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This module implements points in hyperbolic space of arbitrary dimension. It also contains the implementations for specific models of hyperbolic geometry.

This module also implements ideal points in hyperbolic space of arbitrary dimension. It also contains the implementations for specific models of hyperbolic geometry.

Note that not all models of hyperbolic space are bounded, meaning that the ideal boundary is not the topological boundary of the set underlying the model. For example, the unit disk model is bounded with boundary given by the unit sphere. The hyperboloid model is not bounded.

AUTHORS:

• Greg Laun (2013): initial version

EXAMPLES:

We can construct points in the upper half plane model, abbreviated UHP for convenience:

```
sage: UHP = HyperbolicPlane().UHP()
sage: UHP.get_point(2 + I)
Point in UHP I + 2
sage: g = UHP.get_point(3 + I)
sage: g.dist(UHP.get_point(I))
arccosh(11/2)
```

We can also construct boundary points in the upper half plane model:

```
sage: UHP.get_point(3)
Boundary point in UHP 3
```

Some more examples:

```
sage: HyperbolicPlane().UHP().get_point(0)
Boundary point in UHP 0
sage: HyperbolicPlane().PD().get_point(I/2)
Point in PD 1/2*I
sage: HyperbolicPlane().KM().get_point((0,1))
Boundary point in KM (0, 1)
sage: HyperbolicPlane().HM().get_point((0,0,1))
Point in HM (0, 0, 1)
```
class sage.geometry.hyperbolic_space.hyperbolic_point.HyperbolicPoint(model, coordinates, is_boundary, check=True, **graphics_options)

Bases: Element

Abstract base class for hyperbolic points. This class should never be instantiated.

INPUT:

• model – the model of the hyperbolic space

• coordinates – the coordinates of a hyperbolic point in the appropriate model

• is_boundary – whether the point is a boundary point

• check – (default: True) if True, then check to make sure the coordinates give a valid point in the model

EXAMPLES:

Comparison between different models is performed via coercion:

```
sage: UHP = HyperbolicPlane().UHP()
sage: p = UHP.get_point(.2 + .3*I); p
Point in UHP 0.200000000000000 + 0.300000000000000*I

sage: PD = HyperbolicPlane().PD()
sage: q = PD.get_point(0.2 + 0.3*I); q
Point in PD 0.200000000000000 + 0.300000000000000*I

sage: p == q
False
sage: PD(p)
Point in PD 0.231213872832370 - 0.502890173410405*I

sage: bool(p.coordinates() == q.coordinates())
True
```

Similarly for boundary points:

```
sage: p = UHP.get_point(-1); p
Boundary point in UHP -1

sage: q = PD.get_point(-1); q
Boundary point in PD -1

sage: p == q
True
sage: PD(p)
Boundary point in PD -1
```

It is an error to specify a point that does not lie in the appropriate model:

```
sage: HyperbolicPlane().UHP().get_point(0.2 - 0.3*I)
Traceback (most recent call last):
  ...
ValueError: 0.200000000000000 - 0.300000000000000*I is not a valid point in the UHP.
```
model

sage: HyperbolicPlane().PD().get_point(1.2)
Traceback (most recent call last):
  ...  
ValueError: 1.20000000000000 is not a valid point in the PD model

sage: HyperbolicPlane().KM().get_point((1,1))
Traceback (most recent call last):
  ...  
ValueError: (1, 1) is not a valid point in the KM model

sage: HyperbolicPlane().HM().get_point((1, 1, 1))
Traceback (most recent call last):
  ...  
ValueError: (1, 1, 1) is not a valid point in the HM model

It is an error to specify an interior point of hyperbolic space as a boundary point:

sage: HyperbolicPlane().UHP().get_point(0.2 + 0.3*I, is_boundary=True)
Traceback (most recent call last):
  ...  
ValueError: 0.200000000000000 + 0.300000000000000*I is not a valid boundary point in the UHP model

coordinates()

Return the coordinates of the point.

EXAMPLES:

sage: HyperbolicPlane().UHP().get_point(2 + I).coordinates()
I + 2

sage: HyperbolicPlane().PD().get_point(1/2 + 1/2*I).coordinates()
1/2*I + 1/2

sage: HyperbolicPlane().KM().get_point((1/3, 1/4)).coordinates()
(1/3, 1/4)

sage: HyperbolicPlane().HM().get_point((0,0,1)).coordinates()
(0, 0, 1)

graphics_options()

Return the graphics options of the current point.

EXAMPLES:

sage: p = HyperbolicPlane().UHP().get_point(2 + I, color="red")
sage: p.graphics_options()
{'color': 'red'}

is_boundary()

Return True if self is a boundary point.
EXAMPLES:

```sage
sage: PD = HyperbolicPlane().PD()
sage: p = PD.get_point(0.5+.2*I)
sage: p.is_boundary()
False
sage: p = PD.get_point(I)
sage: p.is_boundary()
True
```

**model()**

Return the model to which the *HyperbolicPoint* belongs.

EXAMPLES:

```sage
sage: HyperbolicPlane().UHP().get_point(I).model()
Hyperbolic plane in the Upper Half Plane Model
sage: HyperbolicPlane().PD().get_point(0).model()
Hyperbolic plane in the Poincare Disk Model
sage: HyperbolicPlane().KM().get_point((0,0)).model()
Hyperbolic plane in the Klein Disk Model
sage: HyperbolicPlane().HM().get_point((0,0,1)).model()
Hyperbolic plane in the Hyperboloid Model
```

**show**(boundary=True, **options)**

Plot self.

EXAMPLES:

```sage
sage: HyperbolicPlane().PD().get_point(0).show()
Graphics object consisting of 2 graphics primitives
sage: HyperbolicPlane().KM().get_point((0,0)).show()
Graphics object consisting of 2 graphics primitives
sage: HyperbolicPlane().HM().get_point((0,0,1)).show()
Graphics3d Object
```

**symmetry_involution()**

Return the involutory isometry fixing the given point.

EXAMPLES:

```sage
sage: z = HyperbolicPlane().UHP().get_point(3 + 2*I)
sage: z.symmetry_involution()
Isometry in UHP
\[
\begin{bmatrix}
\frac{3}{2} & -\frac{13}{2} \\
\frac{1}{2} & -\frac{3}{2}
\end{bmatrix}
\]
sage: HyperbolicPlane().UHP().get_point(I).symmetry_involution()
Isometry in UHP
\[
\begin{bmatrix}
0 & -1 \\
1 & 0
\end{bmatrix}
\]
```
sage: HyperbolicPlane().PD().get_point(0).symmetry_involution()
Isometry in PD
[-I 0]
[ 0 I]

sage: HyperbolicPlane().KM().get_point((0, 0)).symmetry_involution()
Isometry in KM
[-1 0 0]
[ 0 -1 0]
[ 0 0 1]

sage: HyperbolicPlane().HM().get_point((0,0,1)).symmetry_involution()
Isometry in HM
[-1 0 0]
[ 0 -1 0]
[ 0 0 1]

sage: p = HyperbolicPlane().UHP().random_element()
sage: A = p.symmetry_involution()
sage: p.dist(A*p)  # abs tol 1e-10
0

sage: A.preserves_orientation()
True

sage: A*A == HyperbolicPlane().UHP().get_isometry(identity_matrix(2))
True

to_model(model)
Convert self to the model.

INPUT:

• other – (a string representing) the image model

EXAMPLES:

sage: UHP = HyperbolicPlane().UHP()
sage: PD = HyperbolicPlane().PD()
sage: PD.get_point(1/2+I/2).to_model(UHP)
Point in UHP I + 2

sage: PD.get_point(1/2+I/2).to_model('UHP')
Point in UHP I + 2

update_graphics(update=False, **options)
Update the graphics options of a HyperbolicPoint. If update is True, update rather than overwrite.

EXAMPLES:

sage: p = HyperbolicPlane().UHP().get_point(I); p.graphics_options()
{}

sage: p.update_graphics(color = "red"); p.graphics_options()
{"color": 'red'}
class sage.geometry.hyperbolic_space.hyperbolic_point.HyperbolicPointUHP(model, coordinates, is_boundary, check=True, **graphics_options)

Bases: HyperbolicPoint

A point in the UHP model.

INPUT:

• the coordinates of a point in the unit disk in the complex plane \( \mathbb{C} \)

EXAMPLES:

```
sage: HyperbolicPlane().UHP().get_point(2*I)
Point in UHP 2*I

sage: HyperbolicPlane().UHP().get_point(1)
Boundary point in UHP 1
```

show(boundary=True, **options)

Plot self.

EXAMPLES:

```
sage: HyperbolicPlane().UHP().get_point(I).show()
Graphics object consisting of 2 graphics primitives

sage: HyperbolicPlane().UHP().get_point(0).show()
Graphics object consisting of 2 graphics primitives

sage: HyperbolicPlane().UHP().get_point(infinity).show()
Traceback (most recent call last):
... NotImplementedError: can't draw the point infinity
```

symmetry_involution()

Return the involutory isometry fixing the given point.

EXAMPLES:

```
sage: HyperbolicPlane().UHP().get_point(3 + 2*I).symmetry_involution()
Isometry in UHP
[  3/2  -13/2]
[  1/2   -3/2]
```
Chapter Two

Hyperbolic Isometries

This module implements the abstract base class for isometries of hyperbolic space of arbitrary dimension. It also contains the implementations for specific models of hyperbolic geometry.

The isometry groups of all implemented models are either matrix Lie groups or are doubly covered by matrix Lie groups. As such, the isometry constructor takes a matrix as input. However, since the isometries themselves may not be matrices, quantities like the trace and determinant are not directly accessible from this class.

Authors:

- Greg Laun (2013): initial version

Examples:

We can construct isometries in the upper half plane model, abbreviated UHP for convenience:

```python
sage: UHP = HyperbolicPlane().UHP()
sage: UHP.get_isometry(matrix(2,[1,2,3,4]))
Isometry in UHP
[1 2]
[3 4]
sage: A = UHP.get_isometry(matrix(2,[0,1,1,0]))
sage: A.inverse()
Isometry in UHP
[0 1]
[1 0]
```

Class `sage.geometry.hyperbolic_space.hyperbolic_isometry.HyperbolicIsometry(model, A, check=True)`

Bases: `Morphism`

Abstract base class for hyperbolic isometries. This class should never be instantiated.

Input:

- A – a matrix representing a hyperbolic isometry in the appropriate model

Examples:

```python
sage: HyperbolicPlane().HM().get_isometry(identity_matrix(3))
Isometry in HM
[1 0 0]
[0 1 0]
[0 0 1]
```
**attracting_fixed_point()**

For a hyperbolic isometry, return the attracting fixed point; otherwise raise a `ValueError`.

OUTPUT:

* a hyperbolic point

EXAMPLES:

```sage
sage: UHP = HyperbolicPlane().UHP()
sage: A = UHP.get_isometry(matrix(2, [4, 0, 0, 1/4]))
sage: A.attracting_fixed_point()
Boundary point in UHP +Infinity
```

**axis()**

For a hyperbolic isometry, return the axis of the transformation; otherwise raise a `ValueError`.

EXAMPLES:

```sage
sage: UHP = HyperbolicPlane().UHP()
sage: H = UHP.get_isometry(matrix(2, [2, 0, 0, 1/2]))
sage: H.axis()
Geodesic in UHP from 0 to +Infinity
```

It is an error to call this function on an isometry that is not hyperbolic:

```sage
sage: P = UHP.get_isometry(matrix(2, [1, 4, 0, 1]))
sage: P.axis()
Traceback (most recent call last):
...
ValueError: the isometry is not hyperbolic: axis is undefined
```

**classification()**

Classify the hyperbolic isometry as elliptic, parabolic, hyperbolic or a reflection.

A hyperbolic isometry fixes two points on the boundary of hyperbolic space, a parabolic isometry fixes one point on the boundary of hyperbolic space, and an elliptic isometry fixes no points.

EXAMPLES:

```sage
sage: UHP = HyperbolicPlane().UHP()
sage: H = UHP.get_isometry(matrix(2, [2, 0, 0, 1/2]))
sage: H.classification()
'hyperbolic'
sage: P = UHP.get_isometry(matrix(2, [1, 1, 0, 1]))
sage: P.classification()
'parabolic'
sage: E = UHP.get_isometry(matrix(2, [-1, 0, 0, 1]))
sage: E.classification()
'reflection'
```

**fixed_geodesic()**

If self is a reflection in a geodesic, return that geodesic.

EXAMPLES:
sage: A = HyperbolicPlane().PD().get_isometry(matrix([[0, 1], [1, 0]]))
sage: A.fixed_geodesic()
Geodesic in PD from -1 to 1

fixed_point_set()

Return a list containing the fixed point set of orientation-preserving isometries.

OUTPUT:
list of hyperbolic points or a hyperbolic geodesic

EXAMPLES:

sage: KM = HyperbolicPlane().KM()
sage: H = KM.get_isometry(matrix([[5/3,0,4/3], [0,1,0], [4/3,0,5/3]]))
sage: g = H.fixed_point_set(); g
Geodesic in KM from (1, 0) to (-1, 0)
sage: H(g.start()) == g.start()
True
sage: H(g.end()) == g.end()
True
sage: A = KM.get_isometry(matrix([[1,0,0], [0,-1,0], [0,0,1]]))
sage: A.preserves_orientation()
False
sage: A.fixed_point_set()
Geodesic in KM from (1, 0) to (-1, 0)

sage: B = KM.get_isometry(identity_matrix(3))
sage: B.fixed_point_set()
Traceback (most recent call last):
...  
ValueError: the identity transformation fixes the entire hyperbolic plane

is_identity()

Return True if self is the identity isometry.

EXAMPLES:

sage: UHP = HyperbolicPlane().UHP()
sage: UHP.get_isometry(matrix(2,[4,1,3,2])).is_identity()
False
sage: UHP.get_isometry(identity_matrix(2)).is_identity()
True

matrix()

Return the matrix of the isometry.

Note: We do not allow the matrix constructor to work as these may be elements of a projective group (ex. $PSL(n, \mathbb{R})$), so these isometries aren’t true matrices.

EXAMPLES:
model()

Return the model to which self belongs.

EXAMPLES:

\[
\text{sage: HyperbolicPlane().UHP().get_isometry(identity_matrix(2)).model()}
\]
Hyperbolic plane in the Upper Half Plane Model

\[
\text{sage: HyperbolicPlane().PD().get_isometry(identity_matrix(2)).model()}
\]
Hyperbolic plane in the Poincare Disk Model

\[
\text{sage: HyperbolicPlane().KM().get_isometry(identity_matrix(3)).model()}
\]
Hyperbolic plane in the Klein Disk Model

\[
\text{sage: HyperbolicPlane().HM().get_isometry(identity_matrix(3)).model()}
\]
Hyperbolic plane in the Hyperboloid Model

preserves_orientation()

Return True if self is orientation-preserving and False otherwise.

EXAMPLES:

\[
\text{sage: UHP = HyperbolicPlane().UHP()}
\text{sage: A = UHP.get_isometry(identity_matrix(2))}
\text{sage: A.preserves_orientation()}
\]
True

\[
\text{sage: B = UHP.get_isometry(matrix(2, 1, 0, 0, 1/0))}
\text{sage: B.preserves_orientation()}
\]
False

repelling_fixed_point()

For a hyperbolic isometry, return the attracting fixed point; otherwise raise a ValueError.

OUTPUT:

• a hyperbolic point

EXAMPLES:

\[
\text{sage: UHP = HyperbolicPlane().UHP()}
\text{sage: A = UHP.get_isometry(Mat(2, 1, 0, 0, 1/0))}
\text{sage: A.repelling_fixed_point()}
\]
Boundary point in UHP 0

to_model(other)

Convert the current object to image in another model.

INPUT:

• other – (a string representing) the image model

EXAMPLES:
For hyperbolic elements, return the translation length; otherwise, raise a `ValueError`.

EXAMPLES:
Hyperbolic Geometry, Release 10.2

```python
sage: UHP = HyperbolicPlane().UHP()
sage: H = UHP.get_isometry(matrix(2,[2,0,0,1/2]))
sage: H.translation_length()
2*arccosh(5/4)

sage: f_1 = UHP.get_point(-1)
sage: f_2 = UHP.get_point(1)
sage: H = UHP.isometry_from_fixed_points(f_1, f_2)
sage: p = UHP.get_point(exp(i*7*pi/8))
sage: bool((p.dist(H*p) - H.translation_length()) < 10**-9)
True
```

class sage.geometry.hyperbolic_space.hyperbolic_isometry.HyperbolicIsometryKM(model, A, check=True)

Bases: HyperbolicIsometry

Create a hyperbolic isometry in the KM model.

INPUT:

• a matrix in $SO(2,1)$

EXAMPLES:

```python
sage: HyperbolicPlane().KM().get_isometry(identity_matrix(3))
Isometry in KM
[1 0 0]
[0 1 0]
[0 0 1]
```

class sage.geometry.hyperbolic_space.hyperbolic_isometry.HyperbolicIsometryPD(model, A, check=True)

Bases: HyperbolicIsometry

Create a hyperbolic isometry in the PD model.

INPUT:

• a matrix in $PU(1,1)$

EXAMPLES:

```python
sage: HyperbolicPlane().PD().get_isometry(identity_matrix(2))
Isometry in PD
[1 0]
[0 1]
```

`preserves_orientation()`

Return True if self preserves orientation and False otherwise.

EXAMPLES:

```python
sage: PD = HyperbolicPlane().PD()
sage: PD.get_isometry(matrix([-I, 0], [0, I])).preserves_orientation()
True
sage: PD.get_isometry(matrix([[0, I], [I, 0]])).preserves_orientation()
False
```
class sage.geometry.hyperbolic_space.hyperbolic_isometry.HyperbolicIsometryUHP(model, A, check=True)

Bases: HyperbolicIsometry

Create a hyperbolic isometry in the UHP model.

INPUT:
  • a matrix in \( GL(2, \mathbb{R}) \)

EXAMPLES:

```python
sage: HyperbolicPlane().UHP().get_isometry(identity_matrix(2))
Isometry in UHP
[[1 0]
 [0 1]]
```

attracting_fixed_point()

Return the attracting fixed point; otherwise raise a ValueError.

OUTPUT:
  • a hyperbolic point

EXAMPLES:

```python
sage: UHP = HyperbolicPlane().UHP()
sage: A = matrix(2, [4, 0, 0, 1/4])
sage: UHP.get_isometry(A).attracting_fixed_point()
Boundary point in UHP +Infinity
```

classification()

Classify the hyperbolic isometry as elliptic, parabolic, or hyperbolic.

A hyperbolic isometry fixes two points on the boundary of hyperbolic space, a parabolic isometry fixes one point on the boundary of hyperbolic space, and an elliptic isometry fixes no points.

EXAMPLES:

```python
sage: UHP = HyperbolicPlane().UHP()
sage: UHP.get_isometry(identity_matrix(2)).classification()  # 'identity'
sage: UHP.get_isometry(4*identity_matrix(2)).classification()  # 'identity'
sage: UHP.get_isometry(matrix(2, [2, 0, 0, 1/2])).classification()  # 'hyperbolic'
sage: UHP.get_isometry(matrix(2, [0, 3, -1/3, 6])).classification()  # 'hyperbolic'
sage: UHP.get_isometry(matrix(2, [1, 1, 0, 1])).classification()  # 'parabolic'
sage: UHP.get_isometry(matrix(2, [-1, 0, 0, 1])).classification()  # 'reflection'
```
fixed_point_set()

Return a list or geodesic containing the fixed point set of orientation-preserving isometries.

OUTPUT:

list of hyperbolic points or a hyperbolic geodesic

EXAMPLES:

```
sage: UHP = HyperbolicPlane().UHP()
sage: H = UHP.get_isometry(matrix(2, [-2/3,-1/3,-1/3,-2/3]))
sage: g = H.fixed_point_set(); g
Geodesic in UHP from -1 to 1
sage: H(g.start()) == g.start()
True
sage: H(g.end()) == g.end()
True
sage: A = UHP.get_isometry(matrix(2,[0,1,1,0]))
sage: A.preserves_orientation()
False
sage: A.fixed_point_set()
Geodesic in UHP from 1 to -1
```

preserves_orientation()

Return True if self is orientation-preserving and False otherwise.

EXAMPLES:

```
sage: UHP = HyperbolicPlane().UHP()
sage: A = identity_matrix(2)
sage: UHP.get_isometry(A).preserves_orientation()
True
sage: B = matrix(2,[0,1,1,0])
sage: UHP.get_isometry(B).preserves_orientation()
False
```

repelling_fixed_point()

Return the repelling fixed point; otherwise raise a ValueError.

OUTPUT:

• a hyperbolic point

EXAMPLES:

```
sage: UHP = HyperbolicPlane().UHP()
sage: A = matrix(2,[4,0,0,1/4])
sage: UHP.get_isometry(A).repelling_fixed_point()
Boundary point in UHP 0
```
**translation_length()**

For hyperbolic elements, return the translation length; otherwise, raise a `ValueError`.

**EXAMPLES:**

```python
sage: UHP = HyperbolicPlane().UHP()
sage: UHP.get_isometry(matrix(2,[2,0,0,1/2])).translation_length()
2*arccosh(5/4)
```

```python
sage: H = UHP.isometry_from_fixed_points(-1,1)
sage: p = UHP.get_point(exp(i*7*pi/8))
sage: Hp = H(p)
sage: bool((UHP.dist(p, Hp) - H.translation_length()) < 10**-9)
True
```

**sage.geometry.hyperbolic_space.hyperbolic_isometry.moebius_transform(A, z)**

Given a matrix $A$ in $GL(2, \mathbb{C})$ and a point $z$ in the complex plane return the Möbius transformation action of $A$ on $z$.

**INPUT:**

- $A$ – a $2 \times 2$ invertible matrix over the complex numbers
- $z$ – a complex number or infinity

**OUTPUT:**

- a complex number or infinity

**EXAMPLES:**

```python
sage: from sage.geometry.hyperbolic_space.hyperbolic_model import moebius_transform
sage: moebius_transform(matrix(2,[1,2,3,4]),2 + I)
-2/109*I + 43/109
sage: y = var('y')
sage: moebius_transform(matrix(2,[1,0,0,1]),x + I*y)
x + I*y
```

The matrix must be square and $2 \times 2$:

```python
sage: moebius_transform(matrix([[3,1,2],[1,2,5]]),I)
Traceback (most recent call last):
  ... TypeError: A must be an invertible 2x2 matrix over the complex numbers or a
  symbolic ring
```

```python
sage: moebius_transform(identity_matrix(3),I)
Traceback (most recent call last):
  ... TypeError: A must be an invertible 2x2 matrix over the complex numbers or a
  symbolic ring
```

The matrix can be symbolic or can be a matrix over the real or complex numbers, but must be provably invertible:

```python
sage: a,b,c,d = var('a,b,c,d')
sage: moebius_transform(matrix(2,[a,b,c,d]),I)
(I*a + b)/(I*c + d)
```
sage: moebius_transform(matrix(2,[1,b,c,b*c+1]),I)
\frac{(b + I)}{(b*c + I*c + 1)}
sage: moebius_transform(matrix(2,[0,0,0,0]),I)
Traceback (most recent call last):
...
TypeError: A must be an invertible 2x2 matrix over the complex numbers or a
symbolic ring
CHAPTER
THREE

HYPERBOLIC GEODESICS

This module implements the abstract base class for geodesics in hyperbolic space of arbitrary dimension. It also contains the implementations for specific models of hyperbolic geometry.

AUTHORS:

• Greg Laun (2013): initial version

EXAMPLES:

We can construct geodesics in the upper half plane model, abbreviated UHP for convenience:

```
sage: g = HyperbolicPlane().UHP().get_geodesic(2, 3)
sage: g
Geodesic in UHP from 2 to 3
```

This geodesic can be plotted using `plot()`, in this example we will show the axis.

```
sage: g.plot(axes=True)  # needs sage.plot
Graphics object consisting of 2 graphics primitives
```

```
sage: g = HyperbolicPlane().UHP().get_geodesic(I, 3 + I)
sage: g.length()
arccosh(11/2)
sage: g.plot(axes=True)  # needs sage.plot
Graphics object consisting of 2 graphics primitives
```

Geodesics of both types in UHP are supported:

```
sage: g = HyperbolicPlane().UHP().get_geodesic(I, 3*I)
sage: g
Geodesic in UHP from I to 3*I
sage: g.plot()  # needs sage.plot
Graphics object consisting of 2 graphics primitives
```

Geodesics are oriented, which means that two geodesics with the same graph will only be equal if their starting and ending points are the same:

```
sage: g1 = HyperbolicPlane().UHP().get_geodesic(1,2)
sage: g2 = HyperbolicPlane().UHP().get_geodesic(2,1)
```

(continues on next page)
Todo: Implement a parent for all geodesics of the hyperbolic plane? Or implement geodesics as a parent in the subobjects category?

```python
sage: g1 == g2
False
```

```python
class sage.geometry.hyperbolic_space.hyperbolic_geodesic.HyperbolicGeodesic(model, start, end, **graphics_options)

Bases: sageobject

Abstract base class for oriented geodesics that are not necessarily complete.

INPUT:

• start – a HyperbolicPoint or coordinates of a point in hyperbolic space representing the start of the geodesic
• end – a HyperbolicPoint or coordinates of a point in hyperbolic space representing the end of the geodesic

EXAMPLES:

We can construct a hyperbolic geodesic in any model:

```python
sage: HyperbolicPlane().UHP().get_geodesic(1, 0)
Geodesic in UHP from 1 to 0
sage: HyperbolicPlane().PD().get_geodesic(1, 0)
Geodesic in PD from 1 to 0
sage: HyperbolicPlane().KM().get_geodesic((0,1/2), (1/2, 0))
Geodesic in KM from (0, 1/2) to (1/2, 0)
sage: HyperbolicPlane().HM().get_geodesic((0,0,1), (0,1, sqrt(2))
Geodesic in HM from (0, 0, 1) to (0, 1, sqrt(2))
```

angle(other)
Return the angle between any two given geodesics if they intersect.

INPUT:

• other – a hyperbolic geodesic in the same model as self

OUTPUT:

• the angle in radians between the two given geodesics

EXAMPLES:

```python
sage: PD = HyperbolicPlane().PD()
sage: g = PD.get_geodesic(3/5*I + 4/5, 15/17*I + 8/17)
sage: h = PD.get_geodesic(4/5*I + 3/5, I)
sage: g.angle(h)
1/2*pi
```

common_perpendicular(other)
Return the unique hyperbolic geodesic perpendicular to two given geodesics, if such a geodesic exists. If none exists, raise a ValueError.

INPUT:
Chapter 3. Hyperbolic Geodesics
• other – a hyperbolic geodesic in the same model as self

OUTPUT:
• a hyperbolic geodesic

EXAMPLES:

```sage
sage: g = HyperbolicPlane().UHP().get_geodesic(2,3)
sage: h = HyperbolicPlane().UHP().get_geodesic(4,5)
sage: g.common_perpendicular(h)
Geodesic in UHP from 1/2*sqrt(3) + 7/2 to -1/2*sqrt(3) + 7/2
```

It is an error to ask for the common perpendicular of two intersecting geodesics:

```sage
sage: g = HyperbolicPlane().UHP().get_geodesic(2,4)
sage: h = HyperbolicPlane().UHP().get_geodesic(3, infinity)
sage: g.common_perpendicular(h)
Traceback (most recent call last):
...
ValueError: geodesics intersect; no common perpendicular exists
```

complete()

Return the geodesic with ideal endpoints in bounded models. Raise a `NotImplementedError` in models that are not bounded. In the following examples we represent complete geodesics by a dashed line.
EXAMPLES:

```python
sage: H = HyperbolicPlane()
sage: UHP = H.UHP()
sage: UHP.get_geodesic(1 + I, 1 + 3*I).complete()
Geodesic in UHP from 1 to +Infinity
```

```python
sage: PD = H.PD()
sage: PD.get_geodesic(0, I/2).complete()
Geodesic in PD from -I to I
sage: PD.get_geodesic(0.25*(-1-I),0.25*(1-I)).complete()
Geodesic in PD from -0.895806416477617 - 0.444444444444444*I to 0.
```

```python
sage: KM = H.KM()
sage: KM.get_geodesic((0,0), (0,1/2)).complete()
Geodesic in KM from (0, -1) to (0, 1)
sage: KM.get_geodesic(-I, 1).complete()
Geodesic in KM from -I to 1
```

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sage: HM = H.HM()
sage: HM.get_geodesic((0,0,1), (1, 0, sqrt(2))).complete()
Geodesic in HM from (0, 0, 1) to (1, 0, sqrt(2))

sage: g = HM.get_geodesic((0,0,1), (1, 0, sqrt(2))).complete()
sage: g.is_complete()
True

dist(other)
Return the hyperbolic distance from a given hyperbolic geodesic to another geodesic or point.

INPUT:
• other – a hyperbolic geodesic or hyperbolic point in the same model

OUTPUT:
• the hyperbolic distance

EXAMPLES:

sage: g = HyperbolicPlane().UHP().get_geodesic(2, 4.0)
sage: h = HyperbolicPlane().UHP().get_geodesic(5, 7.0)
sage: bool(abs(g.dist(h).n() - 1.92484730023841) < 10**-9)
True
If the second object is a geodesic ultraparallel to the first, or if it is a point on the boundary that is not one of the first object’s endpoints, then return +infinity

```
sage: g = HyperbolicPlane().UHP().get_geodesic(2, 2+I)
sage: p = HyperbolicPlane().UHP().get_point(5)
sage: g.dist(p)
+Infinity
```

end()

Return the starting point of the geodesic.

EXAMPLES:

```
sage: g = HyperbolicPlane().UHP().get_geodesic(I, 3*I)
sage: g.end()
Point in UHP 3*I
```

distance()

Return a list containing the start and endpoints.

EXAMPLES:

```
sage: g = HyperbolicPlane().UHP().get_geodesic(I, 3*I)
sage: g.endpoints()
[Point in UHP I, Point in UHP 3*I]
```

graphics_options()

Return the graphics options of self.

EXAMPLES:

```
sage: g = HyperbolicPlane().UHP().get_geodesic(I, 3*I, color="red")
sage: g.graphics_options()
{'color': 'red'}
```

ideal_endpoints()

Return the ideal endpoints in bounded models. Raise a NotImplementedError in models that are not bounded.

EXAMPLES:

```
sage: H = HyperbolicPlane()
sage: UHP = H.UHP()
sage: UHP.get_geodesic(1 + I, 1 + 3*I).ideal_endpoints()
[Boundary point in UHP 1, Boundary point in UHP +Infinity]
sage: PD = H.PD()
sage: PD.get_geodesic(0, I/2).ideal_endpoints()
[Boundary point in PD -I, Boundary point in PD I]
sage: KM = H.KM()
sage: KM.get_geodesic((0,0), (0, 1/2)).ideal_endpoints()
[Boundary point in KM (0, -1), Boundary point in KM (0, 1)]
sage: HM = H.HM()
```

(continues on next page)
intersection(\texttt{other})

Return the point of intersection of two geodesics (if such a point exists).

**INPUT:**

- \texttt{other} – a hyperbolic geodesic in the same model as \texttt{self}

**OUTPUT:**

- a hyperbolic point or geodesic

**EXAMPLES:**

```python
sage: PD = HyperbolicPlane().PD()
```

is\_asymptotically\_parallel(\texttt{other})

Return True if \texttt{self} and \texttt{other} are asymptotically parallel and False otherwise.

**INPUT:**

- \texttt{other} – a hyperbolic geodesic

**EXAMPLES:**

```python
sage: g = HyperbolicPlane().UHP().get_geodesic(-2,5)
sage: h = HyperbolicPlane().UHP().get_geodesic(-2,4)
sage: g.is_asymptotically_parallel(h)
True
```

Ultraparallel geodesics are not asymptotically parallel:

```python
sage: g = HyperbolicPlane().UHP().get_geodesic(-2,5)
sage: h = HyperbolicPlane().UHP().get_geodesic(-1,4)
sage: g.is_asymptotically_parallel(h)
False
```

No hyperbolic geodesic is asymptotically parallel to itself:

```python
g = HyperbolicPlane().UHP().get_geodesic(-2,5)
sage: g.is_asymptotically_parallel(g)
False
```

is\_complete()

Return True if \texttt{self} is a complete geodesic (that is, both endpoints are on the ideal boundary) and False otherwise.

If we represent complete geodesics using green color and incomplete using red colors we have the following graphic:

Notice, that there is no visual indication that the vertical geodesic is complete

**EXAMPLES:**
is_parallel(\texttt{other})
Return True if the two given hyperbolic geodesics are either ultra parallel or asymptotically parallel and False otherwise.

**INPUT:**
- \texttt{other} – a hyperbolic geodesic in any model

**OUTPUT:**
True if the given geodesics are either ultra parallel or asymptotically parallel, False if not.

**EXAMPLES:**

```python
sage: g = HyperbolicPlane().UHP().get_geodesic(-2,5)
sage: h = HyperbolicPlane().UHP().get_geodesic(5,12)
sage: g.is_parallel(h)
True
```

```python
sage: g = HyperbolicPlane().UHP().get_geodesic(-2,5)
sage: h = HyperbolicPlane().UHP().get_geodesic(-2,4)
sage: g.is_parallel(h)
True
```

```python
sage: g = HyperbolicPlane().UHP().get_geodesic(-2,2)
sage: h = HyperbolicPlane().UHP().get_geodesic(-1,4)
sage: g.is_parallel(h)
False
```

No hyperbolic geodesic is either ultra parallel or asymptotically parallel to itself:

```python
sage: g = HyperbolicPlane().UHP().get_geodesic(-2,5)
sage: g.is_parallel(g)
False
```

is_ultra_parallel(\texttt{other})
Return True if self and other are ultra parallel and False otherwise.

**INPUT:**
- \texttt{other} – a hyperbolic geodesic

**EXAMPLES:**

```python
sage: from sage.geometry.hyperbolic_space.hyperbolic_geodesic import *
....: import *  
(continues on next page)"
sage: g = HyperbolicPlane().UHP().get_geodesic(0,1)
sage: h = HyperbolicPlane().UHP().get_geodesic(-3,-1)
sage: g.is_ultra_parallel(h)
True

sage: g = HyperbolicPlane().UHP().get_geodesic(-2,5)
sage: h = HyperbolicPlane().UHP().get_geodesic(2,6)
sage: g.is_ultra_parallel(h)
False

sage: g = HyperbolicPlane().UHP().get_geodesic(-2,5)
(sage: g.is_ultra_parallel(g)
False

length()

Return the Hyperbolic length of the hyperbolic line segment.

EXAMPLES:

sage: g = HyperbolicPlane().UHP().get_geodesic(2 + I, 3 + I/2)
sage: g.length()
arccosh(9/4)
**midpoint()**

Return the (hyperbolic) midpoint of a hyperbolic line segment.

EXAMPLES:

```plaintext
sage: g = HyperbolicPlane().UHP().random_geodesic()
sage: m = g.midpoint()
sage: end1, end2 = g.endpoints()
sage: bool(abs(m.dist(end1) - m.dist(end2)) < 10**-9)
True
```

Complete geodesics have no midpoint:

```plaintext
sage: HyperbolicPlane().UHP().get_geodesic(0,2).midpoint()
Traceback (most recent call last):
  ... ValueError: the length must be finite
```

**model()**

Return the model to which the `HyperbolicGeodesic` belongs.

EXAMPLES:

```plaintext
sage: UHP = HyperbolicPlane().UHP()
sage: UHP.get_geodesic(I, 2*I).model()  
Hyperbolic plane in the Upper Half Plane Model
sage: PD = HyperbolicPlane().PD()
sage: PD.get_geodesic(0, I/2).model()  
Hyperbolic plane in the Poincare Disk Model
sage: KM = HyperbolicPlane().KM()
sage: KM.get_geodesic((0, 0), (0, 1/2)).model()  
Hyperbolic plane in the Klein Disk Model
sage: HM = HyperbolicPlane().HM()
sage: HM.get_geodesic((0, 0, 1), (0, 1, sqrt(2))).model()  
Hyperbolic plane in the Hyperboloid Model
```

**perpendicular_bisector()**

Return the perpendicular bisector of `self` if `self` has finite length. Here distance is hyperbolic distance.

EXAMPLES:

```plaintext
sage: PD = HyperbolicPlane().PD()
sage: g = PD.get_geodesic(-0.3+0.4*I,+0.7-0.1*I)
sage: h = g.perpendicular_bisector().complete()
sage: P = g.plot(color='blue') + h.plot(color='orange'); P
Graphics object consisting of 4 graphics primitives
```

Complete geodesics cannot be bisected:

```plaintext
sage: g = HyperbolicPlane().PD().get_geodesic(0, 1)
sage: g.perpendicular_bisector()  
Traceback (most recent call last):
```

(continues on next page)
... 
ValueError: the length must be finite

reflection_involution()

Return the involution fixing self.

EXAMPLES:

```python
sage: H = HyperbolicPlane()
sage: gU = H.UHP().get_geodesic(2,4)
sage: RU = gU.reflection_involution(); RU
Isometry in UHP
[ 3 -8]
[ 1 -3]
sage: RU*gU == gU
True
sage: gP = H.PD().get_geodesic(0, I)
sage: RP = gP.reflection_involution(); RP
Isometry in PD
[ 1 0]
[ 0 -1]
sage: RP*gP == gP
True
sage: gK = H.KM().get_geodesic((0,0), (0,1))
sage: RK = gK.reflection_involution(); RK
Isometry in KM
[-1 0 0]
[ 0 1 0]
[ 0 0 1]
sage: RK*gK == gK
True
```

The above tests go through the Upper Half Plane. It remains to test that the matrices in the models do what we intend.

```python
sage: from sage.geometry.hyperbolic_space.hyperbolic_isometry
     .... import moebius_transform
sage: R = H.PD().get_geodesic(-1,1).reflection_involution()
sage: bool(moebius_transform(R.matrix(), 0) == 0)
True
```
start()
Return the starting point of the geodesic.

EXAMPLES:

```
sage: g = HyperbolicPlane().UHP().get_geodesic(I, 3*I)
sage: g.start()
Point in UHP I
```

to_model(model)
Convert the current object to image in another model.

INPUT:

- model – the image model

EXAMPLES:

```
sage: UHP = HyperbolicPlane().UHP()
sage: PD = HyperbolicPlane().PD()
sage: UHP.get_geodesic(I, 2*I).to_model(PD)
Geodesic in PD from 0 to 1/3*I
sage: UHP.get_geodesic(I, 2*I).to_model('PD')
Geodesic in PD from 0 to 1/3*I
```

update_graphics(update=False, **options)
Update the graphics options of self.

INPUT:

- update – if True, the original option are updated rather than overwritten

EXAMPLES:

```
sage: g = HyperbolicPlane().UHP().get_geodesic(I, 2*I)
sage: g.graphics_options()
{}
sage: g.update_graphics(color = "red"); g.graphics_options()
{'color': 'red'}
sage: g.update_graphics(color = "blue"); g.graphics_options()
{'color': 'blue'}
sage: g.update_graphics(True, size = 20); g.graphics_options()
{'color': 'blue', 'size': 20}
```

class sage.geometry.hyperbolic_space.hyperbolic_geodesic.HyperbolicGeodesicHM(model, start, end, **graphics_options)

Bases: HyperbolicGeodesic

A geodesic in the hyperboloid model.
Valid points in the hyperboloid model satisfy $x^2 + y^2 - z^2 = -1$

INPUT:

- start – a HyperbolicPoint in hyperbolic space representing the start of the geodesic
• end – a HyperbolicPoint in hyperbolic space representing the end of the geodesic

EXAMPIES:

```
sage: HM = HyperbolicPlane().HM()
sage: p1 = HM.get_point((4, -4, sqrt(33)))
sage: p2 = HM.get_point((-3, -3, sqrt(19)))
sage: g = HM.get_geodesic(p1, p2)
sage: g = HM.get_geodesic((4, -4, sqrt(33)), (-3, -3, sqrt(19)))
```

plot(show_hyperboloid=True, **graphics_options)

Plot self.

EXAMPLES:

```
sage: from sage.geometry.hyperbolic_space.hyperbolic_geodesic import *
sage: g = HyperbolicPlane().HM().random_geodesic()
sage: g.plot() # needs sage.plot
```

class sage.geometry.hyperbolic_space.hyperbolic_geodesic.HyperbolicGeodesicKM(model, start, end, **graphics_options)
Bases: HyperbolicGeodesic
A geodesic in the Klein disk model.
Geodesics are represented by the chords, straight line segments with ideal endpoints on the boundary circle.

INPUT:
• start – a HyperbolicPoint in hyperbolic space representing the start of the geodesic
• end – a HyperbolicPoint in hyperbolic space representing the end of the geodesic

EXAMPLES:

```sage
KM = HyperbolicPlane().KM()
sage: g = KM.get_geodesic((0.1,0.9),(-0.1,-0.9))
sage: h = KM.get_geodesic((-0.707106781,-0.707106781),(0.707106781,-0.707106781))
sage: P = g.plot(color='orange')+h.plot(); P
```

Graphics object consisting of 4 graphics primitives
class sage.geometry.hyperbolic_space.hyperbolic_geodesic.HyperbolicGeodesicPD(model, start, end, **graphics_options)

Bases: HyperbolicGeodesic

A geodesic in the Poincaré disk model.

Geodesics in this model are represented by segments of circles contained within the unit disk that are orthogonal to the boundary of the disk, plus all diameters of the disk.

INPUT:

- start – a HyperbolicPoint in hyperbolic space representing the start of the geodesic
- end – a HyperbolicPoint in hyperbolic space representing the end of the geodesic

EXAMPLES:

```python
sage: PD = HyperbolicPlane().PD()
sage: g = PD.get_geodesic(PD.get_point(I), PD.get_point(-I/2))
sage: g = PD.get_geodesic(I,-I/2)
sage: h = PD.get_geodesic(-1/2+I/2,1/2+I/2)
```
**plot**(boundary=True, **options)

Plot self.

**EXAMPLES:**

First some lines:

```python
sage: PD = HyperbolicPlane().PD()
sage: PD.get_geodesic(0, 1).plot()
# needs sage.plot
```

Graphics object consisting of 2 graphics primitives

Then some generic geodesics:

```python
sage: PD.get_geodesic(-0.5, 0.3+0.4*I).plot()
# needs sage.plot
```

Graphics object consisting of 2 graphics primitives

```python
sage: g = PD.get_geodesic(-1, exp(3*I*pi/7))
sage: G = g.plot(linestyle="dashed", color="red"); G
# needs sage.plot
```

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Chapter 3. Hyperbolic Geodesics
class sage.geometry.hyperbolic_space.hyperbolic_geodesic.HyperbolicGeodesicUHP(model, start, end, **graphics_options)

Bases: HyperbolicGeodesic

Create a geodesic in the upper half plane model.

The geodesics in this model are represented by circular arcs perpendicular to the real axis (half-circles whose origin is on the real axis) and straight vertical lines ending on the real axis.

INPUT:

- start – a HyperbolicPoint in hyperbolic space representing the start of the geodesic
- end – a HyperbolicPoint in hyperbolic space representing the end of the geodesic
EXAMPLES:

```python
sage: UHP = HyperbolicPlane().UHP()
sage: g = UHP.get_geodesic(UHP.get_point(I), UHP.get_point(2 + I))
sage: g = UHP.get_geodesic(I, 2 + I)
sage: h = UHP.get_geodesic(-1, -1+2*I)
```

angle(\(other\))

Return the angle between the completions of any two given geodesics if they intersect.

INPUT:

- \(other\) – a hyperbolic geodesic in the UHP model

OUTPUT:

- the angle in radians between the two given geodesics

EXAMPLES:

```python
sage: UHP = HyperbolicPlane().UHP()
sage: g = UHP.get_geodesic(2, 4)
sage: h = UHP.get_geodesic(3, 3 + I)
sage: g.angle(h)
1/2*pi
```

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If the geodesics are identical, return angle 0:

```
sage: g.angle(g)
0
```

It is an error to ask for the angle of two geodesics that do not intersect:

```
sage: g = UHP.get_geodesic(2, 4)
sage: h = UHP.get_geodesic(5, 7)
sage: g.angle(h)
Traceback (most recent call last):
  ... ValueError: geodesics do not intersect
```

**common_perpendicular**(other)

Return the unique hyperbolic geodesic perpendicular to self and other, if such a geodesic exists; otherwise raise a `ValueError`.

**INPUT:**

- **other** – a hyperbolic geodesic in current model
OUTPUT:
• a hyperbolic geodesic

EXAMPLES:

```python
sage: UHP = HyperbolicPlane().UHP()
sage: g = UHP.get_geodesic(2, 3)
sage: h = UHP.get_geodesic(4, 5)
sage: g.common_perpendicular(h)
Geodesic in UHP from 1/2*sqrt(3) + 7/2 to -1/2*sqrt(3) + 7/2
```

It is an error to ask for the common perpendicular of two intersecting geodesics:

```python
sage: g = UHP.get_geodesic(2, 4)
sage: h = UHP.get_geodesic(3, infinity)
sage: g.common_perpendicular(h)
Traceback (most recent call last):
...
ValueError: geodesics intersect; no common perpendicular exists
```

`ideal_endpoints()`
Determine the ideal (boundary) endpoints of the complete hyperbolic geodesic corresponding to `self`.

OUTPUT:
• a list of 2 boundary points

EXAMPLES:

```
sage: UHP = HyperbolicPlane().UHP()
sage: UHP.get_geodesic(I, 2*I).ideal_endpoints()
[Boundary point in UHP 0, Boundary point in UHP +Infinity]
sage: UHP.get_geodesic(1 + I, 2 + 4*I).ideal_endpoints()
[Boundary point in UHP -sqrt(65) + 9, Boundary point in UHP sqrt(65) + 9]
```

**intersection**(other)

Return the point of intersection of `self` and `other` (if such a point exists).

**INPUT:**

• `other` – a hyperbolic geodesic in the current model

**OUTPUT:**

• a list of hyperbolic points or a hyperbolic geodesic

**EXAMPLES:**

```
sage: UHP = HyperbolicPlane().UHP()
sage: g = UHP.get_geodesic(3, 5)
sage: h = UHP.get_geodesic(4, 7)
sage: g.intersection(h)
[Point in UHP 2/3*sqrt(-2) + 13/3]
```

If the given geodesics do not intersect, the function returns an empty list:

```
sage: g = UHP.get_geodesic(4, 5)
sage: h = UHP.get_geodesic(6, 7)
sage: g.intersection(h)
[]
```

If the given geodesics are asymptotically parallel, the function returns the common boundary point:

```
sage: g = UHP.get_geodesic(4, 5)
sage: h = UHP.get_geodesic(5, 7)
sage: g.intersection(h)
[Boundary point in UHP 5.00000000000000]
```

If the given geodesics are identical, return that geodesic:

```
sage: g = UHP.get_geodesic(4 + I, 18*I)
sage: h = UHP.get_geodesic(4 + I, 18*I)
sage: g.intersection(h)
Geodesic in UHP from I + 4 to 18*I
```

**midpoint**( )

Return the (hyperbolic) midpoint of `self` if it exists.

**EXAMPLES:**
Chapter 3. Hyperbolic Geodesics
sage: UHP = HyperbolicPlane().UHP()
sage: g = UHP.random_geodesic()
sage: m = g.midpoint()
sage: d1 = UHP.dist(m, g.start())
sage: d2 = UHP.dist(m, g.end())
sage: bool(abs(d1 - d2) < 10**-9)
True

Infinite geodesics have no midpoint:

sage: UHP.get_geodesic(0, 2).midpoint()
Traceback (most recent call last):
  ...
ValueError: the length must be finite

perpendicular_bisector()

Return the perpendicular bisector of the hyperbolic geodesic self if that geodesic has finite length.

EXAMPLES:

sage: UHP = HyperbolicPlane().UHP()
sage: g = UHP.random_geodesic()
sage: h = g.perpendicular_bisector().complete()
sage: c = lambda x: x.coordinates()
sage: bool(c(g.intersection(h)[0]) - c(g.midpoint()) < 10**-9)
True

sage: UHP = HyperbolicPlane().UHP()
sage: g = UHP.get_geodesic(1+I, 2+0.5*I)
sage: h = g.perpendicular_bisector().complete()
sage: show(g.plot(color='blue')+h.plot(color='orange'))

Infinite geodesics cannot be bisected:

sage: UHP.get_geodesic(0, 1).perpendicular_bisector()
Traceback (most recent call last):
  ...
ValueError: the length must be finite

plot(boundary=True, **options)

Plot self.

EXAMPLES:

sage: UHP = HyperbolicPlane().UHP()
sage: UHP.get_geodesic(0, 1).plot()  # needs sage.plot
  Graphics object consisting of 2 graphics primitives

sage: UHP.get_geodesic(I, 3+4*I).plot(linestyle="dashed", color="brown")  # needs sage.plot
  Graphics object consisting of 2 graphics primitives
reflection_involution()  
Return the isometry of the involution fixing the geodesic self.

EXAMPLES:

```
sage: UHP = HyperbolicPlane().UHP()
sage: g1 = UHP.get_geodesic(0, 1)
sage: g1.reflection_involution()
Isometry in UHP
[ 1  0]
[ 2 -1]
sage: UHP.get_geodesic(I, 2*I).reflection_involution()
Isometry in UHP
[ 1  0]
[ 0 -1]
```
In this module, a hyperbolic model is a collection of data that allow the user to implement new models of hyperbolic space with minimal effort. The data include facts about the underlying set (such as whether the model is bounded), facts about the metric (such as whether the model is conformal), facts about the isometry group (such as whether it is a linear or projective group), and more. Generally speaking, any data or method that pertains to the model itself – rather than the points, geodesics, or isometries of the model – is implemented in this module.

Abstractly, a model of hyperbolic space is a connected, simply connected manifold equipped with a complete Riemannian metric of constant curvature $-1$. This module records information sufficient to enable computations in hyperbolic space without explicitly specifying the underlying set or its Riemannian metric. Although, see the SageManifolds project if you would like to take this approach.

This module implements the abstract base class for a model of hyperbolic space of arbitrary dimension. It also contains the implementations of specific models of hyperbolic geometry.

AUTHORS:

EXAMPLES:
We illustrate how the classes in this module encode data by comparing the upper half plane (UHP), Poincaré disk (PD) and hyperboloid (HM) models. First we create:

```sage
U = HyperbolicPlane().UHP()
P = HyperbolicPlane().PD()
H = HyperbolicPlane().HM()
```

We note that the UHP and PD models are bounded while the HM model is not:

```sage
U.is_bounded() and P.is_bounded()
```
True
```
```

Sage: H.is_bounded()
False
```

The isometry groups of UHP and PD are projective, while that of HM is linear:

```sage
U.is_isometry_group_projective()
```
True
```
```

Sage: H.is_isometry_group_projective()
False
```

The models are responsible for determining if the coordinates of points and the matrix of linear maps are appropriate for constructing points and isometries in hyperbolic space:
Hyperbolic Geometry, Release 10.2

```sage
sage: U.point_in_model(2 + I)
True
sage: U.point_in_model(2 - I)
False
sage: U.point_in_model(2)
False
sage: U.boundary_point_in_model(2)
True
```

```
class sage.geometry.hyperbolic_space.hyperbolic_model.HyperbolicModel

Bases: Parent, UniqueRepresentation, BindableClass

Abstract base class for hyperbolic models.

Element

alias of HyperbolicPoint

bdry_point_test(p)

Test whether a point is in the model. If the point is in the model, do nothing; otherwise raise a ValueError.

EXAMPLES:

```sage
sage: HyperbolicPlane().UHP().bdry_point_test(2)
sage: HyperbolicPlane().UHP().bdry_point_test(1 + I)
Traceback (most recent call last):
...  ValueError: I + 1 is not a valid boundary point in the UHP model
```

boundary_point_in_model(p)

Return True if the point is on the ideal boundary of hyperbolic space and False otherwise.

INPUT:

• any object that can converted into a complex number

OUTPUT:

• boolean

EXAMPLES:

```sage
sage: HyperbolicPlane().UHP().boundary_point_in_model(I)
False
```

dist(a, b)

Calculate the hyperbolic distance between a and b.

INPUT:

• a, b – a point or geodesic

OUTPUT:

• the hyperbolic distance

EXAMPLES:

```
```python
sage: UHP = HyperbolicPlane().UHP()
sage: p1 = UHP.get_point(5 + 7*I)
sage: p2 = UHP.get_point(1.0 + I)
sage: UHP.dist(p1, p2)
2.23230104635820

sage: PD = HyperbolicPlane().PD()
sage: p1 = PD.get_point(0)
sage: p2 = PD.get_point(I/2)
sage: PD.dist(p1, p2)
arcosh(5/3)

sage: KM = HyperbolicPlane().KM()
sage: p1 = KM.get_point((0, 0))
sage: p2 = KM.get_point((1/2, 1/2))
sage: numerical_approx(KM.dist(p1, p2))
0.881373587019543

sage: HM = HyperbolicPlane().HM()
sage: p1 = HM.get_point((0,0,1))
sage: p2 = HM.get_point((1,0,sqrt(2)))
sage: numerical_approx(HM.dist(p1, p2))
0.881373587019543

Distance between a point and itself is 0:

```python
sage: p = UHP.get_point(47 + I)
sage: UHP.dist(p, p)
0
```

Points on the boundary are infinitely far from interior points:

```python
sage: UHP.get_point(3).dist(UHP.get_point(I))
+Infinity
```

**get_geodesic**(start, end=None, **graphics_options)

Return a geodesic in the appropriate model.

EXAMPLES:

```python
sage: HyperbolicPlane().UHP().get_geodesic(I, 2*I)
Geodesic in UHP from I to 2*I

sage: HyperbolicPlane().PD().get_geodesic(0, I/2)
Geodesic in PD from 0 to 1/2*I

sage: HyperbolicPlane().KM().get_geodesic((1/2, 1/2), (0,0))
Geodesic in KM from (1/2, 1/2) to (0, 0)

sage: HyperbolicPlane().HM().get_geodesic((0,0,1), (1,0, sqrt(2)))
Geodesic in HM from (0, 0, 1) to (1, 0, sqrt(2))
```
get_isometry(A)

Return an isometry in self from the matrix A in the isometry group of self.

EXAMPLES:

```python
sage: HyperbolicPlane().UHP().get_isometry(identity_matrix(2))
Isometry in UHP
[1 0]
[0 1]
```

```python
sage: HyperbolicPlane().PD().get_isometry(identity_matrix(2))
Isometry in PD
[1 0]
[0 1]
```

```python
sage: HyperbolicPlane().KM().get_isometry(identity_matrix(3))
Isometry in KM
[1 0 0]
[0 1 0]
[0 0 1]
```

```python
sage: HyperbolicPlane().HM().get_isometry(identity_matrix(3))
Isometry in HM
[1 0 0]
[0 1 0]
[0 0 1]
```

get_point(coordinates, is_boundary=None, **graphics_options)

Return a point in self.

Automatically determine the type of point to return given either:

1. the coordinates of a point in the interior or ideal boundary of hyperbolic space, or
2. a HyperbolicPoint object.

INPUT:

• a point in hyperbolic space or on the ideal boundary

OUTPUT:

• a HyperbolicPoint

EXAMPLES:

We can create an interior point via the coordinates:

```python
sage: HyperbolicPlane().UHP().get_point(2*I)
Point in UHP 2*I
```

Or we can create a boundary point via the coordinates:

```python
sage: HyperbolicPlane().UHP().get_point(23)
Boundary point in UHP 23
```

However we cannot create points outside of our model:
sage: HyperbolicPlane().UHP().get_point(12 - I)
Traceback (most recent call last):
...
ValueError: -I + 12 is not a valid point in the UHP model

sage: HyperbolicPlane().UHP().get_point(2 + 3*I)
Point in UHP 3*I + 2

sage: HyperbolicPlane().PD().get_point(0)
Point in PD 0

sage: HyperbolicPlane().KM().get_point((0,0))
Point in KM (0, 0)

sage: HyperbolicPlane().HM().get_point((0,0,1))
Point in HM (0, 0, 1)

sage: p = HyperbolicPlane().UHP().get_point(I, color="red")
sage: p.graphics_options()
{'color': 'red'}

sage: HyperbolicPlane().UHP().get_point(12)
Boundary point in UHP 12

sage: HyperbolicPlane().UHP().get_point(infinity)
Boundary point in UHP +Infinity

sage: HyperbolicPlane().PD().get_point(I)
Boundary point in PD I

sage: HyperbolicPlane().KM().get_point((0,-1))
Boundary point in KM (0, -1)

is_bounded()
Return True if self is a bounded model.

EXAMPLES:

sage: HyperbolicPlane().UHP().is_bounded()
True
sage: HyperbolicPlane().PD().is_bounded()
True
sage: HyperbolicPlane().KM().is_bounded()
True
sage: HyperbolicPlane().HM().is_bounded()
False

is_conformal()
Return True if self is a conformal model.

EXAMPLES:
sage: UHP = HyperbolicPlane().UHP()
sage: UHP.is_conformal()
True

**is_isometry_group_projective()**
Return True if the isometry group of self is projective.

**EXAMPLES:**

```python
sage: UHP = HyperbolicPlane().UHP()
sage: UHP.is_isometry_group_projective()
True
```

**isometry_from_fixed_points**(repel, attract)
Given two fixed points repel and attract as hyperbolic points return a hyperbolic isometry with repel as repelling fixed point and attract as attracting fixed point.

**EXAMPLES:**

```python
sage: UHP = HyperbolicPlane().UHP()
sage: PD = HyperbolicPlane().PD()
sage: PD.isometry_from_fixed_points(-I, I)
Isometry in PD
[ 3/4 1/4*I]
[-1/4*I 3/4]
sage: p, q = PD.get_point(1/2 + I/2), PD.get_point(6/13 + 9/13*I)
sage: PD.isometry_from_fixed_points(p, q)
Traceback (most recent call last):
  ... ValueError: fixed points of hyperbolic elements must be ideal
sage: p, q = PD.get_point(4/5 + 3/5*I), PD.get_point(-I)
sage: PD.isometry_from_fixed_points(p, q)
Isometry in PD
[ 1/6*I - 2/3 -1/3*I - 1/6]
[ 1/3*I - 1/6 -1/6*I - 2/3]
```

**isometry_in_model**(A)
Return True if the input matrix represents an isometry of the given model and False otherwise.

**INPUT:**
- a matrix that represents an isometry in the appropriate model

**OUTPUT:**
- boolean

**EXAMPLES:**

```python
sage: HyperbolicPlane().UHP().isometry_in_model(identity_matrix(2))
True
sage: HyperbolicPlane().UHP().isometry_in_model(identity_matrix(3))
False
```
**isometry_test(A)**

Test whether an isometry A is in the model.

If the isometry is in the model, do nothing. Otherwise, raise a ValueError.

**EXAMPLES:**

```
sage: HyperbolicPlane().UHP().isometry_test(identity_matrix(2))
sage: HyperbolicPlane().UHP().isometry_test(matrix(2, [I,1,2,1]))
Traceback (most recent call last):
...
ValueError: [I 1]
[2 1] is not a valid isometry in the UHP model
```

**name()**

Return the name of this model.

**EXAMPLES:**

```
sage: UHP = HyperbolicPlane().UHP()
sage: UHP.name()
'Upper Half Plane Model'
```

**point_in_model(p)**

Return True if the point p is in the interior of the given model and False otherwise.

**INPUT:**

- any object that can converted into a complex number

**OUTPUT:**

- boolean

**EXAMPLES:**

```
sage: HyperbolicPlane().UHP().point_in_model(I)
True
sage: HyperbolicPlane().UHP().point_in_model(-I)
False
```

**point_test(p)**

Test whether a point is in the model. If the point is in the model, do nothing. Otherwise, raise a ValueError.

**EXAMPLES:**

```
sage: from sage.geometry.hyperbolic_space.hyperbolic_model import ...
...HyperbolicModelUHP
sage: HyperbolicPlane().UHP().point_test(2 + I)
sage: HyperbolicPlane().UHP().point_test(2 - I)
Traceback (most recent call last):
...
ValueError: -I + 2 is not a valid point in the UHP model
```
random_element(**kwargs)

Return a random point in self.

The points are uniformly distributed over the rectangle \([-10, 10] \times [0, 10i]\) in the upper half plane model.

EXAMPLES:

```
sage: p = HyperbolicPlane().UHP().random_element()
sage: bool(p.coordinates().imag()) > 0
True

sage: p = HyperbolicPlane().PD().random_element()
sage: HyperbolicPlane().PD().point_in_model(p.coordinates())
True

sage: p = HyperbolicPlane().KM().random_element()
sage: HyperbolicPlane().KM().point_in_model(p.coordinates())
True

sage: p = HyperbolicPlane().HM().random_element().coordinates()
sage: bool((p[0]**2 + p[1]**2 - p[2]**2 - 1) < 10**-8)
True
```

random_geodesic(**kwargs)

Return a random hyperbolic geodesic.

Return the geodesic between two random points.

EXAMPLES:

```
sage: h = HyperbolicPlane().PD().random_geodesic()
sage: all( e.coordinates().abs() <= 1 for e in h.endpoints() )
True
```

random_isometry(preserve_orientation=True, **kwargs)

Return a random isometry in the model of self.

INPUT:

• preserve_orientation – if True return an orientation-preserving isometry

OUTPUT:

• a hyperbolic isometry

EXAMPLES:

```
sage: A = HyperbolicPlane().PD().random_isometry()
sage: A.preserves_orientation()
True

sage: B = HyperbolicPlane().PD().random_isometry(preserve_orientation=False)
sage: B.preserves_orientation()
False
```

random_point(**kwargs)

Return a random point of self.

The points are uniformly distributed over the rectangle \([-10, 10] \times [0, 10i]\) in the upper half plane model.
EXAMPLES:

```python
sage: p = HyperbolicPlane().UHP().random_point()
sage: bool((p.coordinates().imag()) > 0)
True
sage: PD = HyperbolicPlane().PD()
sage: p = PD.random_point()
sage: PD.point_in_model(p.coordinates())
True
```

**short_name()**

Return the short name of this model.

EXAMPLES:

```python
sage: UHP = HyperbolicPlane().UHP()
sage: UHP.short_name()
'UHP'
```

### class sage.geometry.hyperbolic_space.hyperbolic_model.HyperbolicModelHM(space)

Bases: `HyperbolicModel`

Hyperboloid Model.

**boundary_point_in_model(p)**

Return False since the Hyperboloid model has no boundary points.

EXAMPLES:

```python
sage: HM = HyperbolicPlane().HM()
sage: HM.boundary_point_in_model((0,0,1))
False
sage: HM.boundary_point_in_model((1,0,sqrt(2)))
False
sage: HM.boundary_point_in_model((1,2,1))
False
```

**get_background_graphic(**bdry**_options)**

Return a graphic object that makes the model easier to visualize. For the hyperboloid model, the background object is the hyperboloid itself.

EXAMPLES:

```python
sage: H = HyperbolicPlane().HM().get_background_graphic()
```

**isometry_in_model(A)**

Test that the matrix A is in the group $SO(2,1)^+$.  

EXAMPLES:

```python
sage: A = diagonal_matrix([1,1,-1])
sage: HyperbolicPlane().HM().isometry_in_model(A)
True
```
**point_in_model**($p$)

Check whether a complex number lies in the hyperboloid.

**EXAMPLES:**

```python
sage: HM = HyperbolicPlane().HM()
sage: HM.point_in_model((0,0,1))
True
sage: HM.point_in_model((1,0,sqrt(2)))
True
sage: HM.point_in_model((1,2,1))
False
```

**class** `sage.geometry.hyperbolic_space.hyperbolic_model.HyperbolicModelKM`($space$)

Bases: `HyperbolicModel`

Klein Model.

**boundary_point_in_model**($p$)

Check whether a point lies in the unit circle, which corresponds to the ideal boundary of the hyperbolic plane in the Klein model.

**EXAMPLES:**

```python
sage: KM = HyperbolicPlane().KM()
sage: KM.boundary_point_in_model((1, 0))
True
sage: KM.boundary_point_in_model((1/2, 1/2))
False
sage: KM.boundary_point_in_model((1, .2))
False
```

**get_background_graphic**(**bdry_options**)

Return a graphic object that makes the model easier to visualize.

For the Klein model, the background object is the ideal boundary.

**EXAMPLES:**

```python
sage: circ = HyperbolicPlane().KM().get_background_graphic()
```

**isometry_in_model**($A$)

Check if the given matrix $A$ is in the group $SO(2,1)$.

**EXAMPLES:**

```python
sage: A = matrix(3, [[1, 0, 0], [0, 17/8, 15/8], [0, 15/8, 17/8]])
sage: HyperbolicPlane().KM().isometry_in_model(A)
True
```

**point_in_model**($p$)

Check whether a point lies in the open unit disk.

**EXAMPLES:**
class sage.geometry.hyperbolic_space.hyperbolic_model.HyperbolicModelPD(space)

Bases: HyperbolicModel

Poincaré Disk Model.

boundary_point_in_model(p)

Check whether a complex number lies in the open unit disk.

EXAMPLES:

```python
sage: PD = HyperbolicPlane().PD()
sage: PD.boundary_point_in_model(1.00)
True
sage: PD.boundary_point_in_model(1/2 + I/2)
False
sage: PD.boundary_point_in_model(1 + .2*I)
False
```

get_background_graphic(**bdry_options)

Return a graphic object that makes the model easier to visualize.

For the Poincaré disk, the background object is the ideal boundary.

EXAMPLES:

```python
sage: circ = HyperbolicPlane().PD().get_background_graphic()
```

isometry_in_model(A)

Check if the given matrix $A$ is in the group $U(1,1)$.

EXAMPLES:

```python
sage: z = [CC.random_element() for k in range(2)]; z.sort(key=abs)
sage: A = matrix(2,[z[1], z[0],z[0].conjugate(),z[1].conjugate()])
sage: HyperbolicPlane().PD().isometry_in_model(A)
True
```

point_in_model(p)

Check whether a complex number lies in the open unit disk.

EXAMPLES:

```python
sage: PD = HyperbolicPlane().PD()
sage: PD.point_in_model(1.00)
False
sage: PD.point_in_model(1/2 + I/2)
True
```
class sage.geometry.hyperbolic_space.hyperbolic_model.HyperbolicModelUHP(space)
Bases: HyperbolicModel

Upper Half Plane model.

Element
alias of HyperbolicPointUHP

boundary_point_in_model(p)
Check whether a complex number is a real number or \( \infty \). In the UHP.model_name_name, this is the ideal boundary of hyperbolic space.

EXAMPLES:

```python
sage: UHP = HyperbolicPlane().UHP()
sage: UHP.boundary_point_in_model(1 + I)
False
sage: UHP.boundary_point_in_model(infinity)
True
sage: UHP.boundary_point_in_model(CC(infinity))
True
sage: UHP.boundary_point_in_model(RR(infinity))
True
sage: UHP.boundary_point_in_model(1)
True
sage: UHP.boundary_point_in_model(12)
True
sage: UHP.boundary_point_in_model(1 - I)
False
sage: UHP.boundary_point_in_model(-2*I)
False
sage: UHP.boundary_point_in_model(0)
True
sage: UHP.boundary_point_in_model(I)
False
```

get_background_graphic(**bdry_options)

Return a graphic object that makes the model easier to visualize. For the upper half space, the background object is the ideal boundary.

EXAMPLES:

```python
sage: hp = HyperbolicPlane().UHP().get_background_graphic()
```

isometry_from_fixed_points(repel, attract)

Given two fixed points repel and attract as complex numbers return a hyperbolic isometry with repel as repelling fixed point and attract as attracting fixed point.

EXAMPLES:
sage: UHP = HyperbolicPlane().UHP()
sage: UHP.isometry_from_fixed_points(2 + I, 3 + I)
Traceback (most recent call last):
...
ValueError: fixed points of hyperbolic elements must be ideal

sage: UHP.isometry_from_fixed_points(2, 0)
Isometry in UHP
[ -1  0]
[-1/3 -1/3]

isometry_in_model(A)
Check that $A$ acts as an isometry on the upper half plane. That is, $A$ must be an invertible $2 \times 2$ matrix with real entries.

EXAMPLES:

sage: UHP = HyperbolicPlane().UHP()
sage: A = matrix(2,[1,2,3,4])
sage: UHP.isometry_in_model(A)
True
sage: B = matrix(2,[I,2,4,1])
sage: UHP.isometry_in_model(B)
False

An example of a matrix $A$ such that $\det(A) \neq 1$, but the $A$ acts isometrically:

sage: C = matrix(2,[10,0,0,10])
sage: UHP.isometry_in_model(C)
True

point_in_model($p$)
Check whether a complex number lies in the open upper half plane.

EXAMPLES:

sage: UHP = HyperbolicPlane().UHP()
sage: UHP.point_in_model(1 + I)
True
sage: UHP.point_in_model(infinity)
False
sage: UHP.point_in_model(CC(infinity))
False
sage: UHP.point_in_model(RR(infinity))
False
sage: UHP.point_in_model(1)
False
sage: UHP.point_in_model(12)
False
sage: UHP.point_in_model(1 - I)
False
sage: UHP.point_in_model(-2*I)
False
sage: UHP.point_in_model(I)
(continues on next page)
True
sage: UHP.point_in_model(0) # Not interior point
False

random_isometry(preserve_orientation=True, **kwargs)
Return a random isometry in the Upper Half Plane model.

INPUT:
  • preserve_orientation – if True return an orientation-preserving isometry

OUTPUT:
  • a hyperbolic isometry

EXAMPLES:

sage: A = HyperbolicPlane().UHP().random_isometry()
sage: B = HyperbolicPlane().UHP().random_isometry(preserve_orientation=False)
sage: B.preserves_orientation()
False

random_point(**kwargs)
Return a random point in the upper half plane. The points are uniformly distributed over the rectangle $[-10, 10] \times [0, 10i]$.

EXAMPLES:

sage: p = HyperbolicPlane().UHP().random_point().coordinates()
sage: bool((p.imag()) > 0)
True
This module provides a convenient interface for interacting with models of hyperbolic space as well as their points, geodesics, and isometries.

The primary point of this module is to allow the code that implements hyperbolic space to be sufficiently decoupled while still providing a convenient user experience.

The interfaces are by default given abbreviated names. For example, UHP (upper half plane model), PD (Poincaré disk model), KM (Klein disk model), and HM (hyperboloid model).

**Note:** All of the current models of 2 dimensional hyperbolic space use the upper half plane model for their computations. This can lead to some problems, such as long coordinate strings for symbolic points. For example, the vector $\left(1, 0, \sqrt{2}\right)$ defines a point in the hyperboloid model. Performing mapping this point to the upper half plane and performing computations there may return with vector whose components are unsimplified strings have several $\sqrt{2}$'s. Presently, this drawback is outweighed by the rapidity with which new models can be implemented.

**AUTHORS:**


**EXAMPLES:**

```sage
sage: HyperbolicPlane().UHP().get_point(2 + I)
Point in UHP I + 2

sage: HyperbolicPlane().PD().get_point(1/2 + I/2)
Point in PD 1/2*I + 1/2
```

```python
class sage.geometry.hyperbolic_space.hyperbolic_interface.HyperbolicModels(base)
    Bases: Category_realization_of_parent

    The category of hyperbolic models of hyperbolic space.

class ParentMethods
    Bases: object

    super_categories()
        The super categories of self.

    EXAMPLES:
```
sage: from sage.geometry.hyperbolic_space.hyperbolic_interface import
˓→HyperbolicModels
sage: H = HyperbolicPlane()
sage: models = HyperbolicModels(H)
sage: models.super_categories()
[Category of metric spaces,
 Category of realizations of Hyperbolic plane]

class sage.geometry.hyperbolic_space.hyperbolic_interface.HyperbolicPlane

    Bases: Parent, UniqueRepresentation

    The hyperbolic plane \( \mathbb{H}^2 \).

    Here are the models currently implemented:

    - UHP – upper half plane
    - PD – Poincaré disk
    - KM – Klein disk
    - HM – hyperboloid model

    HM
    alias of HyperbolicModelHM

    Hyperboloid
    alias of HyperbolicModelHM

    KM
    alias of HyperbolicModelKM

    KleinDisk
    alias of HyperbolicModelKM

    PD
    alias of HyperbolicModelPD

    PoincareDisk
    alias of HyperbolicModelPD

    UHP
    alias of HyperbolicModelUHP

    UpperHalfPlane
    alias of HyperbolicModelUHP

    a_realization()
    Return a realization of self.

    EXAMPLES:

sage: H = HyperbolicPlane()
sage: H.a_realization()
Hyperbolic plane in the Upper Half Plane Model

sage.geometry.hyperbolic_space.hyperbolic_interface.HyperbolicSpace(n)

    Return \( n \) dimensional hyperbolic space.

    EXAMPLES:
sage: from sage.geometry.hyperbolic_space.hyperbolic_interface import *
˓→HyperbolicSpace
sage: HyperbolicSpace(2)
Hyperbolic plane
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