Research Statement

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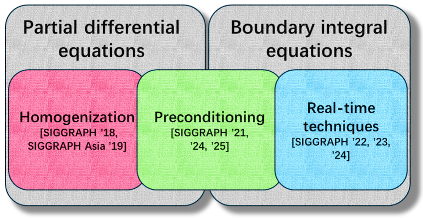
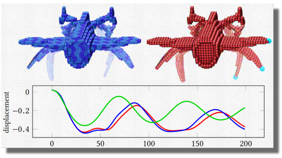


My core research interest lies in the numerical foundations of physically-based simulation and geometry processing, where solving partial differential equations (PDE) or boundary integral equations (BIE) is often a harrowing adventure. Driven by the diverse needs of graphics applications, I have developed a series of methods through contributions to three interconnected yet distinct topics: *homogenization*, *preconditioning*, and *real-time techniques*. Each of these themes is addressed in two to three publications at SIGGRAPH and SIGGRAPH Asia so far. In the following, I briefly discuss for each topic my key achievements.

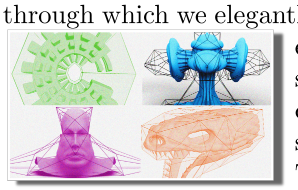
Homogenization. I have been interested in efficient, yet predictive simulations of complex materials (*e.g.*, compounds or porous structures) through numerical homogenization since my PhD days, and I worked from both theoretical and practical perspectives. My first contribution to this field was a two-level numerical coarsening approach for *heterogeneous* and *nonlinear* elasticity (SIGGRAPH '18). This method proposes to optimize *tensorial* and *non-conforming* shape functions on coarse grids for predictive and efficient simulations, thus saving orders of magnitude in time cost compared to high-resolution computations. For the first time, we introduced matrix-valued shape functions in a corotational formulation, which turned out to be crucial for expressing material-induced anisotropy and capturing nonlinear behaviors on the coarse scale. My second contribution was a *multi-level* construction of material-adapted *refinable* and *conforming* basis functions



and associated wavelets to efficiently coarsen linear elasticity (SIGGRAPH Asia '19). The resulting basis functions, in a sense, lie between global eigenfunctions and local polynomial functions: they are not only well adapted to the material inhomogeneity and local in eigenspace, but are also locally supported in 3D space. As a result, the constructed basis functions and their associated wavelets balance computational complexity and accuracy in a refinable way. The hierarchical reduction permits fast solves using *very coarse* grids but still captures the correct physical behavior, even outperforming our previous contribution in terms of granularity and quality of coarse-graining linear materials.

Preconditioning. After finishing my PhD, I became particularly interested in developing efficient and scalable algorithms for solving PDEs and BIEs through preconditioning techniques. And I found that the idea of homogenization is surprisingly key to devising efficient preconditioners. Building on a reformulation of our material-adapted wavelets, I contributed a *multiscale preconditioner* exploiting incomplete Cholesky decomposition (SIGGRAPH '21). It has the same spirit as a multigrid solver, but compared to existing multigrid libraries, our method can be several orders of magnitude faster when solving for *large-scale* and *ill-conditioned* systems due to its better spectrum decomposition. Later on, we discovered that a similar idea could also be a game-changer for solving dense linear systems arising from Boundary Element Methods. Once we realized that the *inverse* of a boundary integral operator behaves conceptually like a differential operator, it became clear that — under the right permutations — it could be made sparse. This insight, initially explored by statisticians studying the covariance matrices in Gaussian Processes, eventually led us to develop a massively parallel construction of an inverse Cholesky preconditioner (SIGGRAPH '24). As a result, we manage to scale up the Method of Fundamental Solutions (MFS) to millions of degrees of freedom. While powerful, this approach was fundamentally limited: it can only support symmetric discretizations of BIEs (*e.g.,* MFS), significantly restricting its applicability across broader classes of discrete BIEs. To overcome this limitation, we extended our construction to the preconditioning of asymmetric BIEs (SIGGRAPH '25) through inverse LU decomposition. Moving from symmetric to asymmetric cases unlocks remarkable gains in both generality and efficiency, allowing us to tackle the full range of boundary integral problems.

Real-time techniques. Recently, I have also become interested in real-time modeling methods without any equation solving to push numerical performance even further. My first contribution on this topic was to derive *regularized Green's functions* for general linear elasticity (SIGGRAPH '22), which systematically extends Pixar's Kelvinlets for real-time digital sculpting. A particularly fun aspect of this work is its sound mathematical derivation through Fourier analysis, through which we elegantly addressed the singularity issues of Green's functions and sidestepped the need for closed-form



expressions, which often do not exist for general linear operators. Our solution is rooted in spherical harmonic functions, and appears as an infinite series that is nicely decomposed into a directional term, a radial term and a material-dependent term. However, Green's functions only support pointwise deformation primitives, which can be too local and blind to boundary effects. To overcome this, we exploited a boundary integral reformulation of linear elasticity to derive *tensorial barycentric coordinates* for cage-based deformations (SIGGRAPH '23). This allows for interactive, detailed deformation through simple manipulations of boundary cages, yet providing richer and more controllable volumetric effects than previous methods. Initially, the resulting Somigliana Coordinates were evaluated using numerical quadrature due to their complex integrands. The annoyance of relying on numerical integration motivated us to seek closed-form expressions, which we successfully obtained the following year (SIGGRAPH '24). Interestingly, this result emerged as a byproduct of our development of novel 3D biharmonic coordinates, which were designed to better align the deformed geometry to prescribed boundary values and derivatives by leveraging the fourth-order differential operator.