

# modepy: Basis Functions, Interpolation, and Quadrature (not just) for Finite Elements

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## Software

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## Summary

modepy is a Python library for defining reference elements, equipping them with appropriate approximation spaces, and numerically performing calculus operations (derivatives, integrals) on those spaces. It is written in pure, type-annotated Python 3, offering comprehensive documentation and minimal runtime dependencies (mainly NumPy).

modepy focuses on high-order accuracy — given an element size  $h$ , this refers to the asymptotic decay of the approximation error as  $O(h^n)$ , for  $n \geq 3$ , assuming sufficient smoothness of the solution being approximated. For a problem in  $d$  dimensions, the number of unknowns scales as  $O(h^{-d})$ . Therefore, if accuracy is desired at manageable cost, high-order methods are crucial.

A popular approach for accurate approximation of functions on geometrically complex domains is the use of *unstructured discretizations*, e.g. in the Finite Element Method (FEM). The geometry is typically represented as a disjoint union (a “mesh”) of primitive geometric shapes, most often simplices and quadrilaterals. Given the means to perform calculus operations on these *reference elements* and mapping functions from them to the *global* elements, calculus operations become available on the entire domain. These primitives are chiefly useful in the numerical solution of integral and (partial) differential equations. Additional applications include computer graphics, Computer Aided Design (CAD), and robotics. Those, in turn, can be used to model many physical phenomena, including fluid flow, electromagnetism, and solid mechanics. modepy has been used to construct FEM solvers ([Glusa, 2021](#); [Klöckner & others, 2025a](#)) and integral equation solvers ([Klöckner & others, 2025b](#)) that run on both CPUs and GPUs.

## Statement of need

The functionality outlined above is often embedded in an ad-hoc manner in larger codes, restricting scope and reusability. modepy addresses this need by providing a reusable, generalizable, and composable implementation.

There are several other libraries in the literature with similar goals, but important differences and limitations. FInAT ([Ham et al., 2025](#)) (and the earlier FIAT ([Homolya et al., 2025](#))) offers reference elements and basis functions, but is tightly coupled to the FEniCS/Firedrake ecosystem. Similarly, StartUpDG.jl ([Chan et al., 2024](#)) has a focus on the needs of discontinuous Galerkin FEM in the Trixi framework. QuadPy ([Schlömer et al., 2021](#)) provides access to quadrature rules, but it is no longer open source and lacks modepy’s composable. minterpy ([Wicaksono et al., 2025](#)), meanwhile, deals exclusively with polynomial interpolation, with a focus on sparse grids.

The solvers served by modepy typically have tight cost constraints, often adopting HPC techniques (GPU, MPI, etc.). To facilitate separation of implementation and high-performance concerns from the core numerical method, modepy adopts a two-pronged approach. First, if it suffices to represent operations as data in matrix or tabular form, execution of modepy code is not needed in a cost-constrained setting. For example, nodes and bilinear forms on reference elements can generally be pre-computed and tabulated. Second, if this tabulation approach falls short, modepy provides data structures to reveal additional internal structure.

Tensor product elements provide an example of this. In this instance, many operator matrices permit a Kronecker product factorization that significantly reduces the asymptotic complexity of a matrix-vector product in higher dimensions (Orszag, 1980). modepy exposes functionality that allows reshaping degrees of freedom arrays to take advantage of such factorizations. Another prominent example is the evaluation of basis functions at points known only at runtime. To facilitate efficient evaluation, modepy allows its functions to be “traced”, in the sense of lazy or deferred evaluation. The resulting expression graph is represented by the pymbolic (Klöckner et al., 2024) software library, that can interoperate with Python ASTs (Python Software Foundation, 2024), SymPy (Meurer et al., 2017), SymEngine (Čertík et al., 2013), etc., for straightforward generation of high-performance code.

## Overview

The high-level concepts available in modepy are shapes (i.e. reference domains), modes (i.e. the basis functions), and nodes (i.e. the degrees of freedom). These are implemented in a user-extensible fashion using the singledispatch mechanism, with inspiration taken from common idiomatic usage in Julia (Bezanson et al., 2017).

## Shapes

The geometry of a reference element is described in modepy by the Shape class. Built-in support exists for Simplex and Hypercube geometries, encompassing the commonly used interval, triangle, tetrahedron, quadrilateral, and hexahedral shapes (see Figure 1). TensorProductShape can be used to compose additional shapes (e.g. prisms, as generated by, e.g. gmsh (Geuzaine & Remacle, 2009)).

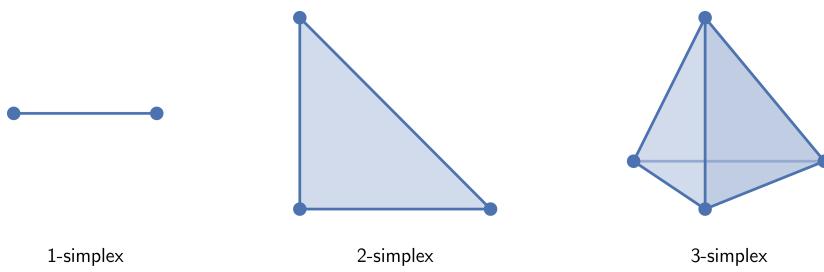


Figure 1: Domains corresponding to the one-, two-, and three-dimensional simplices.

## Modes and Spaces

To perform calculus operations, each reference element can be equipped with a function space described by the FunctionSpace class. These represent a finite-dimensional space of functions  $\phi_i : D \rightarrow \mathbb{R}$ , where  $D$  is the reference element domain, and no specific choice of basis. Predefined choices include the PN space, containing polynomials of total degree at most  $N$ , and the QN space, containing polynomials of maximum degree at most  $N$ . As with shapes, these spaces can be combined using TensorProductSpace. A Basis object is available separately, giving access to basis functions and their derivatives, for, e.g., the monomials, general Jacobi

polynomials, and the Proriol-Koornwinder-Dubiner-Owens (PKDO) basis from Dubiner (1991) (see Figure 2).

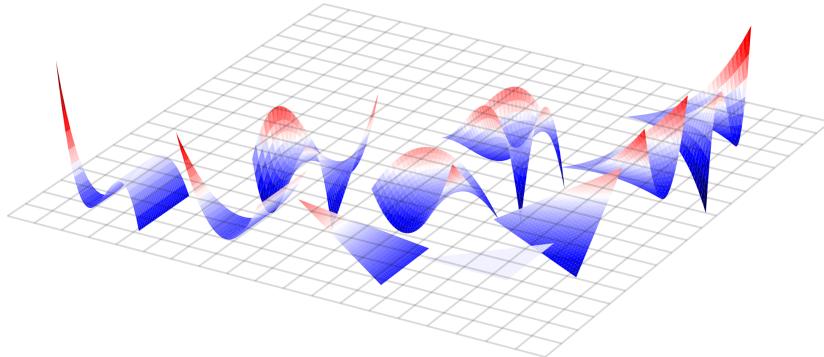


Figure 2: PKDO basis functions for the triangle.

## Nodes

A final component in an FEM discretization (Brenner & Scott, 2007, sec. 3.1) is a set of ‘degrees of freedom’ (‘DOFs’) that uniquely identify a certain function in the span of a basis. modepy supports modal DOFs (i.e. basis coefficients) and nodal DOFs (i.e. function or derivative values at a point). On simplices, the “warp-and-blend” nodes (Warburton, 2007) are available, and on the hypercube, standard tensor product nodes are constructed from one-dimensional Legendre-Gauss(-Lobatto) nodes. modepy can also directly interoperate with the recursivenodes library described in Isaac (2020), which offers additional well-conditioned nodes on the simplex.

## Quadrature

modepy also offers a wide array of quadrature rules that can be used on each reference element. For the interval, Clenshaw–Curtis, Fejér, and Jacobi-Gauss(-Lobatto) are provided. Many more state-of-the-art rules are available, typically up to high order  $n > 20$  from (Grundmann & Möller, 1978; Jaśkowiec & Sukumar, 2021; Vioreanu & Rokhlin, 2014; Witherden & Vincent, 2015; Xiao & Gimbutas, 2010) (see Figure 3). There is also functionality (Vioreanu & Rokhlin, 2014) to allow constructing novel quadratures on a given domain.

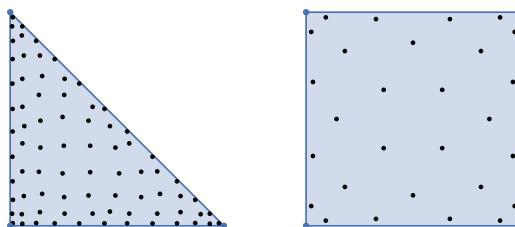


Figure 3: (left) Vioreanu–Rokhlin quadrature points of order 11 and (right) Witherden–Vincent quadrature points of order 11.

## Matrices

modepy’s functionality is rounded out by various tabulation and matrix generation functions. This includes the ability to tabulate operator matrices for fairly general bilinear forms used in FEM.

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## References

Bezanson, J., Edelman, A., Karpinski, S., & Shah, V. B. (2017). Julia: A fresh approach to numerical computing. *SIAM Review*, 59, 65–98. <https://doi.org/10.1137/141000671>

Brenner, S., & Scott, R. (2007). *The mathematical theory of finite element methods*. Springer Science & Business Media. ISBN: 9780387759333

Čertík, O., Fernando, I., Garg, S., Rathnayake, T., & others. (2013). *SymEngine: A fast symbolic manipulation library written in C++*. <https://github.com/symengine/symengine>

Chan, J., Knapp, D., McCallum, M., Ranocha, H., Wang, V. X., & Markert, J. (2024). *StartUpDG.jl: Reference elements and physical meshes for DG* (Version v1.1.5). <https://github.com/jlchan/StartUpDG.jl>

Dubiner, M. (1991). Spectral methods on triangles and other domains. *Journal of Scientific Computing*, 6, 345–390. <https://doi.org/10.1007/bf01060030>

Geuzaine, C., & Remacle, J.-F. (2009). Gmsh: A 3-d finite element mesh generator with built-in pre-and post-processing facilities. *International Journal for Numerical Methods in Engineering*, 79(11), 1309–1331. <https://doi.org/10.1002/nme.2579>

Glusa, C. (2021). *PyNucleus: A finite element code that specifically targets nonlocal operators*. Sandia National Lab (SNL-NM), Albuquerque, NM (United States). <https://github.com/sandialabs/PyNucleus>

Grundmann, A., & Möller, H. M. (1978). Invariant integration formulas for the n-simplex by combinatorial methods. *SIAM Journal on Numerical Analysis*, 15, 282–290. <https://doi.org/10.1137/0715019>

Ham, D. A., Homolya, M., Kirby, R., Mitchell, L., Brubeck, P., cyruscycheng21, FAznaran, ksagiyam, Scroggs, M., Farrell, P. E., Justincrum, Ward, C., celdred, Bendall, T., Betteridge, J., & FabianL1908. (2025). *FlnAT: A smarter library of finite elements* (Version Firedrake\_20250331.0). Zenodo. <https://doi.org/10.5281/zenodo.15114385>

Homolya, M., Brubeck, P., Ham, D. A., Kirby, R., Mitchell, L., Blechta, J., Rognes, M. E., Wells, G. N., Logg, A., cyruscycheng21, Gibson, T. H., Ring, J., Yashchuk, I., Justincrum, k-b-oelgaard, ksagiyam, Richardson, C., mer, N. S., Nixon-Hill, R. W., ... Scroggs, M. (2025). *FIAT: 2025.4.0* (Version 2025.4.0). Zenodo. <https://doi.org/10.5281/zenodo.15302339>

Isaac, T. (2020). Recursive, parameter-free, explicitly defined interpolation nodes for simplices. *SIAM Journal on Scientific Computing*, 42, A4046–a4062. <https://doi.org/10.1137/20m1321802>

Jaśkowiec, J., & Sukumar, N. (2021). High-order symmetric cubature rules for tetrahedra and pyramids. *International Journal for Numerical Methods in Engineering*, 122, 148–171. <https://doi.org/10.1002/nme.6528>

Klöckner, A., & others. (2025a). *Grudge: An environment for discontinuous Galerkin discretizations* (Version hash:193100a). <https://github.com/inducer/grudge>

Klöckner, A., & others. (2025b). *Pytential: Evaluate layer and volume potentials accurately* (Version hash:7395b97f). <https://github.com/inducer/pytential>

Klöckner, A., Wala, M., Fernando, I., Kulkarni, K., Fikl, A., Weiner, Z., Kempf, D., Ham, D. A., Mitchell, L., Wilcox, L. C., Diener, M., Kapyshin, P., Raksi, R., & Gibson, T. H. (2024). *Pymbolic: A package to do symbolic operations for code generation* (Version v2024.2.2). Zenodo. <https://doi.org/10.5281/zenodo.14526145>

Meurer, A., Smith, C. P., Paprocki, M., Čertík, O., Kirpichev, S. B., Rocklin, M., Kumar, A., Ivanov, S., Moore, J. K., Singh, S., & others. (2017). SymPy: Symbolic computing in Python. *PeerJ Computer Science*, 3, e103. <https://doi.org/10.7717/peerj-cs.103>

Orszag, S. A. (1980). Spectral methods for problems in complex geometries. *Journal of Computational Physics*, 37, 70–92. [https://doi.org/10.1016/0021-9991\(80\)90005-4](https://doi.org/10.1016/0021-9991(80)90005-4)

Python Software Foundation. (2024). *ast — abstract syntax trees*. <https://docs.python.org/3/library/ast.html>

Schlömer, N., Papior, N., Arnold, D., Blechta, J., & Zetter, R. (2021). *QuadPy: Numerical integration (quadrature, cubature) in Python* (Version v0.16.10). Zenodo. <https://doi.org/10.5281/zenodo.5541216>

Vioreanu, B., & Rokhlin, V. (2014). Spectra of multiplication operators as a numerical tool. *SIAM Journal on Scientific Computing*, 36, A267–a288. <https://doi.org/10.1137/110860082>

Warburton, T. (2007). An explicit construction of interpolation nodes on the simplex. *Journal of Engineering Mathematics*, 56, 247–262. <https://doi.org/10.1007/s10665-006-9086-6>

Wicaksono, D., Acosta, U. H., Veettil, S. K. T., Kissinger, J., & Hecht, M. (2025). Minterpy: Multivariate polynomial interpolation in Python. *Journal of Open Source Software*, 10(109), 7702. <https://doi.org/10.21105/joss.07702>

Witherden, F. D., & Vincent, P. E. (2015). On the identification of symmetric quadrature rules for finite element methods. *Computers & Mathematics With Applications*, 69, 1232–1241. <https://doi.org/10.1016/j.camwa.2015.03.017>

Xiao, H., & Gimbutas, Z. (2010). A numerical algorithm for the construction of efficient quadrature rules in two and higher dimensions. *Computers & Mathematics With Applications*, 59, 663–676. <https://doi.org/10.1016/j.camwa.2009.10.027>