Decomposing the bone into cuboid subvolumes: Macro-element-stiffness matrix replicates effective anisotropy. Subvolume is considered and treated like a finite Direct discretization of the voxels with hexahedral finite

**Mission of HLRS and its People**
- Science in Performance, Networking and other HPC related topics.
- Supporting Research (~95%), SMEs and Industry (~10%) with HPC...
- Know-How
- Compute capacity
- Systems at the High-Performance Computing Center Stuttgart:
  - HLRS Hawk
  - 26 Petaflops x86
  - 5632 nodes with 2x AMD EPYC ROME 7742, 256 GB memory
  - 192 NVIDIA A100 GPUs
- NEC Cluster (Vulcan)
  - Science in Performance, Networking and other HPC related topics.

**Input data**
- Computed Tomography (CT) datasets of various resolutions, e.g.:
  - Human femoral heads
  - Human proximal tibia
  - Pre processed for:
    - Binary segmentation
    - Direct discretization
    - Datasets are available via DaRus
    - The data Repository of the University of Stuttgart

**Approach**
- Decomposing the bone into cuboid subvolumes:
  - 0.8 mm, 12 mm, 2.4 mm, 4.8 mm or 9.6 mm
  - Direct discretization of the voxels with hexahedral finite micro-elements.
  - Subvolume is considered and treated like a finite macro-element.
  - Macro-element-stiffness matrix replicates effective anisotropy.

**Effective stiffness**
- Stiffness — Resistance against deformation.
- A simple compression test of a structure results in the apparent stiffness.
- The direct tensor computation computes the effective macro elements stiffness.
  - Linear hexahedral: 20 dof, 20 load cases
  - Quadratic hexahedral: 60 dof, 60 load cases

The resulting element stiffness matrices can be mapped to continuum mechanical FEA's.

**An Example Use Case**
- Basic research on human trabecular bone.
- Computing effective or apparent stiffness tensors.
- Supporting continuum mechanical simulations based on fine tuned stiffness information.

**Biomechanical Challenge**
- Trabecular bone consists of many small struts and plates.
  - Highly anisotropic
  - Living organ
  - Patient specific
  - Adapts to stress/strain from external loading.
- Microfocus Computed Tomography for imaging bones:
  - 0.005 - 0.015 mm/Voxel
  - Sufficient for computing effective stiffness tensors.
- Radioactive doses prohibit scanning in situ.
- Clinical Computed Tomography for imaging in situ:
  - ~0.575-0.6 mm/Voxel
  - Resolution too low for computing stiffness tensors.

**Software Stack**
- Fortran
  - Pre processing
  - Direct Tensor Computation (DTC)
  - Initial post processing
  - Tensor optimizations
  - Parallelization with MPI
  - Solver by PETSc
  - Mesh partitioning by Metis
  - Bash/Python
  - Process steering
  - Analyzes

**Profiling and Performance by Morphometry**
- Direct discretization leads to:
  - Precise results
  - High computational effort
  - Size of cuboid subvolumes fixed.
- Bone Volume/Total Volume is a morphometric measure.
- Determination is computationally cheap.
- Profiling of the image for better load balancing is feasible.

**Approach**
- Computationally cheap analysis of the bones morphometry for ideal:
  - Load balancing
  - Scheduling
  - Energy efficiency

**Implementation**
- Step 1: Read the CT image.
  - Decompose into domains.
  - Calculate the morphometric quantity.
- Step 2: Compute the ideal distribution of domains to MPI communicators of ideal size.
  - Prepare the input data for DTC.
- Step 3: Run a modified version of DTC with non-uniform communicators.

**Energy savings are expected around 5-25%**, depending on the size of the domain.