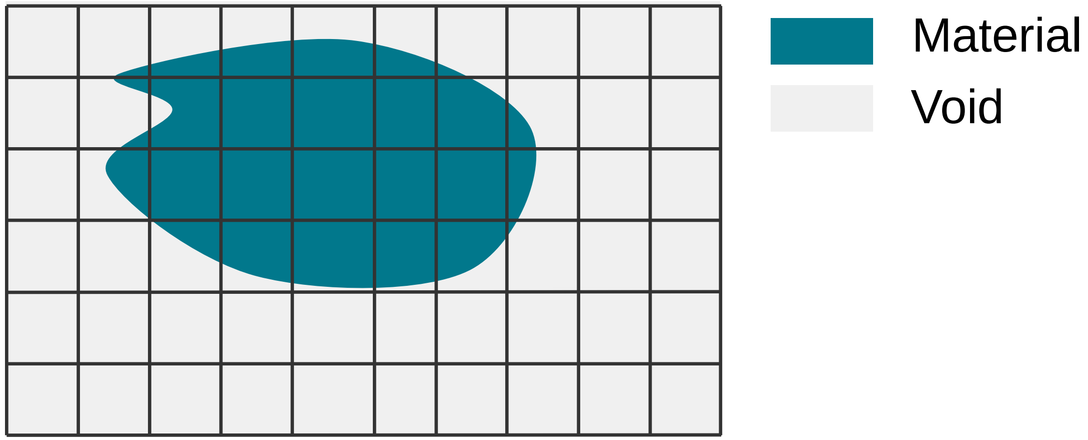
- Lagrangean
  - **Mesh distortion** via node movement following material motion, i. e. regular FEA step
- Intermediate ALE Steps
  - **Mesh smooting**, e. g. average method, equipotential [Winslow 1963, 1990]
  - **Advection**, i. e. material flow, via, e. g., Doner cell, van Leer
- Time step size
  - **CFL stability condition** applies, i. e. $\Delta t_{cr} \approx \min_{nel}\left[\frac{\Delta x^e}{c}, \frac{2\Delta x^e}{v^e}\right]$

ALE Fundamentals

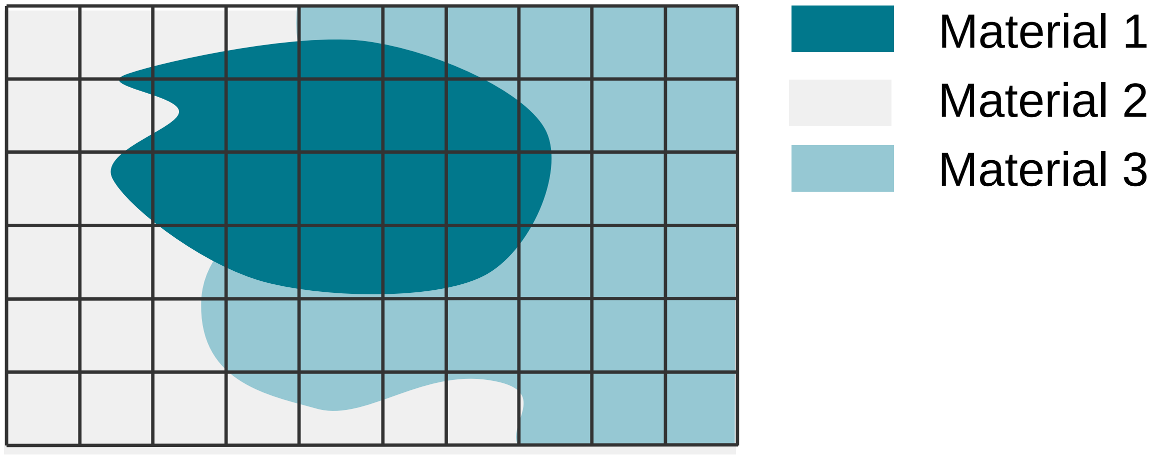
Single vs multi-material ALE

- ALE domain may contain
  - Single material in a vacuum, where only one material obeys an material law → **Single-Material ALE**
  - Several materials, where each material follows its own material law → **Multi-Material ALE**

Single-Material ALE



Multi-Material ALE



Use Single-Material ALE only when fluid-fluid interaction is not of concern

ALE in LS-DYNA

Important Keywords

ALE in LS-DYNA

Overview

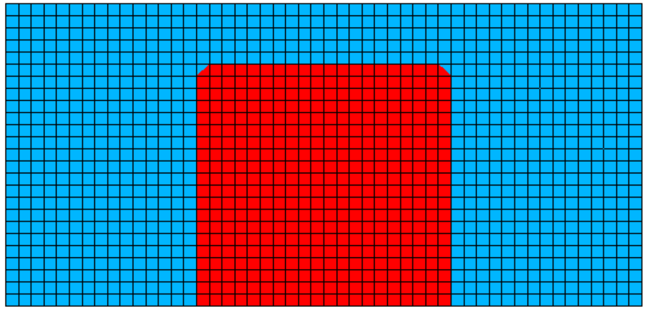
- **Global control** via *CONTROL_ALE, e. g.
  - Adection scheme and advection frequency
  - Reference pressure on ALE domain boundaries
- **Multi-Material Euler/ALE** via *ALE_MULTI-MATERIAL_..., e. g.
  - Multi-Material definitions
  - Initial material distribution
- Material laws via *MAT_, *MAT_ALE_, *EOS_
- **Lagrangean-structure interaction** via *CONSTRAINED_LAGRANGE_IN_SOLID
- For **boundary conditions**, mostly the usual *BOUNDARY_ keywords apply
- Post-processing via *DATABASE_FSI_...

ALE in LS-DYNA

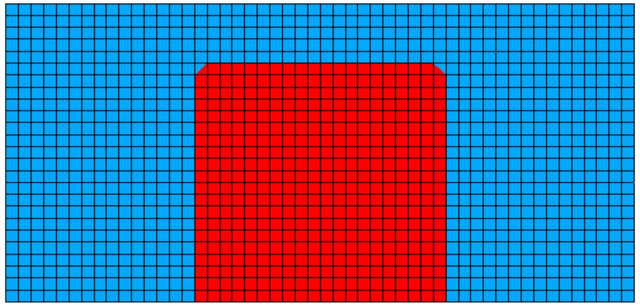
Element formulations

- ELFORM in *SECTION_SOLID defines the ALE/Eulerian formulation

```
*PART
$       PID     SECID       MID      EOSID       HGID
          1         1         1
*SECTION_SOLID
$     SECID    ELFORM
          1        11
*MAT_NULL
$       MID        RO          PC        MU      TEROD      CEROD        YM         PR
          1       ...
```



Eulerian ELFORM



ALE ELFORM

ELFORM

EQ. 5: 1 point integration ALE (single material)
EQ. 6: 1 point integration Eulerian (single material)
…
EQ.11: 1 point integration ALE (multi-material ALE)
EQ.12: 1 point integration ALE (single-material ALE and void)

ALE in LS-DYNA

Multi-Material Definition

- `ELFORM` in `*SECTION_SOLID` defines the ALE/Eulerian formulation

```
*PART
$      PID     SECID       MID     EOSID      HGID
         1         1         1
*SECTION_SOLID
$    SECID    ELFORM
         1        11
*MAT_NULL
$      MID        RO        PC        MU     TEROD     CEROD        YM        PR
         1       ...
```

ELFORM

EQ. 5: 1 point integration ALE (single material)
EQ. 6: 1 point integration Eulerian (single material)
…
EQ.11: 1 point integration ALE (multi-material ALE)
EQ.12: 1 point integration ALE (single-material ALE and void)

ALE in LS-DYNA

Multi-Material Definition

- Multi-Material Euler/ALE via `*ALE_MULTI-MATERIAL_...`

```
*ALE_MULTI-MATERIAL_GROUP
$        sid     idtype
          11          1          Multi-material group 1
          22          1          Multi-material group 2
          33          1          Multi-material group 3
          55          1          Multi-material group 4
         ...        ...
```

SID	part or part-set id
IDTYPE	entity type in SID, i. e. part set, part

Remarks

- Note that the **multi-material ID are assigned automatically** sequentially from top to buttom
- Only materials of same material group can join or mix, respectively

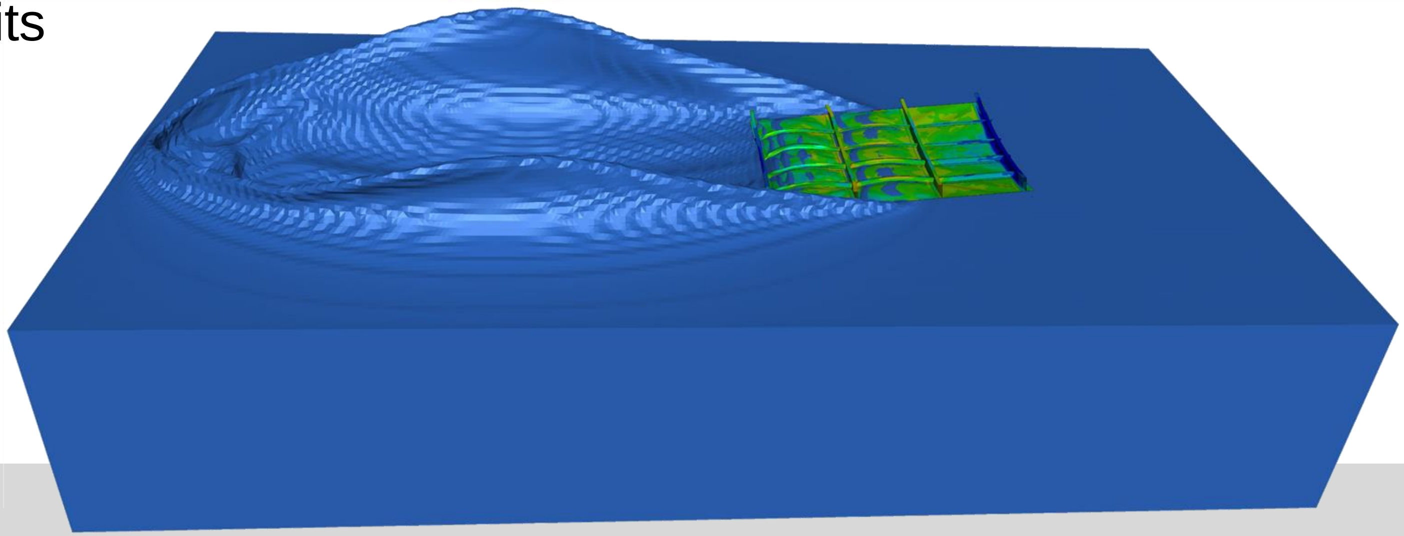
Lagrangean-Structure Interaction

Interaction between ALE and FE

Lagrangean-Structure Interaction

Basic concepts

- Different problems require different simulation strategies
- Finite-Element Analysis (FEA)
  - **Highly efficient**
  - However, element-distortion-capability limits material deformation
- Arbitray Lagrangean Eulerian (ALE)
  - **Large deformation** and **material mixing** possible
  - Less efficient



FEA-ALE interaction

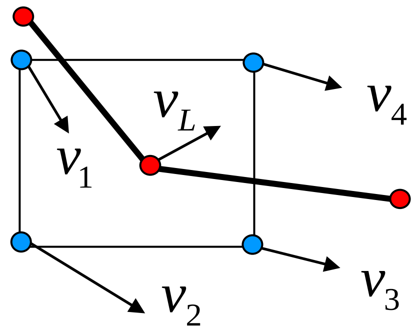
- FEA for mildly deforming structures, e. g. solid structures
- ALE for heavily distorting materials, e. g. pastes, liquids

Lagrangean-Structure Interaction

Methodology

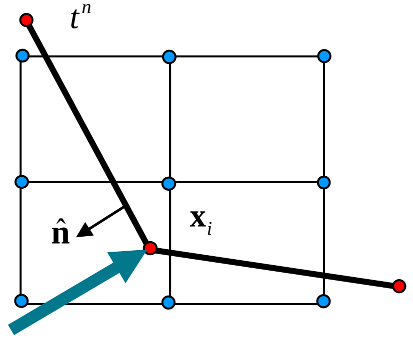
Constraint-based Method

- ALE-Material velocities are computed at coupling point of Lagrangean structure
- Both velocities are forced to be the same



Penalty-based Method

- Penalty method punishes violation of constraint via a penalty force
- Penalty force is proportional to amount of violation, e. g. penetration depth



Remarks

- Interaction activated via `*CONSTAINED_LAGRANGE_IN_SOLID`
- For ALE-rigid-body interaction, penalty method, `CTYPE=4` in `*CONSTRAINED_LAGRANGE_IN_SOLID` is needed

Lagrangean-Structure Interaction

Keyword

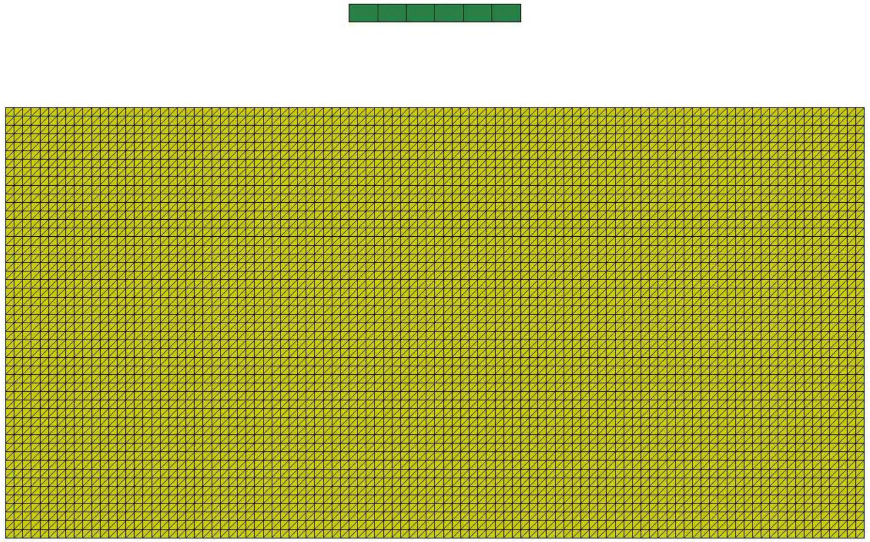
```
*CONSTRAINED_LAGRANGE_IN_SOLID
$    SLAVE    MASTER     SSTYP     MSTYP     NQUAD     CTYPE     DIREC     MCOUP
       401       402         0         0         1         6         1      -998
$    START       END      PFAC      FRIC     FRMIN      NORM   NORMTYP      DAMP
         0         0      -999         0       0.2         0
$       CQ      HMIN      HMAX     ILEAK     PLEAK  LCIDPORO     NVENT    IBLOCK
         0         0         0         2       0.1
```

SLAVE	Slave ID references the **Lagrangean structure**
MASTER	Master ID references the **ALE mesh**
SSTYP	Slave set type, e. g. part set, part or segment
MSTYP	Master set type, e. g. part set or part
NQUAD	Number n of quadrature points to **control leakage**
CTYPE	**Coupling method**, e. g. penalty (CTYPE=4)
…	
MCOUP	Multi-material coupling
PFAC	Penalty-stiffness scaling factor if GT.0
…	
ILEAK	Leakage-control method

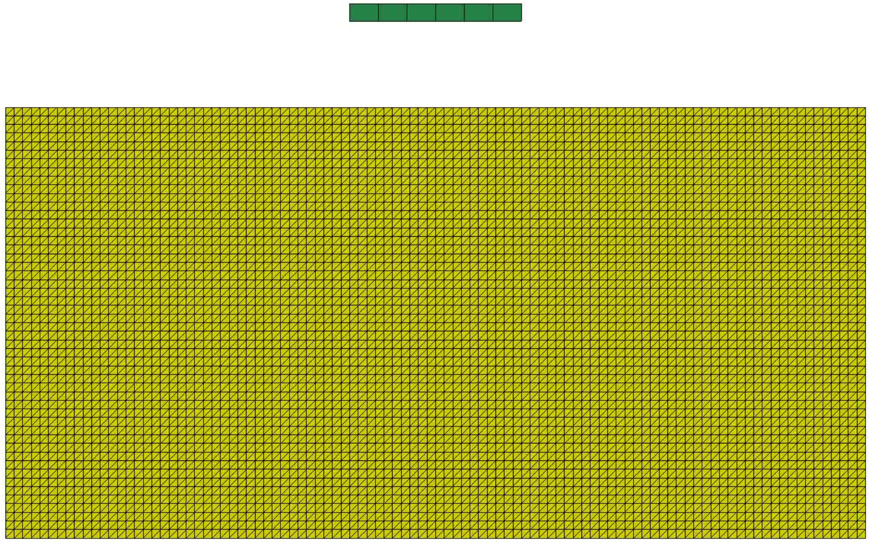
Lagrangean-Structure Interaction

Leakage

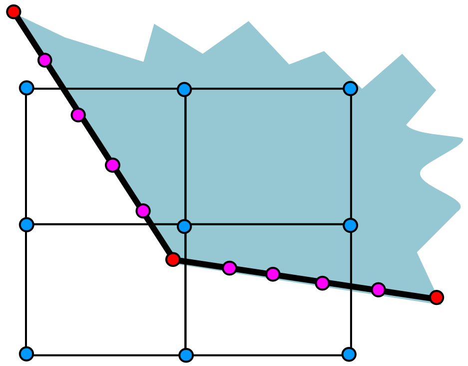
- Leakage occurs if there are too few coupling points



Too few coupling points (NQUAD=1) → leakage



Sufficient coupling points (NQUAD=4) → leakage



At least, three coupling points on lagrangean-structure segment in ALE is recommended

Moving Reference Frame

Moving Reference Frame

Rotation and translation of the ALE domain

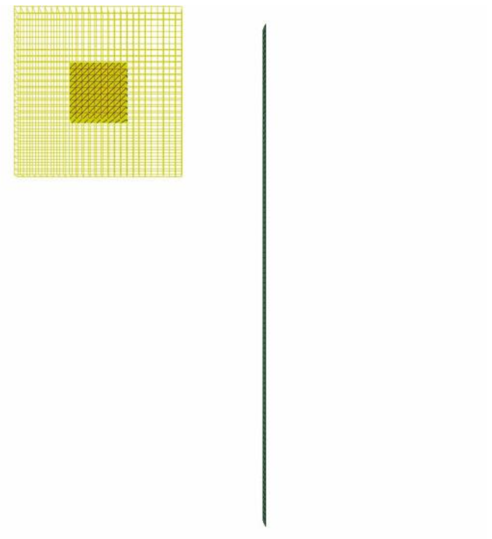
- To reduce the size number of elements, a moving/transforming ALE mesh can be introduced used via `*ALE_REFERENCE_SYSTEM_GROUP`

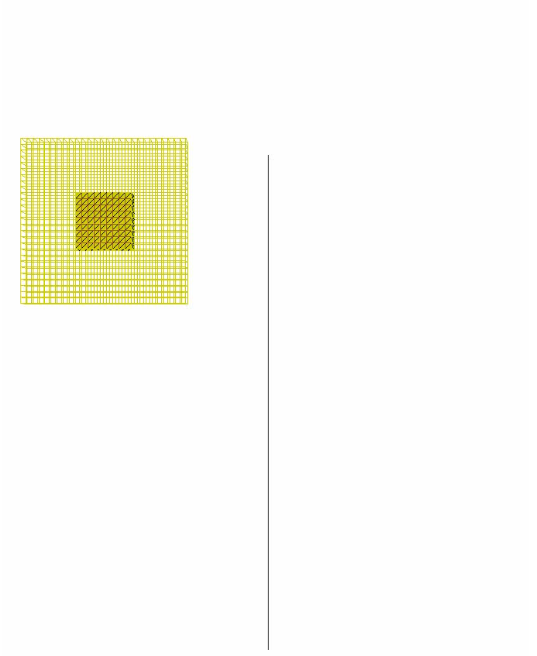
```
*ALE_REFERENCE_SYSTEM_GROUP
$       SID     STYPE    PRTYPE      PRID   BCTRAN    BCEXP    BCROT   ICOORD
          2         1         1                                          1.0
$        XC        YC        ZC    EXPLIM     EFAC
        0.0       0.0       0.0       2.0      0.5
```

…

PRTYPE	reference system type, e. g. following coordinate system, average velocity of ALE
BCTRAN	translational constraints
BCROT	rotational constraints
BCEXP	mesh-expansion/shrinkage constraint

…





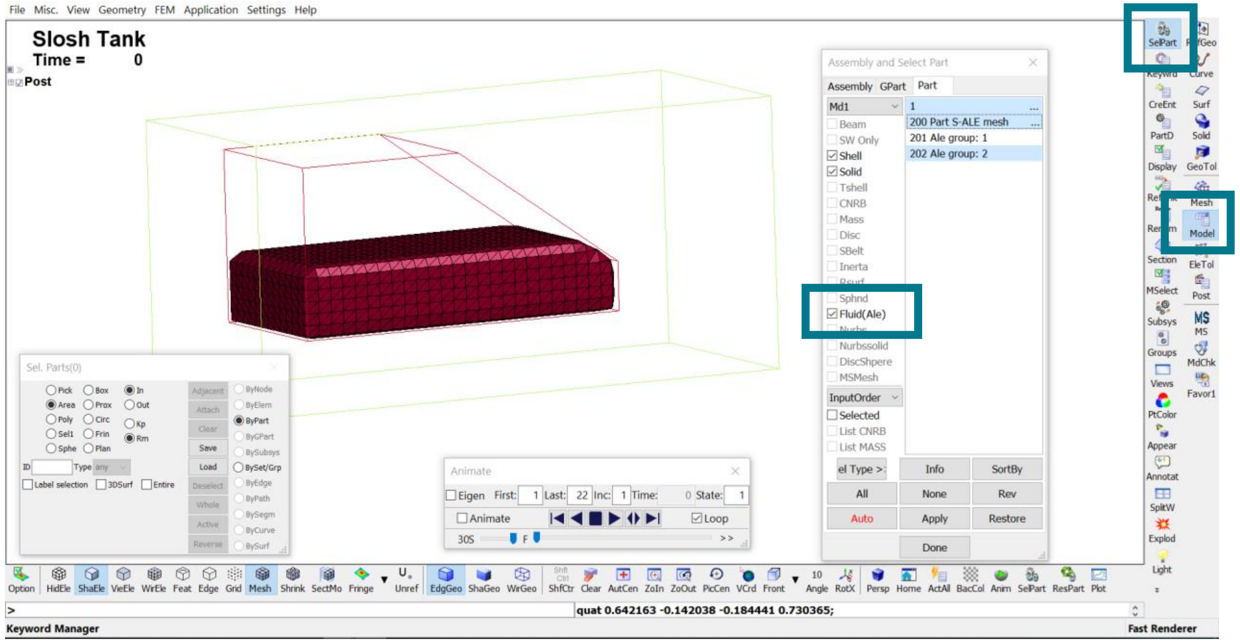
Outputs

Outputs

Visualisation data

ALE group in LS-PrePost

- Go to Model → SelPart
- In the window, tick the check box Fluid(ALE)
- Select the desired ALE groups



Further Databases

- *DATABASE_ALE to select output order of history variables in curve plots and in d3plot
- For specific FSI-related output variables, *DATABASE_FSI_… can be used, e. g.
  - Sensor with offset to Lagrangean surface
- For FSI-pressure fringe plots, use keyword *DATABASE_BINARY_FSIFOR

Hint

In *DATABASE_EXTENT_BINARY use NEIPH to output integration-point data of ALE history variables

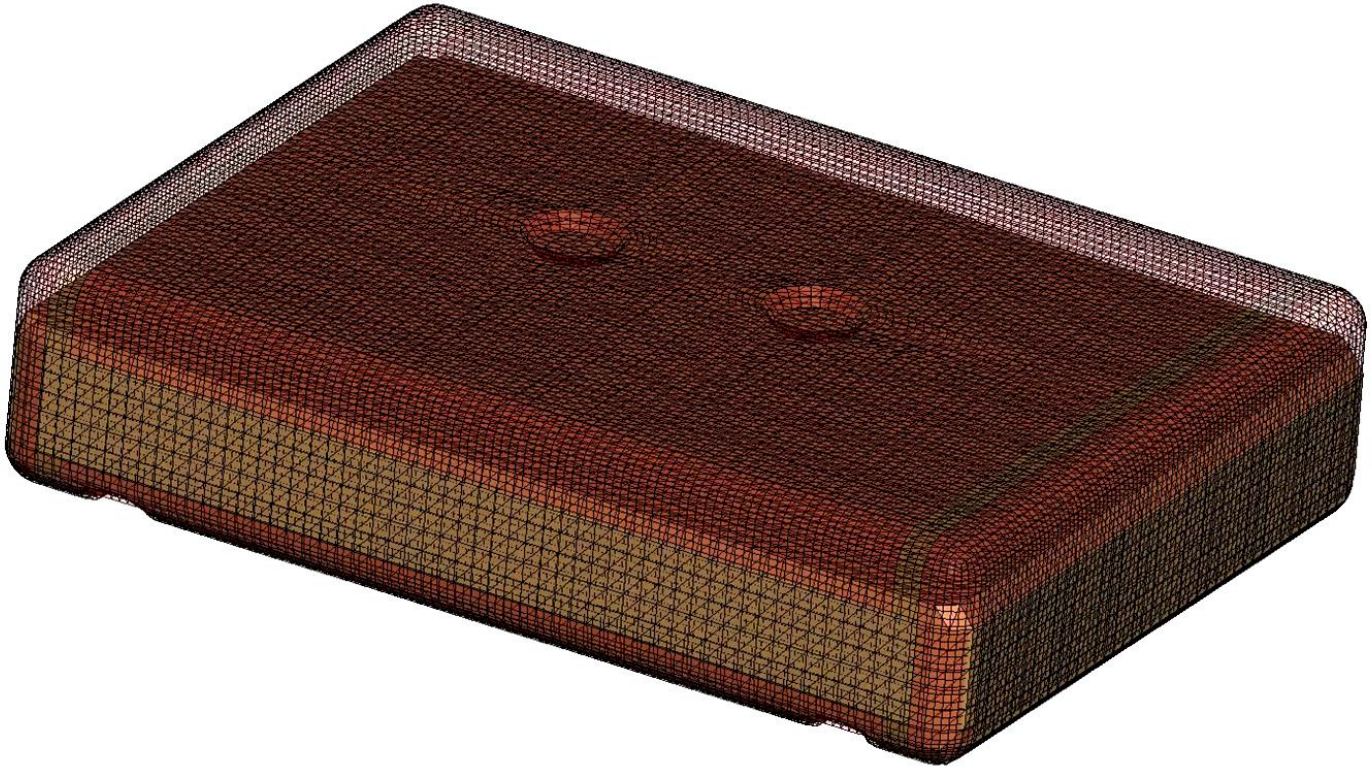
Structured ALE (S-ALE)

Optimization ALE

Structured ALE (S-ALE)

Introduction

- **Same theory** as „old“ ALE, e. g.
  - Mesh smooting
  - Advection
  - Lagrangean-structure coupling
- Different implementation
  - **Automatic mesh generation**
  - More **efficient solver**
  - More stable and user-friendly
- S-ALE features
  - Smaller input decks
  - Easier ALE-mesh modifications
  - Enhanced MPP efficiency



ALE (R12.1, MPP, 4 CPU): 89 min.
S-ALE (R12.1, MPP, 4 CPU): 61 min.
→ **32 % performance enhancment**

Structured ALE (S-ALE)

Keyword Overview

- New class of keywords *ALE_STRUCTURED_
- Mesh generation via
  - *ALE_STRUCTURED_MESH_CONTROL_POINTS a **mesh seed** along global coordinates or following a local coordinate system, see *DEFINE_COORDINATE_NODES
  - *ALE_STRUCTURED_MESH to **create the mesh**
- Define materials
  - *ALE_MULTI-MATERIAL_GROUP to **define multi-material groups**
  - *INITIAL_VOLUME_FRACTION_GEOMETRY to **occupy the newly created structured ALE mesh** with material

Hints

- Use *ALE_STRUCTURED_MESH_TRIM to further tailor mesh to match your needs
- Convert existing „old“ ALE mesh to structured mesh, via CPIDX=-1 in *ALE_STRUCTURED_MESH

Summary

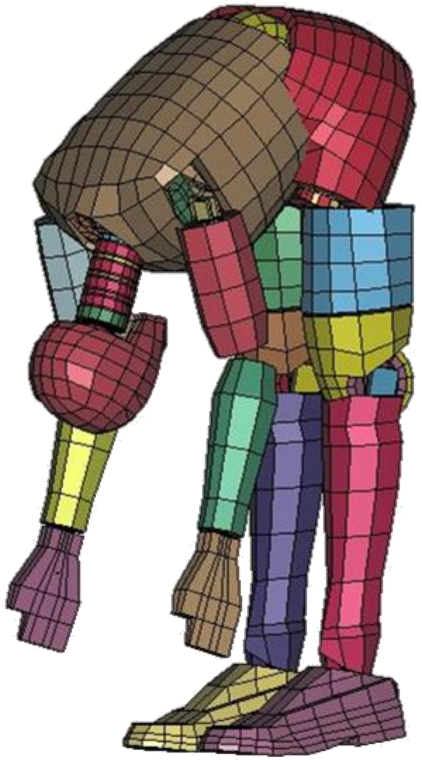
Wrap it all up

Summary

Wrap things up

- **ALE** exploits existing space and time discretization schemes with a twist in the time advancement
  - **Perform Lagrangean step** leading to mesh distortion
  - **Smooth deformed mesh** via mesh motion
  - **Perform advection** (material flow to counter act mesh movement)
- **Explicit method** and, thus, subjected to CFL stability condition
- Applications
  - **Excessive solid deformations**, e. g. in bulk forming
  - **Flow problems**, excl. turbulence and heat transport
- **S-ALE** (enhanced ALE solver)
  - Convenient mesh construction and adaption
  - Usually, **better performance**
  - However, less versatile for complex ALE-domain geometries

Thank You



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