
Finite element Automatic Tabulator (FIAT) Documentation

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FEniCS Project

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FIAT is a Python package for automatic generation of finite element basis functions. It is capable of generating finite element basis functions for a wide range of finite element families on simplices (lines, triangles and tetrahedra), including the Lagrange elements, and the elements of Raviart-Thomas, Brezzi-Douglas-Marini and Nedelec. It is also capable of generating tensor-product elements and a number more exotic elements, such as the Argyris, Hermite and Morley elements.

FIAT is part of the FEniCS Project.

For more information, visit <http://www.fenicsproject.org>.

1.1 Installation

FIAT is normally installed as part of an installation of FEniCS. If you are using FIAT as part of the FEniCS software suite, it is recommended that you follow the [installation instructions for FEniCS](#).

To install FIAT itself, read on below for a list of requirements and installation instructions.

1.1.1 Requirements and dependencies

FIAT requires Python version 2.7 or later and depends on the following Python packages:

- NumPy
- SymPy

These packages will be automatically installed as part of the installation of FIAT, if not already present on your system.

1.1.2 Installation instructions

To install FIAT, download the source code from the [FIAT Bitbucket repository](#), and run the following command:

```
pip install .
```

To install to a specific location, add the `--prefix` flag to the installation command:

```
pip install --prefix=<some directory> .
```

1.2 User manual

Note: This page is work in progress and needs substantial editing.

FIAT (FInite element Automatic Tabulator) is a Python package for defining and evaluating a wide range of different finite element basis functions for numerical partial differential equations. It is intended to make “difficult” elements such as high-order Brezzi-Douglas-Marini~cite{} elements usable by providing abstractions so that they may be implemented succinctly and hence treated as a black box. FIAT is intended for use at two different levels. For one, it is designed to provide a standard API for finite element bases so that programmers may use whatever elements they need in their code. At a lower level, it provides necessary infrastructure to rapidly deploy new kinds of finite elements without expensive symbolic computation or tedious algebraic manipulation. It is my goal that a large number of people use FIAT without ever knowing it. Thanks to several ongoing projects such as Sundance~cite{}, FFC~cite{}, and PETSc~cite{}, it is becoming possible to to define finite element methods using mathematical notation in some high-level or domain-specific language. The primary shortcoming of these projects is their lack of support for general elements. It is one thing to “provide hooks” for general elements, but absent a tool such as FIAT, these hooks remain mainly empty. As these projects mature, I hope to expose users of the finite element method to the exotic world of potentially high-degree finite element on unstructured grids using the best elements in H^1 , $H(\mathrm{div})$, and $H(\mathrm{curl})$.

In this brief (and still developing) guide, I will first present the high-level API for users who wish to instantiate a finite element on a reference domain and evaluate its basis functions and derivatives at some quadrature points. Then, I will explain some of the underlying infrastructure so as to demonstrate how to add new elements.

chapter{Using FIAT: A tutorial with Lagrange elements} section{Importing FIAT} FIAT is organized as a package in Python, consisting of several modules. In order to get some of the packages, we use the line `begin{verbatim} from FIAT import Lagrange, quadrature, shapes end{verbatim}` This loads several modules for the Lagrange elements, quadrature rules, and the simplicial element shapes which FIAT implements. The roles each of these plays will become clear shortly.

section{Important note} Throughout, FIAT defines the reference elements based on the interval $(-1,1)$ rather than the more common $(0,1)$. So, the one-dimensional reference element is $(-1,1)$, the three vertices of the reference triangle are $(-1,-1), (1,-1), (1,1)$, and the four vertices of the reference tetrahedron are $(-1,-1,-1), (1,-1,-1), (-1,1,-1), (-1,-1,1)$.

section{Instantiating elements} FIAT uses a lightweight object-oriented infrastructure to define finite elements. The `verb.Lagrange` module contains a class `verb.Lagrange` modeling the Lagrange finite element family. This class is a subclass of some `verb.FiniteElement` class contained in another module (`verb.polynomial` to be precise). So, having imported the `verb.Lagrange` module, we can create the Lagrange element of degree `verb.2` on triangles by `begin{verbatim} shape = shapes.TRIANGLE degree = 2 U = Lagrange.Lagrange(shape , degree) end{verbatim}` Here, `verb/shapes.TRIANGLE/` is an integer code indicating the two dimensional simplex. `verb.shapes.` also defines `verb.LINE` and `verb.TETRAHEDRON`. Most of the upper-level interface to FIAT is dimensionally abstracted over element shape.

The class `verb.FiniteElement` supports three methods, modeled on the abstract definition of Ciarlet. These methods are `verb.domain_shape()`, `verb.function_space()`, and `verb.dual_basis()`. The first of these returns the code for the shape and the second returns the nodes of the finite element (including information related to topological association of nodes with mesh entities, needed for creating degree of freedom orderings).

section{Quadrature rules} FIAT implements arbitrary-order collapsed quadrature, as discussed in Karniadakis and Sherwin~cite{}, for the simplex of dimension one, two, or three. The simplest way to get a quadrature rule is through the function `verb.make_quadrature(shape,m)`, which takes a shape code and an integer indicating the number of points per direction. For building element matrices using quadratics, we will typically need a second or third order integration rule, so we can get such a rule by `begin{verbatim} >>> Q = quadrature.make_quadrature(shape , 2) end{verbatim}` This uses two points in each direction on the reference square, then maps them to the reference triangle. We may get a `verb/Numeric.array/` of the quadrature weights with the method `verb/Q.get_weights()/` and a list of tuples storing the quadrature points with the method `verb/Q.get_points()/`.

section{Tabulation} FIAT provides functions for tabulating the element basis functions and their derivatives. To get

the `verb.FunctionSpace` object, we do `begin{verbatim} >>> Ufs = U.function_space() end{verbatim}` To get the values of each basis function at each of the quadrature points, we use the `verb.tabulate()` method `begin{verbatim} >>> Ufs.tabulate(Q.get_points())` array([[0.22176167, -0.12319761, -0.11479229, -0.06377178],

```
[-0.11479229, -0.06377178, 0.22176167, -0.12319761], [-0.10696938, 0.18696938, -0.10696938,
0.18696938], [ 0.11074286, 0.19356495, 0.41329796, 0.72239423], [ 0.41329796, 0.72239423,
0.11074286, 0.19356495], [ 0.47595918, 0.08404082, 0.47595918, 0.08404082]])
```

`end{verbatim}` This returns a two-dimensional `verb/Numeric.array/` with rows for each basis function and columns for each input point.

Also, finite element codes require tabulation of the basis functions' derivatives. Each `verb/FunctionSpace/` object also provides a method `verb/tabulate_jet(i,xs)/` that returns a list of Python dictionaries. The `verb.i.th` entry of the list is a dictionary storing the values of all `verb.i.th` order derivatives. Each dictionary maps a multiindex (a tuple of length `verb.i`) to the table of the associated partial derivatives of the basis functions at those points. For example, `begin{verbatim} >>> Ufs_jet = Ufs.tabulate_jet(1 , Q.get_points()) end{verbatim}` tabulates the zeroth and first partial derivatives of the function space at the quadrature points. Then, `begin{verbatim} >>> Ufs_jet[0] {(0, 0):` array([[0.22176167, -0.12319761, -0.11479229, -0.06377178],

```
[-0.11479229, -0.06377178, 0.22176167, -0.12319761], [-0.10696938, 0.18696938, -0.10696938,
0.18696938], [ 0.11074286, 0.19356495, 0.41329796, 0.72239423], [ 0.41329796, 0.72239423,
0.11074286, 0.19356495], [ 0.47595918, 0.08404082, 0.47595918, 0.08404082]])
```

`end{verbatim}` gives us a dictionary mapping the only zeroth-order partial derivative to the values of the basis functions at the quadrature points. More interestingly, we may get the first derivatives in the x- and y- directions with `begin{verbatim} >>> Ufs_jet[1][{(1,0)}]` array([[-0.83278049, -0.06003983, 0.14288254, 0.34993778],

```
[-0.14288254, -0.34993778, 0.83278049, 0.06003983], [ 0. , 0. , 0. , 0. ], [ 0.31010205, 1.28989795,
0.31010205, 1.28989795], [ -0.31010205, -1.28989795, -0.31010205, -1.28989795], [ 0.97566304,
0.40997761, -0.97566304, -0.40997761]])
```

```
>>> Ufs_jet[1][{(0,1)}]
array([[ -8.32780492e-01,  -6.00398310e-02,   1.42882543e-01,   3.49937780e-01],
       [  7.39494156e-17,   4.29608279e-17,   4.38075188e-17,   7.47961065e-17],
       [ -1.89897949e-01,   7.89897949e-01,  -1.89897949e-01,   7.89897949e-01],
       [  3.57117457e-01,   1.50062220e-01,   1.33278049e+00,   5.60039831e-01],
       [  1.02267844e+00,  -7.29858118e-01,   4.70154051e-02,  -1.13983573e+00],
       [ -3.57117457e-01,  -1.50062220e-01,  -1.33278049e+00,  -5.60039831e-01]])
\end{verbatim}
```

chapter{Lower-level API} Not only does FIAT provide a high-level library interface for users to evaluate existing finite element bases, but it also provides lower-level tools. Here, we survey these tools module-by-module.

section{shapes.py} FIAT currently only supports simplicial reference elements, but does so in a fairly dimensionally-independent way (up to tetrahedra).

section{jacobi.py} This is a low-level module that tabulates the Jacobi polynomials and their derivatives, and also provides Gauss-Jacobi points. This module will seldom if ever be imported directly by users. For more information, consult the documentation strings and source code.

section{expansions.py} FIAT relies on orthonormal polynomial bases. These are constructed by mapping appropriate Jacobi polynomials from the reference cube to the reference simplex, as described in the reference of Karniadakis and Sherwin~cite{ }. The module `texttt{expansions.py}` implements these orthonormal expansions. This is also a low-level module that will infrequently be used directly, but it forms the backbone for the module `texttt{polynomial.py}`

section{quadrature.py} FIAT makes heavy use of numerical quadrature, both internally and in the user interface. Internally, many function spaces or degrees of freedom are defined in terms of integral quantities having certain behavior. Keeping with the theme of arbitrary order approximations, FIAT provides arbitrary order quadrature rules on the reference simplices. These are constructed by mapping Gauss-Jacobi rules from the reference cube. While these rules are suboptimal in terms of order of accuracy achieved for a given number of points, they may be generated

mechanically in a simpler way than symmetric quadrature rules. In the future, we hope to have the best symmetric existing rules integrated into FIAT.

Unless one is modifying the quadrature rules available, all of the functionality of `quadrature.py` may be accessed through the single function `make_quadrature`. This function takes the code for a shape and the number of points in each coordinate direction and returns a quadrature rule. Internally, there is a lightweight class hierarchy rooted at an abstract `QuadratureRule` class, where the quadrature rules for different shapes are actually different classes. However, the dynamic typing of Python relieves the user from these considerations. The interface to an instance consists in the following methods `begin` `itemize` `item` `get_points`, which returns a list of the quadrature

points, each stored as a tuple. For dimensional uniformity, one-dimensional quadrature rules are stored as lists of 1-tuples rather than as lists of numbers.

item `get_weights`, which returns a `Numeric.array` of quadrature weights.

item `integrate`, which takes a callable object `f` and returns the (approximate) integral over the domain

item Also, the `__call__` method is overloaded so that a quadrature rule may be applied to a callable object. This is syntactic sugar on top of the `integrate` method.

`end` `itemize`

`polynomial.py` The `polynomial` module provides the bulk of the classes needed to represent polynomial bases and finite element spaces. The class `PolynomialBase` provides a high-level access to the orthonormal expansion bases; it is typically not instantiated directly in an application, but all other kinds of polynomial bases are constructed as linear combinations of the members of a `PolynomialBase` instance. The module provides classes for scalar and vector-valued polynomial sets, as well as an interface to individual polynomials and finite element spaces.

subsection `PolynomialBase`

subsection `PolynomialSet` The `PolynomialSet` function is a factory function interface into the hierarchy

1.3 FIAT package

1.3.1 Submodules

1.3.2 FIAT.P0 module

class `FIAT.P0.P0` (*ref_el*)
 Bases: `FIAT.finite_element.CiarletElement`

class `FIAT.P0.P0Dual` (*ref_el*)
 Bases: `FIAT.dual_set.DualSet`

1.3.3 FIAT.argyris module

class `FIAT.argyris.Argyris` (*ref_el, degree*)
 Bases: `FIAT.finite_element.CiarletElement`

The Argyris finite element.

class `FIAT.argyris.ArgyrisDualSet` (*ref_el, degree*)
 Bases: `FIAT.dual_set.DualSet`

class FIAT.argyris.**QuinticArgyris** (*ref_el*)
 Bases: *FIAT.finite_element.CiarletElement*

The Argyris finite element.

class FIAT.argyris.**QuinticArgyrisDualSet** (*ref_el*)
 Bases: *FIAT.dual_set.DualSet*

1.3.4 FIAT.arnold_winther module

Implementation of the Arnold-Winther finite elements.

class FIAT.arnold_winther.**ArnoldWinther** (*cell, degree*)
 Bases: *FIAT.finite_element.CiarletElement*

The definition of the conforming Arnold-Winther element.

class FIAT.arnold_winther.**ArnoldWintherDual** (*cell, degree*)
 Bases: *FIAT.dual_set.DualSet*

class FIAT.arnold_winther.**ArnoldWintherNC** (*cell, degree*)
 Bases: *FIAT.finite_element.CiarletElement*

The definition of the nonconforming Arnold-Winther element.

class FIAT.arnold_winther.**ArnoldWintherNCDual** (*cell, degree*)
 Bases: *FIAT.dual_set.DualSet*

1.3.5 FIAT.bell module

class FIAT.bell.**Bell** (*ref_el*)
 Bases: *FIAT.finite_element.CiarletElement*

The Bell finite element.

class FIAT.bell.**BellDualSet** (*ref_el*)
 Bases: *FIAT.dual_set.DualSet*

1.3.6 FIAT.bernstein module

class FIAT.bernstein.**Bernstein** (*ref_el, degree*)
 Bases: *FIAT.finite_element.FiniteElement*

A finite element with Bernstein polynomials as basis functions.

degree ()
 The degree of the polynomial space.

tabulate (*order, points, entity=None*)
 Return tabulated values of derivatives up to given order of basis functions at given points.

Parameters

- **order** – The maximum order of derivative.
- **points** – An iterable of points.
- **entity** – Optional (dimension, entity number) pair indicating which topological entity of the reference element to tabulate on. If *None*, default cell-wise tabulation is performed.

`value_shape()`

The value shape of the finite element functions.

`class` FIAT.bernstein.**BernsteinDualSet** (*ref_el, degree*)

Bases: *FIAT.dual_set.DualSet*

The dual basis for Bernstein elements.

FIAT.bernstein.**bernstein_Dx** (*points, ks, order, R2B*)

Evaluates Bernstein polynomials or its derivatives according to reference coordinates.

Parameters

- **points** – array of points in BARYCENTRIC COORDINATES
- **ks** – exponents defining the Bernstein polynomial
- **alpha** – derivative order (returns all derivatives of this specified order)
- **R2B** – linear mapping from reference to barycentric coordinates

Returns dictionary mapping from derivative tuples to arrays of Bernstein polynomial values at given points.

FIAT.bernstein.**bernstein_db** (*points, ks, alpha=None*)

Evaluates Bernstein polynomials or its derivative at barycentric points.

Parameters

- **points** – array of points in barycentric coordinates
- **ks** – exponents defining the Bernstein polynomial
- **alpha** – derivative tuple

Returns array of Bernstein polynomial values at given points.

1.3.7 FIAT.brezzi_douglas_fortin_marini module

`class` FIAT.brezzi_douglas_fortin_marini.**BDFMDualSet** (*ref_el, degree*)

Bases: *FIAT.dual_set.DualSet*

FIAT.brezzi_douglas_fortin_marini.**BDFMSpace** (*ref_el, order*)

`class` FIAT.brezzi_douglas_fortin_marini.**BrezziDouglasFortinMarini** (*ref_el, degree*)

Bases: *FIAT.finite_element.CiarletElement*

The BDFM element

1.3.8 FIAT.brezzi_douglas_marini module

`class` FIAT.brezzi_douglas_marini.**BDMDualSet** (*ref_el, degree, variant, quad_deg*)

Bases: *FIAT.dual_set.DualSet*

`class` FIAT.brezzi_douglas_marini.**BrezziDouglasMarini** (*ref_el, k, variant=None*)

Bases: *FIAT.finite_element.CiarletElement*

The BDM element

Parameters

- **ref_el** – The reference element.

- **k** – The degree.
- **variant** – optional variant specifying the types of nodes.

variant can be chosen from [“point”, “integral”, “integral(quadrature_degree)”] “point” -> dofs are evaluated by point evaluation. Note that this variant has suboptimal convergence order in the H(div)-norm “integral” -> dofs are evaluated by quadrature rule. The quadrature degree is chosen to integrate polynomials of degree $5*k$ so that most expressions will be interpolated exactly. This is important when you want to have (nearly) divergence-preserving interpolation. “integral(quadrature_degree)” -> dofs are evaluated by quadrature rule of degree quadrature_degree

1.3.9 FIAT.bubble module

class FIAT.bubble.**Bubble** (*ref_el, degree*)
 Bases: *FIAT.bubble.CodimBubble*

The bubble finite element: the dofs of the Lagrange FE in the interior of the cell

class FIAT.bubble.**CodimBubble** (*ref_el, degree, codim*)
 Bases: *FIAT.restricted.RestrictedElement*

Bubbles of a certain codimension.

class FIAT.bubble.**FacetBubble** (*ref_el, degree*)
 Bases: *FIAT.bubble.CodimBubble*

The facet bubble finite element: the dofs of the Lagrange FE in the interior of the facets

1.3.10 FIAT.check_format_variant module

FIAT.check_format_variant.**check_format_variant** (*variant, degree, element*)

1.3.11 FIAT.crouzeix_raviart module

class FIAT.crouzeix_raviart.**CrouzeixRaviart** (*cell, degree*)
 Bases: *FIAT.finite_element.CiarletElement*

The Crouzeix-Raviart finite element:

K: Triangle/Tetrahedron Polynomial space: P₁ Dual basis: Evaluation at facet midpoints

class FIAT.crouzeix_raviart.**CrouzeixRaviartDualSet** (*cell, degree*)
 Bases: *FIAT.dual_set.DualSet*

Dual basis for Crouzeix-Raviart element (linears continuous at boundary midpoints).

1.3.12 FIAT.discontinuous module

class FIAT.discontinuous.**DiscontinuousElement** (*element*)
 Bases: *FIAT.finite_element.CiarletElement*

A copy of an existing element where all dofs are associated with the cell

degree ()

Return the degree of the (embedding) polynomial space.

dmats ()

Return dmats: expansion coefficients for basis function derivatives.

get_coeffs ()
Return the expansion coefficients for the basis of the finite element.

get_nodal_basis ()
Return the nodal basis, encoded as a PolynomialSet object, for the finite element.

get_num_members (*arg*)
Return number of members of the expansion set.

get_order ()
Return the order of the element (may be different from the degree)

get_reference_element ()
Return the reference element for the finite element.

mapping ()
Return a list of appropriate mappings from the reference element to a physical element for each basis function of the finite element.

num_sub_elements ()
Return the number of sub-elements.

space_dimension ()
Return the dimension of the finite element space.

tabulate (*order, points, entity=None*)
Return tabulated values of derivatives up to given order of basis functions at given points.

value_shape ()
Return the value shape of the finite element functions.

1.3.13 FIAT.discontinuous_lagrange module

FIAT.discontinuous_lagrange.**DiscontinuousLagrange** (*ref_el, degree*)

class FIAT.discontinuous_lagrange.**DiscontinuousLagrangeDualSet** (*ref_el, degree*)

Bases: *FIAT.dual_set.DualSet*

The dual basis for Lagrange elements. This class works for simplices of any dimension. Nodes are point evaluation at equispaced points. This is the discontinuous version where all nodes are topologically associated with the cell itself

class FIAT.discontinuous_lagrange.**HigherOrderDiscontinuousLagrange** (*ref_el, degree*)

Bases: *FIAT.finite_element.CiarletElement*

The discontinuous Lagrange finite element. It is what it is.

1.3.14 FIAT.discontinuous_pc module

FIAT.discontinuous_pc.**DPC** (*ref_el, degree*)

class FIAT.discontinuous_pc.**DPC0** (*ref_el*)

Bases: *FIAT.finite_element.CiarletElement*

class FIAT.discontinuous_pc.**DPCDualSet** (*ref_el, flat_el, degree*)

Bases: *FIAT.dual_set.DualSet*

The dual basis for DPC elements. This class works for hypercubes of any dimension. Nodes are point evaluation at equispaced points. This is the discontinuous version where all nodes are topologically associated with the cell itself

class FIAT.discontinuous_pc.HigherOrderDPC (*ref_el, degree*)
 Bases: *FIAT.finite_element.CiarletElement*

The DPC finite element. It is what it is.

1.3.15 FIAT.discontinuous_raviart_thomas module

class FIAT.discontinuous_raviart_thomas.DRTDualSet (*ref_el, degree*)
 Bases: *FIAT.dual_set.DualSet*

Dual basis for Raviart-Thomas elements consisting of point evaluation of normals on facets of codimension 1 and internal moments against polynomials. This is the discontinuous version where all nodes are topologically associated with the cell itself

class FIAT.discontinuous_raviart_thomas.DiscontinuousRaviartThomas (*ref_el, q*)
 Bases: *FIAT.finite_element.CiarletElement*

The discontinuous Raviart-Thomas finite element

1.3.16 FIAT.discontinuous_taylor module

FIAT.discontinuous_taylor.DiscontinuousTaylor (*ref_el, degree*)

class FIAT.discontinuous_taylor.DiscontinuousTaylorDualSet (*ref_el, degree*)
 Bases: *FIAT.dual_set.DualSet*

The dual basis for Taylor elements. This class works for intervals. Nodes are function and derivative evaluation at the midpoint.

class FIAT.discontinuous_taylor.HigherOrderDiscontinuousTaylor (*ref_el, degree*)
 Bases: *FIAT.finite_element.CiarletElement*

The discontinuous Taylor finite element. Use a Taylor basis for DG.

1.3.17 FIAT.dual_set module

class FIAT.dual_set.DualSet (*nodes, ref_el, entity_ids*)
 Bases: *object*

get_entity_closure_ids ()

get_entity_ids ()

get_nodes ()

get_reference_element ()

to_riesz (*poly_set*)

This method gives the action of the entire dual set on each member of the expansion set underlying *poly_set*. Then, applying the linear functionals of the dual set to an arbitrary polynomial in *poly_set* is accomplished by (generalized) matrix multiplication.

For scalar-valued spaces, this produces a matrix $:math:R_{[i, j]}$ such that $:math:ell_i(f) = sum_{[j]} a_j ell_i(phi_j)$ for $:math:f=sum_{[j]} a_j phi_j$.

More generally, it will have shape concatenating the number of functionals in the dual set, the value shape of functions it takes, and the number of members of the expansion set.

`FIAT.dual_set.make_entity_closure_ids (ref_el, entity_ids)`

1.3.18 FIAT.enriched module

class `FIAT.enriched.EnrichedElement (*elements)`

Bases: `FIAT.finite_element.FiniteElement`

Class implementing a finite element that combined the degrees of freedom of two existing finite elements.

This is an implementation which does not care about orthogonality of primal and dual basis.

degree ()

Return the degree of the (embedding) polynomial space.

dmats ()

Return dmats: expansion coefficients for basis function derivatives.

elements ()

Return reference to original subelements

get_coeffs ()

Return the expansion coefficients for the basis of the finite element.

get_nodal_basis ()

Return the nodal basis, encoded as a PolynomialSet object, for the finite element.

get_num_members (*arg*)

Return number of members of the expansion set.

tabulate (*order, points, entity=None*)

Return tabulated values of derivatives up to given order of basis functions at given points.

value_shape ()

Return the value shape of the finite element functions.

1.3.19 FIAT.expansions module

Principal orthogonal expansion functions as defined by Karniadakis and Sherwin. These are parametrized over a reference element so as to allow users to get coordinates that they want.

class `FIAT.expansions.LineExpansionSet (ref_el)`

Bases: `object`

Evaluates the Legendre basis on a line reference element.

get_num_members (*n*)

tabulate (*n, pts*)

Returns a numpy array $A[i,j] = \phi_i(\text{pts}[j])$

tabulate_derivatives (*n, pts*)

Returns a tuple of length one (A,) such that $A[i,j] = D \phi_i(\text{pts}[j])$. The tuple is returned for compatibility with the interfaces of the triangle and tetrahedron expansions.

class `FIAT.expansions.PointExpansionSet (ref_el)`

Bases: `object`

Evaluates the point basis on a point reference element.

get_num_members (*n*)

tabulate (*n*, *pts*)

Returns a numpy array $A[i,j] = \phi_i(\text{pts}[j]) = 1.0$.

tabulate_derivatives (*n*, *pts*)

Returns a numpy array of size A where $A[i,j] = \phi_i(\text{pts}[j])$ but where each element is an empty tuple $()$. This maintains compatibility with the interfaces of the interval, triangle and tetrahedron expansions.

class FIAT.expansions.**TetrahedronExpansionSet** (*ref_el*)

Bases: `object`

Collapsed orthonormal polynomial expansion on a tetrahedron.

get_num_members (*n*)

tabulate (*n*, *pts*)

tabulate_derivatives (*n*, *pts*)

tabulate_jet (*n*, *pts*, *order=1*)

class FIAT.expansions.**TriangleExpansionSet** (*ref_el*)

Bases: `object`

Evaluates the orthonormal Dubiner basis on a triangular reference element.

get_num_members (*n*)

tabulate (*n*, *pts*)

tabulate_derivatives (*n*, *pts*)

tabulate_jet (*n*, *pts*, *order=1*)

FIAT.expansions.**get_expansion_set** (*ref_el*)

Returns an ExpansionSet instance appropriate for the given reference element.

FIAT.expansions.**jrc** (*a*, *b*, *n*)

FIAT.expansions.**polynomial_dimension** (*ref_el*, *degree*)

Returns the dimension of the space of polynomials of degree no greater than *degree* on the reference element.

FIAT.expansions.**xi_tetrahedron** (*eta*)

Maps from $[-1,1]^3$ to the $-1/1$ reference tetrahedron.

FIAT.expansions.**xi_triangle** (*eta*)

Maps from $[-1,1]^2$ to the $(-1,1)$ reference triangle.

1.3.20 FIAT.finite_element module

class FIAT.finite_element.**CiarletElement** (*poly_set*, *dual*, *order*, *formdegree=None*, *mapping='affine'*, *ref_el=None*)

Bases: `FIAT.finite_element.FiniteElement`

Class implementing Ciarlet's abstraction of a finite element being a domain, function space, and set of nodes.

Elements derived from this class are nodal finite elements, with a nodal basis generated from polynomials encoded in a *PolynomialSet*.

degree ()

Return the degree of the (embedding) polynomial space.

dmats ()

Return dmats: expansion coefficients for basis function derivatives.

get_coeffs ()

Return the expansion coefficients for the basis of the finite element.

get_nodal_basis ()

Return the nodal basis, encoded as a PolynomialSet object, for the finite element.

get_num_members (*arg*)

Return number of members of the expansion set.

static is_nodal ()

True if primal and dual bases are orthogonal. If false, dual basis is not implemented or is undefined.

All implementations/subclasses are nodal including this one.

tabulate (*order*, *points*, *entity=None*)

Return tabulated values of derivatives up to given order of basis functions at given points.

Parameters

- **order** – The maximum order of derivative.
- **points** – An iterable of points.
- **entity** – Optional (dimension, entity number) pair indicating which topological entity of the reference element to tabulate on. If *None*, default cell-wise tabulation is performed.

value_shape ()

Return the value shape of the finite element functions.

class FIAT.finite_element.**FiniteElement** (*ref_el*, *dual*, *order*, *formdegree=None*, *mapping='affine'*)

Bases: `object`

Class implementing a basic abstraction template for general finite element families. Finite elements which inherit from this class are non-nodal unless they are CiarletElement subclasses.

dual_basis ()

Return the dual basis (list of functionals) for the finite element.

entity_closure_dofs ()

Return the map of topological entities to degrees of freedom on the closure of those entities for the finite element.

entity_dofs ()

Return the map of topological entities to degrees of freedom for the finite element.

get_dual_set ()

Return the dual for the finite element.

get_formdegree ()

Return the degree of the associated form (FEEC)

get_order ()

Return the order of the element (may be different from the degree).

get_reference_element ()

Return the reference element for the finite element.

static is_nodal ()

True if primal and dual bases are orthogonal. If false, dual basis is not implemented or is undefined.

Subclasses may not necessarily be nodal, unless it is a CiarletElement.

mapping()

Return a list of appropriate mappings from the reference element to a physical element for each basis function of the finite element.

num_sub_elements()

Return the number of sub-elements.

space_dimension()

Return the dimension of the finite element space.

tabulate(*order, points, entity=None*)

Return tabulated values of derivatives up to given order of basis functions at given points.

Parameters

- **order** – The maximum order of derivative.
- **points** – An iterable of points.
- **entity** – Optional (dimension, entity number) pair indicating which topological entity of the reference element to tabulate on. If *None*, default cell-wise tabulation is performed.

`FIAT.finite_element.entity_support_dofs(elem, entity_dim)`

Return the map of entity id to the degrees of freedom for which the corresponding basis functions take non-zero values

Parameters

- **elem** – FIAT finite element
- **entity_dim** – Dimension of the cell subentity.

1.3.21 FIAT.functional module

class `FIAT.functional.ComponentPointEvaluation(ref_el, comp, shp, x)`

Bases: `FIAT.functional.Functional`

Class representing point evaluation of a particular component of a vector function at a particular point *x*.

tostr()

class `FIAT.functional.FrobeniusIntegralMoment(ref_el, Q, f_at_qpts)`

Bases: `FIAT.functional.Functional`

class `FIAT.functional.Functional(ref_el, target_shape, pt_dict, deriv_dict, functional_type)`

Bases: `object`

Abstract class representing a linear functional. All FIAT functionals are discrete in the sense that they are written as a weighted sum of (derivatives of components of) their argument evaluated at particular points.

Parameters

- **ref_el** – a `Cell`
- **target_shape** – a tuple indicating the value shape of functions on the functional operates (e.g. if the function eats 2-vectors then `target_shape` is (2,)) and if it eats scalars then `target_shape` is ())
- **pt_dict** – A dict mapping points to lists of information about how the functional is evaluated. Each entry in the list takes the form of a tuple (`wt, comp`) so that (at least if the `deriv_dict` argument is empty), the functional takes the form $\ell(f) = \sum_{q=1}^{N_q} \sum_{k=1}^{K_q} w_k^q f_{c_k}(x_q)$ where f_{c_k} indicates a particular vector or tensor component

- **deriv_dict** – A dict that is similar to *pt_dict*, although the entries of each list are tuples (wt, alpha, comp) with alpha a tuple of nonnegative integers corresponding to the order of partial differentiation in each spatial direction.
- **functional_type** – a string labeling the kind of functional this is.

evaluate (*f*)

Obsolete and broken functional evaluation.

To evaluate the functional, call it on the target function:

```
functional(function)
```

get_point_dict ()

Returns the functional information, which is a dictionary mapping each point in the support of the functional to a list of pairs containing the weight and component.

get_reference_element ()

Returns the reference element.

get_type_tag ()

Returns the type of function (e.g. point evaluation or normal component, which is probably handy for clients of FIAT)

to_riesz (*poly_set*)

Constructs an array representation of the functional so that the functional may be applied to a function expressed in terms of the expansion set underlying *poly_set* by means of contracting coefficients.

That is, *poly_set* will have members all expressed in the form $p = \sum_i \alpha^i \phi_i$ where $\{\phi_i\}_i$ is some orthonormal expansion set and α^i are coefficients. Note: the orthonormal expansion set is always scalar-valued but if the members of *poly_set* are vector or tensor valued the α^i will be scalars or vectors.

This function constructs a tensor *R* such that the contraction of *R* with the array of coefficients α produces the effect of $\ell(f)$

In the case of scalar-value functions, *R* is just a vector of the same length as the expansion set, and $R_i = \ell(\phi_i)$. For vector-valued spaces, R_{ij} will be $\ell(e^i \phi_j)$ where e^i is the canonical unit vector nonzero only in one entry *i*.

tostr ()

```
class FIAT.functional.IntegralLegendreBidirectionalMoment (cell, s1, s2, entity,  
                                                         mom_deg, comp_deg,  
                                                         nm="")
```

Bases: *FIAT.functional.Functional*

Moment of dot(s1, dot(tau, s2)) against Legendre on entity, multiplied by the size of the reference facet

```
class FIAT.functional.IntegralLegendreDirectionalMoment (cell, s, entity, mom_deg,  
                                                         comp_deg, nm="")
```

Bases: *FIAT.functional.Functional*

Moment of v.s against a Legendre polynomial over an edge

```
class FIAT.functional.IntegralLegendreNormalMoment (cell, entity, mom_deg, comp_deg)
```

Bases: *FIAT.functional.IntegralLegendreDirectionalMoment*

Moment of v.n against a Legendre polynomial over an edge

```
class FIAT.functional.IntegralLegendreNormalNormalMoment (cell, entity, mom_deg,  
                                                         comp_deg)
```

Bases: *FIAT.functional.IntegralLegendreBidirectionalMoment*

Moment of dot(n, dot(tau, n)) against Legendre on entity.

class FIAT.functional.**IntegralLegendreNormalTangentialMoment** (*cell*, *entity*,
mom_deg,
comp_deg)

Bases: *FIAT.functional.IntegralLegendreBidirectionalMoment*

Moment of $\text{dot}(n, \text{dot}(\tau, t))$ against Legendre on entity.

class FIAT.functional.**IntegralLegendreTangentialMoment** (*cell*, *entity*, *mom_deg*,
comp_deg)

Bases: *FIAT.functional.IntegralLegendreDirectionalMoment*

Moment of $v \cdot t$ against a Legendre polynomial over an edge

class FIAT.functional.**IntegralMoment** (*ref_el*, *Q*, *f_at_qpts*, *comp=()*, *shp=()*)

Bases: *FIAT.functional.Functional*

Functional representing integral of the input against some tabulated function f .

Parameters

- **ref_el** – a Cell.
- **Q** – a QuadratureRule.
- **f_at_qpts** – an array tabulating the function f at the quadrature points.
- **comp** – Optional argument indicating that only a particular component of the input function should be integrated against f
- **shp** – Optional argument giving the value shape of input functions.

class FIAT.functional.**IntegralMomentOfDivergence** (*ref_el*, *Q*, *f_at_qpts*)

Bases: *FIAT.functional.Functional*

Functional representing integral of the divergence of the input against some tabulated function f .

class FIAT.functional.**IntegralMomentOfEdgeTangentEvaluation** (*ref_el*, *Q*, *P_at_qpts*,
edge)

Bases: *FIAT.functional.Functional*

$\int_e v \cdot t \, p \, ds$

p in Polynomials

Parameters

- **ref_el** – reference element for which e is a dim-1 entity
- **Q** – quadrature rule on the face
- **P_at_qpts** – polynomials evaluated at quad points
- **edge** – which edge.

class FIAT.functional.**IntegralMomentOfFaceTangentEvaluation** (*ref_el*, *Q*, *P_at_qpts*,
facet)

Bases: *FIAT.functional.Functional*

$\int_F v \cdot n \cdot p \, ds$

p in Polynomials

Parameters

- **ref_el** – reference element for which F is a codim-1 entity
- **Q** – quadrature rule on the face
- **P_at_qpts** – polynomials evaluated at quad points

- **facet** – which facet.

class FIAT.functional.**IntegralMomentOfNormalDerivative** (*ref_el*, *facet_no*, *Q*,
f_at_qpts)

Bases: *FIAT.functional.Functional*

Functional giving normal derivative integrated against some function on a facet.

class FIAT.functional.**IntegralMomentOfNormalEvaluation** (*ref_el*, *Q*, *P_at_qpts*, *facet*)

Bases: *FIAT.functional.Functional*

int_F vdot *n* *p* ds *p* in Polynomials :arg *ref_el*: reference element for which F is a codim-1 entity :arg *Q*:
quadrature rule on the face :arg *P_at_qpts*: polynomials evaluated at quad points :arg *facet*: which facet.

class FIAT.functional.**IntegralMomentOfNormalNormalEvaluation** (*ref_el*, *Q*,
P_at_qpts, *facet*)

Bases: *FIAT.functional.Functional*

int_F (*n*^T *tau* *n*) *p* ds *p* in Polynomials :arg *ref_el*: reference element for which F is a codim-1 entity :arg *Q*:
quadrature rule on the face :arg *P_at_qpts*: polynomials evaluated at quad points :arg *facet*: which facet.

class FIAT.functional.**IntegralMomentOfScaledNormalEvaluation** (*ref_el*, *Q*,
P_at_qpts, *facet*)

Bases: *FIAT.functional.Functional*

int_F vdot *n* *p* ds

p in Polynomials

Parameters

- **ref_el** – reference element for which F is a codim-1 entity
- **Q** – quadrature rule on the face
- **P_at_qpts** – polynomials evaluated at quad points
- **facet** – which facet.

class FIAT.functional.**IntegralMomentOfTangentialEvaluation** (*ref_el*, *Q*, *P_at_qpts*,
facet)

Bases: *FIAT.functional.Functional*

int_F vdot *n* *p* ds *p* in Polynomials :arg *ref_el*: reference element for which F is a codim-1 entity :arg *Q*:
quadrature rule on the face :arg *P_at_qpts*: polynomials evaluated at quad points :arg *facet*: which facet.

class FIAT.functional.**IntegralMomentOfTensorDivergence** (*ref_el*, *Q*, *f_at_qpts*)

Bases: *FIAT.functional.Functional*

Like `IntegralMomentOfDivergence`, but on symmetric tensors.

class FIAT.functional.**MonkIntegralMoment** (*ref_el*, *Q*, *P_at_qpts*, *facet*)

Bases: *FIAT.functional.Functional*

face nodes are $\int_F \mathbf{v} \cdot \mathbf{p} \, dA$ where \mathbf{p} in $P_{\{q-2\}}(f)^3$ with $\mathbf{p} \cdot \mathbf{n} = 0$ (cmp. Peter Monk - Finite Element
Methods for Maxwell's equations p. 129) Note that we don't scale by the area of the facet

Parameters

- **ref_el** – reference element for which F is a codim-1 entity
- **Q** – quadrature rule on the face
- **P_at_qpts** – polynomials evaluated at quad points
- **facet** – which facet.

class FIAT.functional.**PointDerivative** (*ref_el, x, alpha*)
 Bases: *FIAT.functional.Functional*

Class representing point partial differentiation of scalar functions at a particular point x.

class FIAT.functional.**PointEdgeTangentEvaluation** (*ref_el, edge_no, pt*)
 Bases: *FIAT.functional.Functional*

Implements the evaluation of the tangential component of a vector at a point on a facet of dimension 1.

tostr ()

class FIAT.functional.**PointEvaluation** (*ref_el, x*)
 Bases: *FIAT.functional.Functional*

Class representing point evaluation of scalar functions at a particular point x.

tostr ()

class FIAT.functional.**PointFaceTangentEvaluation** (*ref_el, face_no, tno, pt*)
 Bases: *FIAT.functional.Functional*

Implements the evaluation of a tangential component of a vector at a point on a facet of codimension 1.

tostr ()

class FIAT.functional.**PointNormalDerivative** (*ref_el, facet_no, pt*)
 Bases: *FIAT.functional.Functional*

Represents d/dn at a point on a facet.

class FIAT.functional.**PointNormalEvaluation** (*ref_el, facet_no, pt*)
 Bases: *FIAT.functional.Functional*

Implements the evaluation of the normal component of a vector at a point on a facet of codimension 1.

class FIAT.functional.**PointNormalSecondDerivative** (*ref_el, facet_no, pt*)
 Bases: *FIAT.functional.Functional*

Represents d^2/dn^2 at a point on a facet.

class FIAT.functional.**PointScaledNormalEvaluation** (*ref_el, facet_no, pt*)
 Bases: *FIAT.functional.Functional*

Implements the evaluation of the normal component of a vector at a point on a facet of codimension 1, where the normal is scaled by the volume of that facet.

tostr ()

class FIAT.functional.**PointwiseInnerProductEvaluation** (*ref_el, v, w, p*)
 Bases: *FIAT.functional.Functional*

This is a functional on symmetric 2-tensor fields. Let u be such a field, p be a point, and v, w be vectors. This implements the evaluation $v^T u(p) w$.

Clearly $v^i u_{ij} w^j = u_{ij} v^i w^j$. Thus the value can be computed from the Frobenius inner product of u with wv^T . This gives the correct weights.

class FIAT.functional.**TensorBidirectionalMomentInnerProductEvaluation** (*ref_el,*
v, w,
Q,
f_at_qpts,
comp_deg)
 Bases: *FIAT.functional.Functional*

This is a functional on symmetric 2-tensor fields. Let u be such a field, f a function tabulated at points, and v, w be vectors. This implements the evaluation $\int v^T u(x) w f(x)$.

Clearly $v^T u_{\{ij\}} w^j = u_{\{ij\}} v^i w^j$. Thus the value can be computed from the Frobenius inner product of u with wv^T . This gives the correct weights.

`FIAT.functional.index_iterator` (*shp*)

Constructs a generator iterating over all indices in *shp* in generalized column-major order. So if *shp* = (2,2), then we construct the sequence (0,0),(0,1),(1,0),(1,1)

1.3.22 FIAT.gauss_legendre module

class `FIAT.gauss_legendre.GaussLegendre` (*ref_el, degree*)

Bases: `FIAT.finite_element.CiarletElement`

1D discontinuous element with nodes at the Gauss-Legendre points.

class `FIAT.gauss_legendre.GaussLegendreDualSet` (*ref_el, degree*)

Bases: `FIAT.dual_set.DualSet`

The dual basis for 1D discontinuous elements with nodes at the Gauss-Legendre points.

1.3.23 FIAT.gauss_lobatto_legendre module

class `FIAT.gauss_lobatto_legendre.GaussLobattoLegendre` (*ref_el, degree*)

Bases: `FIAT.finite_element.CiarletElement`

1D continuous element with nodes at the Gauss-Lobatto points.

class `FIAT.gauss_lobatto_legendre.GaussLobattoLegendreDualSet` (*ref_el, degree*)

Bases: `FIAT.dual_set.DualSet`

The dual basis for 1D continuous elements with nodes at the Gauss-Lobatto points.

1.3.24 FIAT.gauss_radau module

class `FIAT.gauss_radau.GaussRadau` (*ref_el, degree*)

Bases: `FIAT.finite_element.CiarletElement`

1D discontinuous element with nodes at the Gauss-Radau points.

class `FIAT.gauss_radau.GaussRadauDualSet` (*ref_el, degree, right=True*)

Bases: `FIAT.dual_set.DualSet`

The dual basis for 1D discontinuous elements with nodes at the Gauss-Radau points.

1.3.25 FIAT.hdiv_trace module

class `FIAT.hdiv_trace.HDivTrace` (*ref_el, degree*)

Bases: `FIAT.finite_element.FiniteElement`

Class implementing the trace of hdiv elements. This class is a stand-alone element family that produces a DG-facet field. This element is what's produced after performing the trace operation on an existing H(Div) element.

This element is also known as the discontinuous trace field that arises in several DG formulations.

degree ()

Return the degree of the (embedding) polynomial space.

dmats ()

Return dmats: expansion coefficients for basis function derivatives.

get_coeffs ()

Return the expansion coefficients for the basis of the finite element.

get_nodal_basis ()

Return the nodal basis, encoded as a PolynomialSet object, for the finite element.

get_num_members (*arg*)

Return number of members of the expansion set.

static is_nodal ()

True if primal and dual bases are orthogonal. If false, dual basis is not implemented or is undefined.

Subclasses may not necessarily be nodal, unless it is a CiarletElement.

tabulate (*order, points, entity=None*)

Return tabulated values of derivatives up to a given order of basis functions at given points.

Parameters

- **order** – The maximum order of derivative.
- **points** – An iterable of points.
- **entity** – Optional (dimension, entity number) pair indicating which topological entity of the reference element to tabulate on. If `None`, tabulated values are computed by geometrically approximating which facet the points are on.

Note: Performing illegal tabulations on this element will result in either a tabulation table of `numpy.nan` arrays (`entity=None` case), or insertions of the `TraceError` exception class. This is due to the fact that performing cell-wise tabulations, or asking for any order of derivative evaluations, are not mathematically well-defined.

value_shape ()

Return the value shape of the finite element functions.

exception `FIAT.hdiv_trace.TraceError` (*msg*)

Bases: `Exception`

Exception caused by tabulating a trace element on the interior of a cell, or the gradient of a trace element.

`FIAT.hdiv_trace.barycentric_coordinates` (*points, vertices*)

Computes the barycentric coordinates for a set of points relative to a simplex defined by a set of vertices.

Parameters

- **points** – A set of points.
- **vertices** – A set of vertices that define the simplex.

`FIAT.hdiv_trace.construct_dg_element` (*ref_el, degree*)

Constructs a discontinuous galerkin element of a given degree on a particular reference cell.

`FIAT.hdiv_trace.extract_unique_facet` (*coordinates, tolerance=1e-10*)

Determines whether a set of points (described in its barycentric coordinates) are all on one of the facet sub-entities, and return the particular facet and whether the search has been successful.

Parameters

- **coordinates** – A set of points described in barycentric coordinates.

- **tolerance** – A fixed tolerance for geometric identifications.

`FIAT.hdiv_trace.map_from_reference_facet` (*point, vertices*)

Evaluates the physical coordinate of a point using barycentric coordinates.

Parameters

- **point** – The reference points to be mapped to the facet.
- **vertices** – The vertices defining the physical element.

`FIAT.hdiv_trace.map_to_reference_facet` (*points, vertices, facet*)

Given a set of points and vertices describing a facet of a simplex in n-dimensional coordinates (where the points lie on the facet), map the points to the reference simplex of dimension (n-1).

Parameters

- **points** – A set of points in n-D.
- **vertices** – A set of vertices describing a facet of a simplex in n-D.
- **facet** – Integer representing the facet number.

1.3.26 FIAT.hdivcurl module

`FIAT.hdivcurl.Hcurl` (*element*)

`FIAT.hdivcurl.Hdiv` (*element*)

1.3.27 FIAT.hellan_herrmann_johnson module

Implementation of the Hellan-Herrmann-Johnson finite elements.

class `FIAT.hellan_herrmann_johnson.HellanHerrmannJohnson` (*cell, degree*)

Bases: `FIAT.finite_element.CiarletElement`

The definition of Hellan-Herrmann-Johnson element. It is defined only in dimension 2. It consists of piecewise polynomial symmetric-matrix-valued functions of degree r or less with normal-normal continuity.

class `FIAT.hellan_herrmann_johnson.HellanHerrmannJohnsonDual` (*cell, degree*)

Bases: `FIAT.dual_set.DualSet`

Degrees of freedom for Hellan-Herrmann-Johnson elements.

1.3.28 FIAT.hermite module

class `FIAT.hermite.CubicHermite` (*ref_el, deg=3*)

Bases: `FIAT.finite_element.CiarletElement`

The cubic Hermite finite element. It is what it is.

class `FIAT.hermite.CubicHermiteDualSet` (*ref_el*)

Bases: `FIAT.dual_set.DualSet`

The dual basis for Lagrange elements. This class works for simplices of any dimension. Nodes are point evaluation at equispaced points.

1.3.29 FIAT.jacobi module

Several functions related to the one-dimensional jacobi polynomials: Evaluation, evaluation of derivatives, plus computation of the roots via Newton's method. These mainly are used in defining the expansion functions over the simplices and in defining quadrature rules over each domain.

FIAT.jacobi.**eval_jacobi** (*a, b, n, x*)

Evaluates the *n*th jacobi polynomial with weight parameters *a, b* at a point *x*. Recurrence relations implemented from the pseudocode given in Karniadakis and Sherwin, Appendix B

FIAT.jacobi.**eval_jacobi_batch** (*a, b, n, xs*)

Evaluates all jacobi polynomials with weights *a, b* up to degree *n*. *xs* is a numpy.array of points. Returns a two-dimensional array of points, where the rows correspond to the Jacobi polynomials and the columns correspond to the points.

FIAT.jacobi.**eval_jacobi_deriv** (*a, b, n, x*)

Evaluates the first derivative of $P_{\{n\}}^{\{a,b\}}$ at a point *x*.

FIAT.jacobi.**eval_jacobi_deriv_batch** (*a, b, n, xs*)

Evaluates the first derivatives of all jacobi polynomials with weights *a, b* up to degree *n*. *xs* is a numpy.array of points. Returns a two-dimensional array of points, where the rows correspond to the Jacobi polynomials and the columns correspond to the points.

1.3.30 FIAT.kong_mulder_veldhuizen module

class FIAT.kong_mulder_veldhuizen.**KongMulderVeldhuizen** (*ref_el, degree*)

Bases: *FIAT.finite_element.CiarletElement*

The “lumped” simplicial finite element (NB: requires custom quad. “KMV” points to achieve a diagonal mass matrix).

Higher-order triangular and tetrahedral finite elements with mass lumping for solving the wave equation M. J. S. CHIN-JOE-KONG, W. A. MULDER and M. VAN VELDHUIZEN

HIGHER-ORDER MASS-LUMPED FINITE ELEMENTS FOR THE WAVE EQUATION W.A. MULDER

NEW HIGHER-ORDER MASS-LUMPED TETRAHEDRAL ELEMENTS S. GEEVERS, W.A. MULDER, AND J.J.W. VAN DER VEGT

class FIAT.kong_mulder_veldhuizen.**KongMulderVeldhuizenDualSet** (*ref_el, degree*)

Bases: *FIAT.dual_set.DualSet*

The dual basis for KMV simplicial elements.

FIAT.kong_mulder_veldhuizen.**KongMulderVeldhuizenSpace** (*T, deg*)

FIAT.kong_mulder_veldhuizen.**bump** (*T, deg*)

Increase degree of polynomial along face/edges

1.3.31 FIAT.lagrange module

class FIAT.lagrange.**Lagrange** (*ref_el, degree*)

Bases: *FIAT.finite_element.CiarletElement*

The Lagrange finite element. It is what it is.

class FIAT.lagrange.**LagrangeDualSet** (*ref_el, degree*)

Bases: *FIAT.dual_set.DualSet*

The dual basis for Lagrange elements. This class works for simplices of any dimension. Nodes are point evaluation at equispaced points.

1.3.32 FIAT.mardal_tai_winther module

Implementation of the Mardal-Tai-Winther finite elements.

FIAT.mardal_tai_winther.**DivergenceDubinerMoments** (*cell, start_deg, stop_deg, comp_deg*)

class FIAT.mardal_tai_winther.**MardalTaiWinther** (*cell, degree=3*)

Bases: *FIAT.finite_element.CiarletElement*

The definition of the Mardal-Tai-Winther element.

class FIAT.mardal_tai_winther.**MardalTaiWintherDual** (*cell, degree*)

Bases: *FIAT.dual_set.DualSet*

Degrees of freedom for Mardal-Tai-Winther elements.

1.3.33 FIAT.mixed module

class FIAT.mixed.**MixedElement** (*elements, ref_el=None*)

Bases: *FIAT.finite_element.FiniteElement*

A FIAT-like representation of a mixed element.

Parameters

- **elements** – An iterable of FIAT elements.
- **ref_el** – The reference element (optional).

This object offers tabulation of the concatenated basis function tables along with an `entity_dofs` dict.

elements ()

get_nodal_basis ()

is_nodal ()

True if primal and dual bases are orthogonal.

mapping ()

Return a list of appropriate mappings from the reference element to a physical element for each basis function of the finite element.

num_sub_elements ()

Return the number of sub-elements.

tabulate (*order, points, entity=None*)

Tabulate a mixed element by appropriately splatting together the tabulation of the individual elements.

value_shape ()

FIAT.mixed.**concatenate_entity_dofs** (*ref_el, elements*)

Combine the `entity_dofs` from a list of elements into a combined `entity_dof` containing the information for the concatenated DoFs of all the elements.

1.3.34 FIAT.morley module

class FIAT.morley.**Morley** (*ref_el*)
 Bases: *FIAT.finite_element.CiarletElement*

The Morley finite element.

class FIAT.morley.**MorleyDualSet** (*ref_el*)
 Bases: *FIAT.dual_set.DualSet*

The dual basis for Lagrange elements. This class works for simplices of any dimension. Nodes are point evaluation at equispaced points.

1.3.35 FIAT.nedelec module

class FIAT.nedelec.**Nedelec** (*ref_el, k, variant=None*)
 Bases: *FIAT.finite_element.CiarletElement*

Nedelec finite element

Parameters

- **ref_el** – The reference element.
- **k** – The degree.
- **variant** – optional variant specifying the types of nodes.

variant can be chosen from [“point”, “integral”, “integral(quadrature_degree)”] “point” -> dofs are evaluated by point evaluation. Note that this variant has suboptimal convergence order in the H(curl)-norm “integral” -> dofs are evaluated by quadrature rule. The quadrature degree is chosen to integrate polynomials of degree $5*k$ so that most expressions will be interpolated exactly. This is important when you want to have (nearly) curl-preserving interpolation. “integral(quadrature_degree)” -> dofs are evaluated by quadrature rule of degree quadrature_degree

class FIAT.nedelec.**NedelecDual2D** (*ref_el, degree, variant, quad_deg*)
 Bases: *FIAT.dual_set.DualSet*

Dual basis for first-kind Nedelec in 2D.

class FIAT.nedelec.**NedelecDual3D** (*ref_el, degree, variant, quad_deg*)
 Bases: *FIAT.dual_set.DualSet*

Dual basis for first-kind Nedelec in 3D.

FIAT.nedelec.**NedelecSpace2D** (*ref_el, k*)

Constructs a basis for the 2d H(curl) space of the first kind which is $(P_k)^2 + P_k \text{rot}(x)$

FIAT.nedelec.**NedelecSpace3D** (*ref_el, k*)

Constructs a nodal basis for the 3d first-kind Nedelec space

1.3.36 FIAT.nedelec_second_kind module

class FIAT.nedelec_second_kind.**NedelecSecondKind** (*cell, k, variant=None*)
 Bases: *FIAT.finite_element.CiarletElement*

The H(curl) Nedelec elements of the second kind on triangles and tetrahedra: the polynomial space described by the full polynomials of degree k , with a suitable set of degrees of freedom to ensure H(curl) conformity.

Parameters

- **ref_el** – The reference element.
- **k** – The degree.
- **variant** – optional variant specifying the types of nodes.

variant can be chosen from [“point”, “integral”, “integral(quadrature_degree)”] “point” -> dofs are evaluated by point evaluation. Note that this variant has suboptimal convergence order in the H(curl)-norm “integral” -> dofs are evaluated by quadrature rule. The quadrature degree is chosen to integrate polynomials of degree $5*k$ so that most expressions will be interpolated exactly. This is important when you want to have (nearly) curl-preserving interpolation. “integral(quadrature_degree)” -> dofs are evaluated by quadrature rule of degree quadrature_degree

```
class FIAT.nedelec_second_kind.NedelecSecondKindDual(cell, degree, variant,  
                                                    quad_deg)
```

Bases: *FIAT.dual_set.DualSet*

This class represents the dual basis for the Nedelec H(curl) elements of the second kind. The degrees of freedom (L) for the elements of the k 'th degree are

$d = 2$:

vertices: None

edges: $L(f) = f(x_i) * t$ for $(k+1)$ points x_i on each edge

cell: $L(f) = \int f * g * dx$ for g in $RT_{\{k-1\}}$

$d = 3$:

vertices: None

edges: $L(f) = f(x_i) * t$ for $(k+1)$ points x_i on each edge

faces: $L(f) = \int_F f * g * ds$ for g in $RT_{\{k-1\}}(F)$ for each face F

cell: $L(f) = \int f * g * dx$ for g in $RT_{\{k-2\}}$

Higher spatial dimensions are not yet implemented. (For $d = 1$, these elements coincide with the CG_k elements.)

```
generate_degrees_of_freedom(cell, degree, variant, quad_deg)
```

Generate dofs and geometry-to-dof maps (ids).

1.3.37 FIAT.nodal_enriched module

```
class FIAT.nodal_enriched.NodalEnrichedElement(*elements)
```

Bases: *FIAT.finite_element.CiarletElement*

NodalEnriched element is a direct sum of a sequence of finite elements. Dual basis is reorthogonalized to the primal basis for nodality.

The following is equivalent:

- the constructor is well-defined,
- the resulting element is unisolvent and its basis is nodal,
- the supplied elements are unisolvent with nodal basis and their primal bases are mutually linearly independent,
- the supplied elements are unisolvent with nodal basis and their dual bases are mutually linearly independent.

1.3.38 FIAT.orthopoly module

orthopoly.py - A suite of functions for generating orthogonal polynomials and quadrature rules.

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Last updated on Wed Jan 1 14:29:25 MST 2014

Modified by David A. Ham (david.ham@imperial.ac.uk), 2016

FIAT.orthopoly.**gauss** (*alpha*, *beta*)

Compute the Gauss nodes and weights from the recursion coefficients associated with a set of orthogonal polynomials

Inputs: *alpha* - recursion coefficients *beta* - recursion coefficients

Outputs: *x* - quadrature nodes *w* - quadrature weights

Adapted from the MATLAB code by Walter Gautschi <http://www.cs.purdue.edu/archives/2002/wxg/codes/gauss.m>

FIAT.orthopoly.**jacobi** (*N*, *a*, *b*, *x*, *NOPT=1*)

JACOBI computes the Jacobi polynomials which are orthogonal on $[-1, 1]$ with respect to the weight $w(x)=[(1-x)^a]^*[(1+x)^b]$ and evaluate them on the given grid up to $P_N(x)$. Setting *NOPT*=2 returns the L2-normalized polynomials

FIAT.orthopoly.**jacobiD** (*N*, *a*, *b*, *x*, *NOPT=1*)

JACOBID computes the first derivatives of the normalized Jacobi polynomials which are orthogonal on $[-1, 1]$ with respect to the weight $w(x)=[(1-x)^a]^*[(1+x)^b]$ and evaluate them on the given grid up to $P_N(x)$. Setting *NOPT*=2 returns the derivatives of the L2-normalized polynomials

FIAT.orthopoly.**lobatto** (*alpha*, *beta*, *x11*, *x12*)

Compute the Lobatto nodes and weights with the preassigned nodea *x11*,*x12*

Inputs: *alpha* - recursion coefficients *beta* - recursion coefficients *x11* - assigned node location *x12* - assigned node location

Outputs: *x* - quadrature nodes *w* - quadrature weights

Based on the section 7 of the paper “Some modified matrix eigenvalue problems” by Gene Golub, SIAM Review Vol 15, No. 2, April 1973, pp.318–334

FIAT.orthopoly.**mm_log** (*N*, *a*)

MM_LOG Modified moments for a logarithmic weight function.

The call `mm=MM_LOG(n,a)` computes the first *n* modified moments of the logarithmic weight function $w(t)=t^a \log(1/t)$ on $[0, 1]$ relative to shifted Legendre polynomials.

REFERENCE: Walter Gautschi, “On the preceding paper ‘A Legendre polynomial integral’ by James L. Blue”, Math. Comp. 33 (1979), 742-743.

Adapted from the MATLAB implementation: https://www.cs.purdue.edu/archives/2002/wxg/codes/mm_log.m

FIAT.orthopoly.**mod_chebyshev** (*N, mom, alpham, betam*)

Calculate the recursion coefficients for the orthogonal polynomials which are orthogonal with respect to a weight function which is represented in terms of its modified moments which are obtained by integrating the monic polynomials against the weight function.

John C. Wheeler, “Modified moments and Gaussian quadratures” Rocky Mountain Journal of Mathematics, Vol. 4, Num. 2 (1974), 287–296

Walter Gautschi, “Orthogonal Polynomials (in Matlab) Journal of Computational and Applied Mathematics, Vol. 178 (2005) 215–234

Adapted from the MATLAB implementation: <https://www.cs.purdue.edu/archives/2002/wxg/codes/chebyshev.m>

FIAT.orthopoly.**polyval** (*alpha, beta, x*)

Evaluate polynomials on *x* given the recursion coefficients *alpha* and *beta*

FIAT.orthopoly.**rec_jaclog** (*N, a*)

Generate the recursion coefficients *alpha_k*, *beta_k*

$$P_{\{k+1\}}(x) = (x - \alpha_k)P_{\{k\}}(x) - \beta_k P_{\{k-1\}}(x)$$

for the monic polynomials which are orthogonal on [0,1] with respect to the weight $w(x) = x^a \log(1/x)$

Inputs: *N* - polynomial order *a* - weight parameter

Outputs: *alpha* - recursion coefficients *beta* - recursion coefficients

Adapted from the MATLAB code: https://www.cs.purdue.edu/archives/2002/wxg/codes/r_jaclog.m

FIAT.orthopoly.**rec_jacobi** (*N, a, b*)

Generate the recursion coefficients *alpha_k*, *beta_k*

$$P_{\{k+1\}}(x) = (x - \alpha_k)P_{\{k\}}(x) - \beta_k P_{\{k-1\}}(x)$$

for the Jacobi polynomials which are orthogonal on [-1,1] with respect to the weight $w(x) = [(1-x)^a]^*[(1+x)^b]$

Inputs: *N* - polynomial order *a* - weight parameter *b* - weight parameter

Outputs: *alpha* - recursion coefficients *beta* - recursion coefficients

Adapted from the MATLAB code by Dirk Laurie and Walter Gautschi http://www.cs.purdue.edu/archives/2002/wxg/codes/r_jacobi.m

FIAT.orthopoly.**rec_jacobi01** (*N, a, b*)

Generate the recursion coefficients *alpha_k*, *beta_k* for the Jacobi polynomials which are orthogonal on [0,1]

See `rec_jacobi` for the recursion coefficients on [-1,1]

Inputs: *N* - polynomial order *a* - weight parameter *b* - weight parameter

Outputs: *alpha* - recursion coefficients *beta* - recursion coefficients

Adapted from the MATLAB implementation: https://www.cs.purdue.edu/archives/2002/wxg/codes/r_jacobi01.m

1.3.39 FIAT.pointwise_dual module

FIAT.pointwise_dual.**compute_pointwise_dual** (*el, pts*)

Constructs a dual basis to the basis for *el* as a linear combination of a set of pointwise evaluations. This is useful

when the prescribed finite element isn't Ciarlet (e.g. the basis functions are provided explicitly as formulae). Alternately, the element's given dual basis may involve differentiation, making run-time interpolation difficult in FIAT clients. The pointwise dual, consisting only of pointwise evaluations, will effectively replace these derivatives with (automatically determined) finite differences. This is exact on the polynomial space, but is an approximation if applied to functions outside the space.

Parameters

- **el** – a `FiniteElement`.
- **pts** – an iterable of points with the same length as `el`'s dimension. These points must be unisolvent for the polynomial space

Returns a `:class DualSet`

1.3.40 FIAT.polynomial_set module

class `FIAT.polynomial_set.ONPolynomialSet` (*ref_el, degree, shape=()*)

Bases: `FIAT.polynomial_set.PolynomialSet`

Constructs an orthonormal basis out of expansion set by having an identity matrix of coefficients. Can be used to specify ON bases for vector- and tensor-valued sets as well.

class `FIAT.polynomial_set.ONSymTensorPolynomialSet` (*ref_el, degree, size=None*)

Bases: `FIAT.polynomial_set.PolynomialSet`

Constructs an orthonormal basis for symmetric-tensor-valued polynomials on a reference element.

class `FIAT.polynomial_set.PolynomialSet` (*ref_el, degree, embedded_degree, expansion_set, coeffs, dmats*)

Bases: `object`

Implements a set of polynomials as linear combinations of an expansion set over a reference element. `ref_el`: the reference element `degree`: an order labeling the space `embedded_degree`: the degree of polynomial expansion basis that

must be used to evaluate this space

coeffs: A numpy array containing the coefficients of the expansion basis for each member of the set. `Coeffs` is ordered by `coeffs[i,j,k]` where `i` is the label of the member, `k` is the label of the expansion function, and `j` is a (possibly empty) tuple giving the index for a vector- or tensor-valued function.

`get_coeffs()`

`get_degree()`

`get_dmats()`

`get_embedded_degree()`

`get_expansion_set()`

`get_num_members()`

`get_reference_element()`

`get_shape()`

Returns the shape of $\phi(x)$, where $()$ corresponds to scalar $(2,)$ a vector of length 2, etc

`tabulate(pts, jet_order=0)`

Returns the values of the polynomial set.

`tabulate_new(pts)`

take (*items*)

Extracts subset of polynomials given by items.

FIAT.polynomial_set.**form_matrix_product** (*mats, alpha*)

Forms product over mats[i]**alpha[i]

FIAT.polynomial_set.**mis** (*m, n*)

Returns all m-tuples of nonnegative integers that sum up to n.

FIAT.polynomial_set.**polynomial_set_union_normalized** (*A, B*)

Given polynomial sets A and B, constructs a new polynomial set whose span is the same as that of span(A) union span(B). It may not contain any of the same members of the set, as we construct a span via SVD.

FIAT.polynomial_set.**project** (*f, U, Q*)

Computes the expansion coefficients of f in terms of the members of a polynomial set U. Numerical integration is performed by quadrature rule Q.

1.3.41 FIAT.quadrature module

class FIAT.quadrature.**CollapsedQuadratureTetrahedronRule** (*ref_el, m*)

Bases: *FIAT.quadrature.QuadratureRule*

Implements the collapsed quadrature rules defined in Karniadakis & Sherwin by mapping products of Gauss-Jacobi rules from the cube to the tetrahedron.

class FIAT.quadrature.**CollapsedQuadratureTriangleRule** (*ref_el, m*)

Bases: *FIAT.quadrature.QuadratureRule*

Implements the collapsed quadrature rules defined in Karniadakis & Sherwin by mapping products of Gauss-Jacobi rules from the square to the triangle.

class FIAT.quadrature.**GaussJacobiQuadratureLineRule** (*ref_el, m*)

Bases: *FIAT.quadrature.QuadratureRule*

Gauss-Jacobi quadrature rule determined by Jacobi weights a and b using m roots of m:th order Jacobi polynomial.

class FIAT.quadrature.**GaussLegendreQuadratureLineRule** (*ref_el, m*)

Bases: *FIAT.quadrature.QuadratureRule*

Produce the Gauss-Legendre quadrature rules on the interval using the implementation in numpy. This facilitates implementing discontinuous spectral elements.

The quadrature rule uses m points for a degree of precision of 2m-1.

class FIAT.quadrature.**GaussLobattoLegendreQuadratureLineRule** (*ref_el, m*)

Bases: *FIAT.quadrature.QuadratureRule*

Implement the Gauss-Lobatto-Legendre quadrature rules on the interval using Greg von Winckel's implementation. This facilitates implementing spectral elements.

The quadrature rule uses m points for a degree of precision of 2m-3.

class FIAT.quadrature.**QuadratureRule** (*ref_el, pts, wts*)

Bases: *object*

General class that models integration over a reference element as the weighted sum of a function evaluated at a set of points.

get_points ()

get_weights ()

`integrate(f)`

class `FIAT.quadrature.RadauQuadratureLineRule` (*ref_el, m, right=True*)

Bases: `FIAT.quadrature.QuadratureRule`

Produce the Gauss–Radau quadrature rules on the interval using an adaptation of Winkel’s Matlab code.

The quadrature rule uses *m* points for a degree of precision of $2m-1$.

class `FIAT.quadrature.UFCTetrahedronFaceQuadratureRule` (*face_number, degree*)

Bases: `FIAT.quadrature.QuadratureRule`

Highly specialized quadrature rule for the face of a tetrahedron, mapped from a reference triangle, used for higher order Nedelec’s

`jacobian()`

`reference_rule()`

`FIAT.quadrature.compute_gauss_jacobi_points(a, b, m)`

Computes the *m* roots of $P_m^{a,b}$ on $[-1,1]$ by Newton’s method. The initial guesses are the Chebyshev points. Algorithm implemented in Python from the pseudocode given by Karniadakis and Sherwin

`FIAT.quadrature.compute_gauss_jacobi_rule(a, b, m)`

`FIAT.quadrature.make_quadrature(ref_el, m)`

Returns the collapsed quadrature rule using *m* points per direction on the given reference element. In the tensor product case, *m* is a tuple.

`FIAT.quadrature.make_tensor_product_quadrature(*quad_rules)`

Returns the quadrature rule for a TensorProduct cell, by combining the quadrature rules of the components.

1.3.42 FIAT.quadrature_element module

class `FIAT.quadrature_element.QuadratureElement` (*ref_el, points, weights=None*)

Bases: `FIAT.finite_element.FiniteElement`

A set of quadrature points pretending to be a finite element.

static is_nodal()

True if primal and dual bases are orthogonal. If false, dual basis is not implemented or is undefined.

Subclasses may not necessarily be nodal, unless it is a CiarletElement.

tabulate (*order, points, entity=None*)

Return the identity matrix of size (num_quad_points, num_quad_points), in a format that monomialintegration and monomialtabulation understands.

value_shape()

The QuadratureElement is scalar valued

1.3.43 FIAT.quadrature_schemes module

Quadrature schemes on cells

This module generates quadrature schemes on reference cells that integrate exactly a polynomial of a given degree using a specified scheme.

Scheme options are:

scheme="default"

scheme="canonical" (collapsed Gauss scheme)

Background on the schemes:

Keast rules for tetrahedra: Keast, P. Moderate-degree tetrahedral quadrature formulas, *Computer Methods in Applied Mechanics and Engineering* 55(3):339-348, 1986. [http://dx.doi.org/10.1016/0045-7825\(86\)90059-9](http://dx.doi.org/10.1016/0045-7825(86)90059-9)

`FIAT.quadrature_schemes.create_quadrature(ref_el, degree, scheme='default')`

Generate quadrature rule for given reference element that will integrate an polynomial of order 'degree' exactly.

For low-degree (≤ 6) polynomials on triangles and tetrahedra, this uses hard-coded rules, otherwise it falls back to a collapsed Gauss scheme on simplices. On tensor-product cells, it is a tensor-product quadrature rule of the subcells.

Parameters

- **cell** – The FIAT cell to create the quadrature for.
- **degree** – The degree of polynomial that the rule should integrate exactly.

1.3.44 FIAT.raviart_thomas module

class `FIAT.raviart_thomas.RTDualSet(ref_el, degree, variant, quad_deg)`

Bases: `FIAT.dual_set.DualSet`

Dual basis for Raviart-Thomas elements consisting of point evaluation of normals on facets of codimension 1 and internal moments against polynomials

`FIAT.raviart_thomas.RTSpace(ref_el, deg)`

Constructs a basis for the the Raviart-Thomas space $(P_k)^d + P_k x$

class `FIAT.raviart_thomas.RaviartThomas(ref_el, k, variant=None)`

Bases: `FIAT.finite_element.CiarletElement`

The Raviart Thomas element

Parameters

- **ref_el** – The reference element.
- **k** – The degree.
- **variant** – optional variant specifying the types of nodes.

variant can be chosen from ["point", "integral", "integral(quadrature_degree)"] "point" -> dofs are evaluated by point evaluation. Note that this variant has suboptimal convergence order in the $H(\text{div})$ -norm "integral" -> dofs are evaluated by quadrature rule. The quadrature degree is chosen to integrate polynomials of degree $5*k$ so that most expressions will be interpolated exactly. This is important when you want to have (nearly) divergence-preserving interpolation. "integral(quadrature_degree)" -> dofs are evaluated by quadrature rule of degree quadrature_degree

1.3.45 FIAT.reference_element module

Abstract class and particular implementations of finite element reference simplex geometry/topology.

Provides an abstract base class and particular implementations for the reference simplex geometry and topology. The rest of FIAT is abstracted over this module so that different reference element geometry (e.g. a vertex at (0,0) versus at (-1,-1)) and orderings of entities have a single point of entry.

Currently implemented are UFC and Default Line, Triangle and Tetrahedron.

class FIAT.reference_element.Cell (*shape, vertices, topology*)

Bases: `object`

Abstract class for a reference cell. Provides accessors for geometry (vertex coordinates) as well as topology (orderings of vertices that make up edges, faces, etc).

construct_subelement (*dimension*)

Constructs the reference element of a cell subentity specified by subelement dimension.

Parameters *dimension* – tuple for tensor product cells, *int* otherwise

get_connectivity ()

Returns a dictionary encoding the connectivity of the element.

The dictionary's keys are the spatial dimensions pairs ((1, 0), (2, 0), (2, 1), ...) and each value is a list with entities of second dimension ordered by local dim0-dim1 numbering.

get_dimension ()

Returns the subelement dimension of the cell. For tensor product cells, this a tuple of dimensions for each cell in the product. For all other cells, this is the same as the spatial dimension.

get_entity_transform (*dim, entity_i*)

Returns a mapping of point coordinates from the *entity_i*-th subentity of dimension *dim* to the cell.

Parameters

- *dim* – tuple for tensor product cells, *int* otherwise
- *entity_i* – entity number (integer)

get_shape ()

Returns the code for the element's shape.

get_spatial_dimension ()

Returns the spatial dimension in which the element lives.

get_topology ()

Returns a dictionary encoding the topology of the element.

The dictionary's keys are the spatial dimensions (0, 1, ...) and each value is a dictionary mapping.

get_vertices ()

Returns an iterable of the element's vertices, each stored as a tuple.

get_vertices_of_subcomplex (*t*)

Returns the tuple of vertex coordinates associated with the labels contained in the iterable *t*.

class FIAT.reference_element.DefaultLine

Bases: `FIAT.reference_element.Simplex`

This is the reference line with vertices (-1.0,) and (1.0,).

get_facet_element ()

class FIAT.reference_element.DefaultTetrahedron

Bases: `FIAT.reference_element.Simplex`

This is the reference tetrahedron with vertices (-1,-1,-1), (1,-1,-1),(-1,1,-1), and (-1,-1,1).

get_facet_element ()

class FIAT.reference_element.DefaultTriangle

Bases: `FIAT.reference_element.Simplex`

This is the reference triangle with vertices (-1.0,-1.0), (1.0,-1.0), and (-1.0,1.0).

`get_facet_element ()`

class `FIAT.reference_element.IntrepidTetrahedron`

Bases: `FIAT.reference_element.Simplex`

This is the reference tetrahedron with vertices (0,0,0), (1,0,0),(0,1,0), and (0,0,1) used in the Intrepid project.

`get_facet_element ()`

class `FIAT.reference_element.IntrepidTriangle`

Bases: `FIAT.reference_element.Simplex`

This is the Intrepid triangle with vertices (0,0),(1,0),(0,1)

`get_facet_element ()`

class `FIAT.reference_element.Point`

Bases: `FIAT.reference_element.Simplex`

This is the reference point.

construct_subelement (*dimension*)

Constructs the reference element of a cell subentity specified by subelement dimension.

Parameters *dimension* – subentity dimension (integer). Must be zero.

`FIAT.reference_element.ReferenceElement`

alias of `FIAT.reference_element.Simplex`

class `FIAT.reference_element.Simplex` (*shape, vertices, topology*)

Bases: `FIAT.reference_element.Cell`

Abstract class for a reference simplex.

compute_edge_tangent (*edge_i*)

Computes the nonnormalized tangent to a 1-dimensional facet. returns a single vector.

compute_face_edge_tangents (*dim, entity_id*)

Computes all the edge tangents of any k-face with $k \geq 1$. The result is a array of `binom(dim+1,2)` vectors. This agrees with `compute_edge_tangent` when $dim=1$.

compute_face_tangents (*face_i*)

Computes the two tangents to a face. Only implemented for a tetrahedron.

compute_normal (*facet_i*)

Returns the unit normal vector to facet *i* of codimension 1.

compute_normalized_edge_tangent (*edge_i*)

Computes the unit tangent vector to a 1-dimensional facet

compute_normalized_tangents (*dim, i*)

Computes tangents in any dimension based on differences between vertices and the first vertex of the *i*:th facet of dimension *dim*. Returns a (possibly empty) list. These tangents are normalized to have unit length.

compute_reference_normal (*facet_dim, facet_i*)

Returns the unit normal in infinity norm to *facet_i*.

compute_scaled_normal (*facet_i*)

Returns the unit normal to *facet_i* of scaled by the volume of that facet.

compute_tangents (*dim, i*)

Computes tangents in any dimension based on differences between vertices and the first vertex of the *i*:th

facet of dimension *dim*. Returns a (possibly empty) list. These tangents are *NOT* normalized to have unit length.

get_dimension ()

Returns the subelement dimension of the cell. Same as the spatial dimension.

get_entity_transform (*dim, entity*)

Returns a mapping of point coordinates from the *entity*-th subentity of dimension *dim* to the cell.

Parameters

- **dim** – subentity dimension (integer)
- **entity** – entity number (integer)

make_points (*dim, entity_id, order*)

Constructs a lattice of points on the *entity_id*:th facet of dimension *dim*. Order indicates how many points to include in each direction.

volume ()

Computes the volume of the simplex in the appropriate dimensional measure.

volume_of_subcomplex (*dim, facet_no*)

class FIAT.reference_element.**TensorProductCell** (**cells*)

Bases: *FIAT.reference_element.Cell*

A cell that is the product of FIAT cells.

compute_reference_normal (*facet_dim, facet_i*)

Returns the unit normal in infinity norm to *facet_i* of subelement dimension *facet_dim*.

construct_subelement (*dimension*)

Constructs the reference element of a cell subentity specified by subelement dimension.

Parameters **dimension** – dimension in each “direction” (tuple)

contains_point (*point, epsilon=0*)

Checks if reference cell contains given point (with numerical tolerance).

get_dimension ()

Returns the subelement dimension of the cell, a tuple of dimensions for each cell in the product.

get_entity_transform (*dim, entity_i*)

Returns a mapping of point coordinates from the *entity_i*-th subentity of dimension *dim* to the cell.

Parameters

- **dim** – subelement dimension (tuple)
- **entity_i** – entity number (integer)

volume ()

Computes the volume in the appropriate dimensional measure.

class FIAT.reference_element.**UFCHexahedron**

Bases: *FIAT.reference_element.Cell*

This is the reference hexahedron with vertices (0.0, 0.0, 0.0), (0.0, 0.0, 1.0), (0.0, 1.0, 0.0), (0.0, 1.0, 1.0), (1.0, 0.0, 0.0), (1.0, 0.0, 1.0), (1.0, 1.0, 0.0) and (1.0, 1.0, 1.0).

compute_reference_normal (*facet_dim, facet_i*)

Returns the unit normal in infinity norm to *facet_i*.

construct_subelement (*dimension*)

Constructs the reference element of a cell subentity specified by subelement dimension.

Parameters *dimension* – subentity dimension (integer)

contains_point (*point, epsilon=0*)

Checks if reference cell contains given point (with numerical tolerance).

get_dimension ()

Returns the subelement dimension of the cell. Same as the spatial dimension.

get_entity_transform (*dim, entity_i*)

Returns a mapping of point coordinates from the *entity_i*-th subentity of dimension *dim* to the cell.

Parameters

- **dim** – entity dimension (integer)
- **entity_i** – entity number (integer)

volume ()

Computes the volume in the appropriate dimensional measure.

class FIAT.reference_element.**UFCInterval**

Bases: *FIAT.reference_element.UFCSimplex*

This is the reference interval with vertices (0.0,) and (1.0,).

class FIAT.reference_element.**UFCQuadrilateral**

Bases: *FIAT.reference_element.Cell*

This is the reference quadrilateral with vertices (0.0, 0.0), (0.0, 1.0), (1.0, 0.0) and (1.0, 1.0).

compute_reference_normal (*facet_dim, facet_i*)

Returns the unit normal in infinity norm to *facet_i*.

construct_subelement (*dimension*)

Constructs the reference element of a cell subentity specified by subelement dimension.

Parameters *dimension* – subentity dimension (integer)

contains_point (*point, epsilon=0*)

Checks if reference cell contains given point (with numerical tolerance).

get_dimension ()

Returns the subelement dimension of the cell. Same as the spatial dimension.

get_entity_transform (*dim, entity_i*)

Returns a mapping of point coordinates from the *entity_i*-th subentity of dimension *dim* to the cell.

Parameters

- **dim** – entity dimension (integer)
- **entity_i** – entity number (integer)

volume ()

Computes the volume in the appropriate dimensional measure.

class FIAT.reference_element.**UFCSimplex** (*shape, vertices, topology*)

Bases: *FIAT.reference_element.Simplex*

construct_subelement (*dimension*)

Constructs the reference element of a cell subentity specified by subelement dimension.

Parameters *dimension* – subentity dimension (integer)

contains_point (*point, epsilon=0*)

Checks if reference cell contains given point (with numerical tolerance).

`get_facet_element ()`

class FIAT.reference_element.UFCTetrahedron

Bases: *FIAT.reference_element.UFCSimplex*

This is the reference tetrahedron with vertices (0,0,0), (1,0,0),(0,1,0), and (0,0,1).

compute_normal (*i*)

UFC consistent normals.

class FIAT.reference_element.UFCTriangle

Bases: *FIAT.reference_element.UFCSimplex*

This is the reference triangle with vertices (0.0,0.0), (1.0,0.0), and (0.0,1.0).

compute_normal (*i*)

UFC consistent normal

FIAT.reference_element.**compute_unflattening_map** (*topology_dict*)

This function returns unflattening map for the given tensor product topology dict.

FIAT.reference_element.**default_simplex** (*spatial_dim*)

Factory function that maps spatial dimension to an instance of the default reference simplex of that dimension.

FIAT.reference_element.**flatten_entities** (*topology_dict*)

This function flattens topology dict of TensorProductCell and entity_dofs dict of TensorProductElement

FIAT.reference_element.**flatten_reference_cube** (*ref_el*)

This function flattens a Tensor Product hypercube to the corresponding UFC hypercube

FIAT.reference_element.**is_hypercube** (*cell*)

FIAT.reference_element.**lattice_iter** (*start, finish, depth*)

Generator iterating over the depth-dimensional lattice of integers between start and (finish-1). This works on simplices in 1d, 2d, 3d, and beyond

FIAT.reference_element.**linalg_subspace_intersection** (*A, B*)

Computes the intersection of the subspaces spanned by the columns of 2-dimensional arrays A,B using the algorithm found in Golub and van Loan (3rd ed) p. 604. A should be in $\mathbb{R}^{\{m,p\}}$ and B should be in $\mathbb{R}^{\{m,q\}}$. Returns an orthonormal basis for the intersection of the spaces, stored in the columns of the result.

FIAT.reference_element.**make_affine_mapping** (*xs, ys*)

Constructs (A,b) such that $x \rightarrow A * x + b$ is the affine mapping from the simplex defined by xs to the simplex defined by ys.

FIAT.reference_element.**make_lattice** (*verts, n, interior=0*)

Constructs a lattice of points on the simplex defined by verts. For example, the 1:st order lattice will be just the vertices. The optional argument interior specifies how many points from the boundary to omit. For example, on a line with $n = 2$, and $interior = 0$, this function will return the vertices and midpoint, but with $interior = 1$, it will only return the midpoint.

FIAT.reference_element.**tuple_sum** (*tree*)

This function calculates the sum of elements in a tuple, it is needed to handle nested tuples in TensorProductCell. Example: `tuple_sum(((1, 0), 1))` returns 2 If input argument is not the tuple, returns input.

FIAT.reference_element.**ufc_cell** (*cell*)

Handle incoming calls from FFC.

FIAT.reference_element.**ufc_simplex** (*spatial_dim*)

Factory function that maps spatial dimension to an instance of the UFC reference simplex of that dimension.

FIAT.reference_element.**volume** (*verts*)

Constructs the volume of the simplex spanned by verts

1.3.46 FIAT.regge module

Implementation of the generalized Regge finite elements.

```
class FIAT.regge.Regge (cell, degree)  
    Bases: FIAT.finite_element.CiarletElement
```

The generalized Regge elements for symmetric-matrix-valued functions. $\text{REG}(r)$ in dimension n is the space of polynomial symmetric-matrix-valued functions of degree r or less with tangential-tangential continuity.

```
class FIAT.regge.ReggeDual (cell, degree)  
    Bases: FIAT.dual_set.DualSet
```

Degrees of freedom for generalized Regge finite elements.

1.3.47 FIAT.restricted module

```
class FIAT.restricted.RestrictedElement (element, indices=None, restric-  
                                           tion_domain=None)  
    Bases: FIAT.finite_element.CiarletElement
```

Restrict given element to specified list of dofs.

```
FIAT.restricted.sorted_by_key (mapping)  
    Sort dict items by key, allowing different key types.
```

1.3.48 FIAT.serendipity module

```
class FIAT.serendipity.Serendipity (ref_el, degree)  
    Bases: FIAT.finite_element.FiniteElement
```

```
degree ()
```

```
dmats ()
```

```
entity_closure_dofs ()
```

Return the map of topological entities to degrees of freedom on the closure of those entities for the finite element.

```
entity_dofs ()
```

Return the map of topological entities to degrees of freedom for the finite element.

```
get_coeffs ()
```

```
get_dual_set ()
```

Return the dual for the finite element.

```
get_nodal_basis ()
```

```
get_num_members (arg)
```

```
space_dimension ()
```

Return the dimension of the finite element space.

```
tabulate (order, points, entity=None)
```

Return tabulated values of derivatives up to given order of basis functions at given points.

Parameters

- **order** – The maximum order of derivative.
- **points** – An iterable of points.

- **entity** – Optional (dimension, entity number) pair indicating which topological entity of the reference element to tabulate on. If `None`, default cell-wise tabulation is performed.

value_shape ()

`FIAT.serendipity.e_lambda_0 (i, dim, dx, dy, dz, x_mid, y_mid, z_mid)`

`FIAT.serendipity.f_lambda_0 (i, dim, dx, dy, dz, x_mid, y_mid, z_mid)`

`FIAT.serendipity.i_lambda_0 (i, dx, dy, dz, x_mid, y_mid, z_mid)`

`FIAT.serendipity.tr (n)`

`FIAT.serendipity.unisolvent_pts (K, deg)`

`FIAT.serendipity.unisolvent_pts_hex (K, deg)`

Gives a set of unisolvent points for the hex serendipity space of order `deg`. The S element is not dual to these nodes, but a dual basis can be constructed from them.

`FIAT.serendipity.unisolvent_pts_quad (K, deg)`

Gives a set of unisolvent points for the quad serendipity space of order `deg`. The S element is not dual to these nodes, but a dual basis can be constructed from them.

`FIAT.serendipity.v_lambda_0 (dim, dx, dy, dz)`

1.3.49 FIAT.tensor_product module

class `FIAT.tensor_product.FlattenedDimensions (element)`

Bases: `FIAT.finite_element.FiniteElement`

A wrapper class that flattens entity dimensions of a FIAT element defined on a `TensorProductCell` to one with quadrilateral/hexahedron entities. `TensorProductCell` has dimension defined as a tuple of factor element dimensions (i, j) in 2D and (i, j, k) in 3D. Flattened dimension is a sum of the tuple elements.

degree ()

Return the degree of the (embedding) polynomial space.

dmats ()

Return dmats: expansion coefficients for basis function derivatives.

get_coeffs ()

Return the expansion coefficients for the basis of the finite element.

get_nodal_basis ()

Return the nodal basis, encoded as a `PolynomialSet` object, for the finite element.

get_num_members (arg)

Return number of members of the expansion set.

is_nodal ()

True if primal and dual bases are orthogonal. If false, dual basis is not implemented or is undefined.

Subclasses may not necessarily be nodal, unless it is a `CiarletElement`.

tabulate (order, points, entity=None)

Return tabulated values of derivatives up to given order of basis functions at given points.

value_shape ()

Return the value shape of the finite element functions.

class `FIAT.tensor_product.TensorProductElement (A, B)`

Bases: `FIAT.finite_element.FiniteElement`

Class implementing a finite element that is the tensor product of two existing finite elements.

degree ()
Return the degree of the (embedding) polynomial space.

dmats ()
Return dmats: expansion coefficients for basis function derivatives.

get_coeffs ()
Return the expansion coefficients for the basis of the finite element.

get_nodal_basis ()
Return the nodal basis, encoded as a PolynomialSet object, for the finite element.

get_num_members (*arg*)
Return number of members of the expansion set.

is_nodal ()
True if primal and dual bases are orthogonal. If false, dual basis is not implemented or is undefined.
Subclasses may not necessarily be nodal, unless it is a CiarletElement.

tabulate (*order, points, entity=None*)
Return tabulated values of derivatives up to given order of basis functions at given points.

value_shape ()
Return the value shape of the finite element functions.

1.3.50 Module contents

Finite element Automatic Tabulator – supports constructing and evaluating arbitrary order Lagrange and many other elements. Simplices in one, two, and three dimensions are supported.

1.4 Release notes

1.4.1 Changes in the next release

Summary of changes

- No changes yet.

Note: Developers should use this page to track and list changes during development. At the time of release, this page should be published (and renamed) to list the most important changes in the new release.

Detailed changes

Note: At the time of release, make a verbatim copy of the ChangeLog here (and remove this note).

1.4.2 Changes in version 2019.1.0

FIAT 2019.1.0 was released on 2019-04-17.

Summary of changes

- Added an implementation of the Bell finite element (K. Bell 1969 doi:10.1002/nme.1620010180), with extra basis functions for transformation theory from Kirby (2018) doi:10.5802/smai-jcm.33.

1.4.3 Changes in version 2018.1.0

FIAT 2018.1.0 was released on 2018-06-14.

Summary of changes

- Remove Python 2 support
- Generalize `Bubble` element to `CodimBubble` to create bubbles on entity of arbitrary codimension; add `FacetBubble`, keep `Bubble` (as bubble on cell)

1.4.4 Changes in version 2017.2.0

FIAT 2017.2.0 was released on 2017-12-05.

Summary of changes

- Add quadrilateral and hexahedron reference cells
- Add quadrilateral and hexahedron elements (with a wrapping class for `TensorProductElement`)

1.4.5 Changes in version 2017.1.0.post1

FIAT 2017.1.0.post1 was released on 2017-09-12.

Summary of changes

- Change PyPI package name to `fenics-fiat`.

1.4.6 Changes in version 2017.1.0

FIAT 2017.1.0 was released on 2017-05-09.

Summary of changes

- Extended the discontinuous trace element `HDivTrace` to support tensor product reference cells. Tabulating the trace defined on a tensor product cell relies on the argument `entity` to specify a facet of the cell. The backwards compatibility case `entity=None` does not support tensor product tabulation as a result. Tabulating the trace of triangles or tetrahedron remains unaffected and works as usual with or without an `entity` argument.

1.4.7 Changes in version 2016.2.0

FIAT 2016.2.0 was released on 2016-11-30.

Summary of changes

- More elegant edge-based degrees of freedom are used for generalized Regge finite elements. This is an internal change and is not visible to other parts of FEniCS.
- The name of the mapping for generalized Regge finite element is changed to “double covariant piola” from “pullback as metric”. Geometrically, this mapping is just the pullback of covariant 2-tensor fields in terms of proxy matrix-fields. Because the mapping for 1-forms in FEniCS is currently named “covariant piola”, this mapping for symmetric tensor product of 1-forms is thus called “double covariant piola”. This change causes multiple internal changes downstream in UFL and FFC. But this change should not be visible to the end-user.
- Added support for the Hellan-Herrmann-Johnson element (symmetric matrix fields with normal-normal continuity in 2D).
- Add method `FiniteElement.is_nodal()` for checking element nodality
- Add `NodalEnrichedElement` which merges dual bases (nodes) of given elements and orthogonalizes basis for nodality
- Restructuring `finite_element.py` with the addition of a non-nodal class `FiniteElement` and a nodal class `CiarletElement`. `FiniteElement` is designed to be used to create elements where, in general, a nodal basis isn’t well-defined. `CiarletElement` implements the usual nodal abstraction of a finite element.
- Removing `trace.py` and `trace_hdiv.py` with a new implementation of the trace element of an `HDiv`-conforming element: `HDivTrace`. It is also mathematically equivalent to the former `DiscontinuousLagrangeTrace`, that is, the DG field defined only on co-dimension 1 entities.
- All nodal finite elements inherit from `CiarletElement`, and the non-nodal `TensorProductElement`, `EnrichedElement` and `HDivTrace` inherit from `FiniteElement`.

Detailed changes

- Enable Travis CI on GitHub
- Add Firedrake quadrilateral cell
- Add tensor product cell
- Add facet -> cell coordinate transformation
- Add Bubble element
- Add discontinuous Taylor element
- Add broken element and $H(\text{div})$ trace element
- Add element restrictions onto mesh entities
- Add tensor product elements (for tensor product cells)
- Add $H(\text{div})$ and $H(\text{curl})$ element-modifiers for TPEs
- Add enriched element, i.e. sum of elements (e.g. for building Mini)
- Add multidimensional Taylor elements
- Add Gauss Lobatto Legendre elements
- Finding non-vanishing DoFs on a facets
- Add tensor product quadrature rule
- Make regression tests working again after few years

- Prune modules having only `__main__` code including `transform_morley`, `transform_hermit` (ff86250820e2b18f7a0df471c97afa87207e9a7d)
- Remove `newdubiner` module (b3b120d40748961fdd0727a4e6c62450198d9647, reference removed by cb65a84ac639977b7be04962cc1351481ca66124)
- Switch from `homebrew factorial/gamma` to `math` module (wraps C std lib)

1.4.8 Changes in version 2016.1.0

FIAT 2016.1.0 was released on 2016-06-23.

- Minor fixes

1.4.9 Changes in version 1.6.0

FIAT 1.6.0 was released on 2015-07-28.

- Support DG on facets through the element `Discontinuous Lagrange Trace`

[FIXME: These links don't belong here, should go under API reference somehow.]

- [genindex](#)
- [modindex](#)

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