

The HERmitian Package

Divisors and Riemann-Roch Spaces of Algebraic Function Fields of Hermitian Curves

Version 0.1

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Chapter 1

Introduction

This chapter describes the GAP package HERmitian. This package implements functionalities for divisors and Riemann-Roch spaces of an algebraic function field of Hermitian.

If you are viewing this with on-line help, type:

Example `gap> ?HERmitian package`

to see the functions provided by the HERmitian package.

1.1 Unpacking the HERmitian Package

If the HERmitian package was obtained as a part of the GAP distribution from the “Download” section of the GAP website, you may proceed to Section ?? . Alternatively, the HERmitian package may be installed using a separate archive, for example, for an update or an installation in a non-default location (see (**Reference: GAP Root Directories**)).

Below we describe the installation procedure for the .tar.gz archive format. Installation using other archive formats is performed in a similar way.

To install the HERmitian package, download the package archive from the [package webpage](#), unpack the archive file, which should have a name of form HERmitian-XXX.tar.gz for some version number XXX, by typing

```
gzip -dc HERmitian-XXX.tar.gz | tar xpv
```

It may be unpacked in one of the following locations:

- in the pkg directory of your GAP 4 installation;
- or in a directory named .gap/pkg in your home directory (to be added to the GAP root directory unless GAP is started with -r option);
- or in a directory named pkg in another directory of your choice (e.g. in the directory mygap in your home directory).

In the latter case one must start GAP with the -l option, e.g. if your private pkg directory is a subdirectory of mygap in your home directory you might type:

```
gap -l ";myhomedir/mygap"
```

where myhomedir is the path to your home directory, which (since GAP 4.3) may be replaced by a tilde (the empty path before the semicolon is filled in by the default path of the GAP 4 home directory).

1.2 Loading the HERmitian Package

To use the HERmitian Package you have to request it explicitly. This is done by calling `LoadPackage` (**Reference: `LoadPackage`**):

```
----- Example -----
gap> LoadPackage("HERmitian");
-----
Loading  HERmitian 0.1
by Gábor P. Nagy (http://www.math.u-szeged.hu/~nagyg)
For help, type: ?HERmitian package
-----
true
```

If GAP cannot find a working binary, the call to `LoadPackage` will still succeed but a warning is issued informing that the `HelloWorld()` function will be unavailable.

If you want to load the HERmitian package by default, you can put the `LoadPackage` command into your `gaprc` file (see Section **(Reference: The `gap.ini` and `gaprc` files)**).

1.3 Testing the HERmitian Package

You can run tests for the package by

```
----- Example -----
gap> Test(Filename(DirectoriesPackageLibrary("HERmitian"), "../tst/testall.tst"));
```

Chapter 2

Mathematical background

Our notation and terminology are standard. The reader is referred to [HKT08], [Sti09]. For the decoding of algebraic-geometric codes see the survey paper [HP95].

2.1 Algebraic curves, places, divisors

An algebraic plane curve X over the field K is given by a polynomial $f(X, Y) \in K[X, Y]$ of degree n ; the usual notation is $X : f(X, Y) = 0$. The *affine points* of X are pairs $(x, y) \in L^2$, where L is an extension field of K and $f(x, y) = 0$ holds. We say that (x, y) is a *smooth point* of X if $(\frac{\partial f}{\partial X}(x, y), \frac{\partial f}{\partial Y}(x, y)) \neq (0, 0)$. At a smooth affine point $(x, y) \in L^2$, the curve has formal local parametrization $(\xi(t), \eta(t)) \in L[[t]]^2$ such that $\xi(0) = x$, $\eta(0) = y$ and $f(\xi(t), \eta(t)) = 0$. Non smooth points are called *singular*.

The affine curve $X : f(X, Y) = 0$ has *homogeneous equation* $F(X, Y, Z) = 0$ with $F(X, Y, Z) = Z^n f(\frac{X}{Z}, \frac{Y}{Z})$. The *projective points* of X satisfy $F(x, y, z) = 0$. In particular, the affine point (x, y) of \mathcal{X} corresponds to a projective point $(x : y : 1)$. The points of X at infinity are given by the homogeneous equation $F(X, Y, 0) = 0$. Smoothness and local parametrization at projective points are defined in the obvious way. We say that the projective point $(x : y : z)$ of X is *defined over* L if $x/y, y/z, z/x$ are either infinite or in L . Notice that any singular point (affine or projective) is defined over an algebraic extension of the underlying field K .

The algebraic curve X is said to be *nonsingular* or *smooth*, if all its points are smooth. This implies that f is absolutely irreducible. For smooth algebraic plane curves, the concept of a *place* is equivalent with the concept of a point, when X is considered as a curve over the algebraic closure of K . A *divisor* is a formal sum $D = n_1 P_1 + \dots + n_k P_k$ with integers n_1, \dots, n_k and places P_1, \dots, P_k . The degree of D is $n_1 + \dots + n_k$. The integer n_i is the *valuation* $v_{P_i}(D)$ of D at P_i ; for $P \neq P_i$ one has $v_P(D) = 0$. The *support* of D is the set of places P such that $v_P(D) \neq 0$.

2.2 Function fields and Riemann-Roch spaces

Let $X : f(X, Y) = 0$ be a smooth plane algebraic curve. The function field $K(X)$ of X is generated by the variables x, y subject to the algebraic relation $f(x, y) = 0$. In particular, each element of $K(X)$ can be written as $a(x, y)/b(x, y)$ with $a, b \in K[X, Y]$. Let $h \in K(X)$ and a place P of X , we define the valuation $v_P(h)$ as the subdegree of $h(\xi(t), \eta(t))$, where $(\xi(t), \eta(t))$ is the formal local parametrization at P . If $v_P(h) > 0$ then P is a *zero* of h , if $v_P(h) < 0$ then P is a *pole* of h . If $v_P(h) \geq 0$, then $h(P) = h(\xi(0), \eta(0))$ is a well-defined element of K .

For every non-zero function $h \in K(X)$, $\text{Div}(h)$ stands for the principal divisor associated with h while $\text{Div}(h)_0$ and $\text{Div}(h)_\infty$ for its zero and pole divisor. Furthermore, for every separable function $h \in K(X)$, dh is the exact differential arising from h , and Ω denotes the set of all these differentials. Also, $\text{res}_P(dh)$ is the residue of dh at a place of P of $K(X)$.

For any divisor A of $K(X)$, the *Riemann-Roch space* of A is

$$\mathcal{L}(A) = \{h \in K(X) \setminus \{0\} \mid \text{Div}(h) \succeq -A\} \cup \{0\}.$$

We denote $\ell(A) = \dim(\mathcal{L}(A))$. Furthermore, the *differential space* of A is

$$\Omega(A) = \{dh \in \Omega \mid \text{Div}(dh) \succeq A\} \cup \{0\}.$$

Both the Riemann-Roch and the differential spaces are linear spaces over K . Their dimensions are given by the theorem of Riemann-Roch:

$$\ell(A) = \deg(A) + 1 - g + \ell(W - A).$$

Here, W is a canonical divisor of X , and g is the *genus* of X . The latter is the most important birational invariant of an algebraic curve. For smooth curves of degree n , the genus formula is

$$g = \frac{(n-1)(n-2)}{2}.$$

The theorem of Riemann-Roch implies

$$\ell(A) \geq \deg(A) + 1 - g,$$

with equality if $\deg(A) > 2g - 2$.

2.3 Automorphisms of algebraic curves

Let $X : f(X, Y) = 0$ be a smooth plane algebraic curve with function field $K(X) = K(x, y)$, where the elements x, y are subject to the algebraic relation $f(x, y) = 0$. We assume that K is the constant field of $K(X)$. An *automorphism* of X is an automorphism of the function field, leaving all elements of K fixed. In particular, for any automorphism α of X , there are polynomials $u, v, w \in K[X, Y]$ such that

$$\alpha : (x, y) \rightarrow \left(\frac{u(x, y)}{w(x, y)}, \frac{v(x, y)}{w(x, y)} \right).$$

Substituting formal power series in α , we obtain an action of α on the set of places of X . This extends to an action on divisors, differentials and Riemann-Roch spaces.

2.4 Algebraic plane curves over finite fields

Let p be a prime and K an algebraically closed field of characteristic p . For $q = p^e$ we define the *Frobenius automorphism* $\text{Frob}_q : x \mapsto x^q$ of K . This extends to an Frobenius map of K -polynomials (acting on the coefficients) and of affine and projective points over K (acting on the coordinates). The curve X is said to be \mathbb{F}_q -rational, if it is Frob_q -invariant. Moreover, the Frobenius action extends to places and divisors of \mathbb{F}_q -rational curves, which allows us to speak of places and divisors defined over

\mathbb{F}_q . Let X be an algebraic plane curve over \mathbb{F}_q and P a place of X . Let r be the smallest positive integer such that P is defined over \mathbb{F}_{q^r} . Then, the divisor

$$P + P^{\text{Frob}_q} + P^{\text{Frob}_q^2} + \dots + P^{\text{Frob}_q^{r-1}}$$

is an \mathbb{F}_q -rational place of degree r of X .

If A is an \mathbb{F}_q -rational divisor then the Riemann-Roch space $\mathcal{L}(A)$ has a basis which consists of \mathbb{F}_q -rational elements of the function field of X . Hence, we can view $\mathcal{L}(A)$ as an \mathbb{F}_q -linear space of dimension $\ell(A)$. Similarly, $\Omega(A)$ can be seen as a vector space over \mathbb{F}_q .

If X is an algebraic curve over \mathbb{F}_q and α is an automorphism of X , then we say that α is defined over \mathbb{F}_q provided α commutes with the Frobenius map Frob_q . The automorphisms of X which are defined over \mathbb{F}_q form a subgroup of $\text{Aut}(X)$.

2.5 Algebraic-geometry codes

Algebraic-geometry (AG) codes are linear codes constructed from algebraic curves defined over a finite field \mathbb{F}_q . The best known such general construction was originally introduced by Goppa, see [Gop88]. It provides linear codes from certain rational functions whose poles are prescribed by a given \mathbb{F}_q -rational divisor G , by evaluating them at some set of \mathbb{F}_q -rational places disjoint from $\text{supp}(G)$. The dual to such a code can be obtained by computing residues of differential forms. The former are the *functional* codes, and the latter are the *differential* codes.

Let X be a smooth plane curve defined over the finite field \mathbb{F}_q . Write $D = Q_1 + \dots + Q_n$ for the \mathbb{F}_q -rational places Q_1, \dots, Q_n . Let G be another divisor of $\mathbb{F}_q(X)$ whose support $\text{supp}(G)$ contains none of the places Q_i with $1 \leq i \leq n$. For any function $h \in \mathcal{L}(G)$, the *evaluation* of h at D is given by

$$\text{ev}_D(h) = (h(Q_1), \dots, h(Q_n)).$$

This defines the *evaluation map* $\text{ev}_D : \mathcal{L}(G) \rightarrow \mathbb{F}_q^n$ which is \mathbb{F}_q -linear and also injective when $n > \deg(G)$. Therefore, its image is a subspace of the vector space \mathbb{F}_q^n , or equivalently, an AG $[n, k, d]$ -code where $d \geq n - \deg(G)$ and if $\deg(G) > 2g - 2$ then $k = \deg(G) + 1 - g$. Such a code is the *functional* code

$$C_L(D, G) = \{(h(Q_1), \dots, h(Q_n)) \mid h \in \mathcal{L}(G)\}$$

with *designed minimum distance* $n - \deg(G)$. The dual code

$$C_\Omega(D, G) = \{(\text{res}_{Q_1}(dh), \dots, \text{res}_{Q_n}(dh)) \mid dh \in \Omega(G - D)\}$$

of $C_L(D, G)$ is named a *differential code*. The differential code $C_\Omega(D, G)$ is a $[n, \ell(G - D) - \ell(G) + \deg D, d]$ -code with $d \geq \deg(G) - (2g - 2)$, and its designed minimum distance is $\deg(G) - (2g - 2)$.

Typically the divisor G is taken to be a multiple mP of a single place P of degree one. Such codes are the *one-point* codes, and have been extensively investigated. It has been shown however that AG-codes with better parameters than the comparable one-point Hermitian code may be obtained by allowing the divisor G to be more general, see [MM05] and the references therein.

2.6 Hermitian curves over finite fields

This package implements places, divisors and Riemann-Roch spaces of the *Hermitian curve* H_q defined over \mathbb{F}_{q^2} . We quote the most important geometric and combinatorial properties of H_q , the refer-

ences are [Hir98] and [HP73]. In the projective plane $PG(2, \mathbb{F}_{q^2})$ equipped with homogeneous coordinates $(X : Y : Z)$, a canonical form of H_q is $X^{q+1} - Y^q Z - YZ^q = 0$ so that

$$H_q : X^{q+1} = Y^q + Y$$

in the affine equation. Every \mathbb{F}_{q^2} -rational place of the function field $\mathbb{F}_{q^2}(H_q)$ of H_q corresponds to a point of H_q in $PG(2, \mathbb{F}_{q^2})$, and this holds true for the degree one places of the constant field extension $\mathbb{F}_{q^{2k}}(H_q)$ which correspond to the points of H_q in $PG(2, \mathbb{F}_{q^{2k}})$. Moreover, a place P of degree $r > 1$ of $\mathbb{F}_{q^2}(H_q)$ is represented by a divisor $P_1 + P_2 + \dots + P_r$ of the constant field extension $\mathbb{F}_{q^{2r}}(H_q)$ where P_i are degree one places of $\mathbb{F}_{q^{2r}}(H_q)$ with $P_i = P_1^{\text{Frob}_{q^2}^i}$ for $i = 0, 1, \dots, r-1$. Furthermore,

$$|H_q(\mathbb{F}_{q^2})| = |H_q(\mathbb{F}_{q^4})| = q^3 + 1$$

and

$$|H_q(\mathbb{F}_{q^6})| = q^6 + 1 + q^4(q-1),$$

where $H_q(K)$ denotes the set of K -rational points of the projective curve H_q . A line l of $PG(2, \mathbb{F}_{q^2})$ is either a tangent to H_q at an \mathbb{F}_{q^2} -rational point of H_q or it meets H_q at $q+1$ distinct \mathbb{F}_{q^2} -rational points. In terms of intersection divisors, see \cite[Section 6.2]{HKT_book},

$$I(H_q, l) = (q+1)Q$$

for the point $Q \in H_q(\mathbb{F}_{q^2})$ of tangent l of H_q , and

$$I(H_q, l) = \sum_{i=1}^{q+1} Q_i$$

for the $q+1$ distinct points of intersections Q_1, \dots, Q_{q+1} of l and H_q .

Through every point $V \in PG(2, \mathbb{F}_{q^2})$ not in $H_q(\mathbb{F}_{q^2})$ there are $q^2 - q + 1$ secants and $q+1$ tangents to H_q . The corresponding $q+1$ tangency points are the common points of H_q with the polar line of V relative to the unitary polarity associated to H_q . Let $V = (1 : 0 : 0)$. Then the line l_∞ of equation $Z = 0$ is tangent at $P_\infty = (0 : 1 : 0)$ while another line through V with equation $Y - cZ = 0$ is either a tangent or a secant according as $c^q + c$ is 0 or not.

If K is the algebraic closure of \mathbb{F}_{q^2} with $q > 2$, then the group of K -automorphisms of the Hermitian curve H_q is the projective unitary group $PGU(3, q)$. In particular, all automorphisms of H_q are defined over \mathbb{F}_{q^2} . The automorphism group act doubly transitively on the set of \mathbb{F}_{q^2} -rational points.

Chapter 3

How to use the package

3.1 Hermitian curves

The following functions are available:

3.1.1 IsHermitian_Curve

▷ `IsHermitian_Curve(obj)` (Category)

Hermitian curve $H(q)$ is an algebraic curve over an algebraically closed field, having an affine equation $X^{q+1} = Y^q + Y$. The base field of $H(q)$ is $GF(q^2)$.

3.1.2 Hermitian_Curve

▷ `Hermitian_Curve(K, hratfn)` (operation)

Returns: The corresponding Hermitian curve $H(q)$ over the algebraic closure of the field K . The indeterminates X, Y of `hratfn` generate the corresponding Hermitian function field $K(X, Y)$ such that $X^{q+1} = Y^q + Y$. K must be a finite field of square order. The points of $H(q)$ are either affine $P(a, b)$ satisfying $a^{q+1} = b^q + b$, or the infinite point `[infinity]`. One can use the `in` operation to test if a point lies on the Hermitian curve.

3.1.3 IndeterminatesOfHermitian_Curve

▷ `IndeterminatesOfHermitian_Curve(Hq)` (function)

Returns: The indeterminates of the function field of the Hermitian curve \mathcal{C} .

3.1.4 Genus

▷ `Genus(Hq)` (attribute)

The genus of the Hermitian curve $H(q)$ is $q(q-1)/2$.

3.1.5 UnderlyingField

▷ `UnderlyingField(Hq)` (attribute)

The underlying field of a Hermitian curve is the field of coefficients of the corresponding algebraic function field, it is a finite field of square order.

3.1.6 AllRationalAffinePlacesOfHermitian_Curve

▷ AllRationalAffinePlacesOfHermitian_Curve(Hq) (operation)

Returns: All rational affine places of the Hermitian curve Hq . The number of rational affine places of $H(q)$ is q^3 .

3.1.7 AllRationalPlacesOfHermitian_Curve

▷ AllRationalPlacesOfHermitian_Curve(Hq) (operation)

Returns: All rational places of the Hermitian curve Hq . Here, a place is a 1-point divisor of degree one, that is, defined over $GF(q^2)$. Notice that the place at infinity is rational. The number of rational places of $H(q)$ is $q^3 + 1$.

3.1.8 RandomRationalPlaceOfHermitian_Curve

▷ RandomRationalPlaceOfHermitian_Curve(Hq) (operation)

Returns: A random rational place of the Hermitian curve Hq . Here, a place is a 1-point divisor of degree one, that is, defined over $GF(q^2)$. Notice that the place at infinity is rational.

3.1.9 RandomPlaceOfGivenDegreeOfHermitian_Curve

▷ RandomPlaceOfGivenDegreeOfHermitian_Curve(Hq, d) (operation)

Returns: A random place of degree d of the Hermitian curve Hq , that is, a place defined over the field $GF(q^{2d})$. Notice that the place at infinity has degree 1.

Example

```
gap> q:=5;
5
gap> Y:=HermitianIndeterminates(GF(q^2),"Y1","Y2");
[ Y1, Y2 ]
gap> Hq:=Hermitian_Curve(Y[1]);
<Hermitian curve over GF(25) with indeterminates [ Y1, Y2 ]>
gap>
gap> UnderlyingField(Hq);
GF(5^2)
gap> p:=RandomPlaceOfGivenDegreeOfHermitian_Curve(Hq,3);
<Hermitian place [ Z(5^6)^12002, Z(5^6)^14911 ] over indeterminates [ Y1, Y2 ]>
gap> p in Hq;
true
gap> [ infinity ] in Hq;
true
gap> [0,0] in Hq;
false
gap> Z(q)*[0,0] in Hq;
true
gap> Size( AllRationalPlacesOfHermitian_Curve(Hq) );
126
```

3.2 Automorphisms of Hermitian curves

3.2.1 FrobeniusAutomorphismOfHermitian_Curve

▷ `FrobeniusAutomorphismOfHermitian_Curve(Hq)` (attribute)

Returns: The Frobenius automorphism of the underlying field of the Hermitian curve Hq . More precisely, the output is an AC-Frobenius automorphism in the sense of the package `OnAlgClosure`, acting on the algebraic closure of the underlying finite field.

3.2.2 IsHermitian_CurveAutomorphism

▷ `IsHermitian_CurveAutomorphism(obj)` (Category)

With automorphisms of an algebraic curve C one means the automorphisms of the corresponding algebraic function field $K(C)$. For a Hermitian curve $H(q)$ over a finite field, $Aut(GF(q)(H(q)))$ is isomorphic to the projective general linear group $PGU(3, q)$. In particular, an automorphism of $H(q)$ can be represented by a 3×3 unitary matrix over $GF(q^2)$.

3.2.3 Hermitian_CurveAutomorphism

▷ `Hermitian_CurveAutomorphism(Hq, mat)` (operation)

Returns: The automorphism of the Hermitian curve $H(q)$, given by the unitary matrix mat .

3.2.4 AutomorphismGroup

▷ `UnitaryGroupToHermitian_CurveAutGroup(matgr, Hq)` (function)

Returns: the group G of automorphisms of the Hermitian curve Hq , which correspond to the unitary group $matgr$.

The permutation action of $matgr$ on the set of rational places of Hq is stored as a nice monomorphism of G . ▷ `AutomorphismGroup(Hq)` (operation)

Returns: The automorphism group of the Hermitian curve Hq . The elements are Hermitian curve automorphisms. The group is isomorphic to $PGU(3, q)$, where $GF(q^2)$ is the underlying field of Hq .

Example

```
gap> aut:=AutomorphismGroup(Hq);
<group of Hermitian curve automorphisms of size 378000>
gap> Random(aut);
Hermitian_CurveAut([ [ Z(5)^0, Z(5^2)^11, Z(5^2)^19 ], [ Z(5^2)^20, Z(5^2)^16, Z(5^2)^21 ], [ Z(5^2)^21, Z(5^2)^16, Z(5^2)^20 ] ])
```

3.3 Hermitian divisors

The following functions are available:

3.3.1 IsHermitian_Divisor

▷ `IsHermitian_Divisor(obj)` (Category)

A Hermitian divisor is a divisor of an algebraic function field of the Hermitian curve $H(q) : X^{q+1} = Y^q + Y$. Hermitian divisors form an additive commutative group.

3.3.2 IsHermitian_Place

▷ `IsHermitian_Place(obj)` (filter)

In this implementation, a Hermitian place is a Hermitian divisor of degree one and support length one.

3.3.3 Hermitian_DivisorConstruct

▷ `Hermitian_DivisorConstruct(Hq, pts, ords)` (function)

Returns: The Hermitian divisor over Hq with (projective) points from pts and corresponding orders from $ords$. It checks the input.

3.3.4 IndeterminatesOfHermitian_Divisor

▷ `IndeterminatesOfHermitian_Divisor(D)` (function)

Returns: The pair of indeterminates of the function field of the Hermitian divisor D .

3.3.5 Hermitian_Divisor

▷ `Hermitian_Divisor(Hq, pts, ords)` (operation)

▷ `Hermitian_Divisor(Hq, pairs)` (operation)

Returns: The corresponding Hermitian divisor over the Hermitian curve Hq . The list pts must be points of Hq ; the infinite point is `[infinity]`. The list $ords$ contains the respective orders. The elements of the list $pairs$ are the point-order pairs.

3.3.6 Hermitian_Place

▷ `Hermitian_Place(Hq, pt)` (operation)

Returns: The corresponding place of the Hermitian curve Hq , where pt is either an affine point Hq , or the infinite point `[infinity]`.

3.3.7 ZeroHermitian_Divisor

▷ `ZeroHermitian_Divisor(Hq)` (operation)

Returns: The zero divisor over the Hermitian curve Hq .

3.3.8 SupremumHermitian_Divisor

▷ `SupremumHermitian_Divisor(D1, D2)` (function)

Returns: The place-wise maximum of the orders of $D1$ and $D2$.

3.3.9 InfimumHermitian_Divisor

▷ `InfimumHermitian_Divisor(D1, D2)` (function)

Returns: The place-wise minimum of the orders of $D1$ and $D2$.

3.3.10 PositivePartOfHermitian_Divisor

- ▷ `PositivePartOfHermitian_Divisor(D)` (function)
Returns: The positive part of the divisor D .

3.3.11 NegativePartOfHermitian_Divisor

- ▷ `NegativePartOfHermitian_Divisor(D)` (function)
Returns: The negative part of the divisor D .

3.3.12 UnderlyingField

- ▷ `UnderlyingField(D)` (attribute)

The underlying field of a Hermitian divisor is the field of coefficients of the corresponding Hermitian curve.

3.3.13 Support

- ▷ `Support(D)` (attribute)

The support of a Hermitian divisor is the set of points with nonzero orders.

3.3.14 Valuation

- ▷ `Valuation(D , pt)` (operation)

The valuation of a Hermitian divisor D at the point or place pt is its corresponding order.

3.3.15 Value

- ▷ `Value(f , pl)` (operation)
Returns: The value of a Hermitian rational function f at the place pl .

3.3.16 IsRationalHermitian_Divisor

- ▷ `IsRationalHermitian_Divisor(D)` (attribute)
Returns: True if D is invariant under the Frobenius automorphism of the underlying Hermitian curve.

3.3.17 PrincipalHermitian_Divisor

- ▷ `PrincipalHermitian_Divisor(Hq , f)` (operation)
Returns: The principal divisor of the rational function f of the Hermitian curve Hq .

3.3.18 IsInfiniteHermitian_Place

▷ IsInfiniteHermitian_Place(p)

(attribute)

Returns: True if p is a Hermitian place at the infinite line.

Example

```
gap> p_infty:=Hermitian_Place(Hq,[infinity]);
<Hermitian place [ infinity ] over indeterminates [ Y1, Y2 ]>
gap> d:=3*p_infty-4*p;
<Hermitian divisor with support of length 2 over indeterminates [ Y1, Y2 ]>
gap> Support(d);
[ [ infinity ], [ Z(5^6)^12002, Z(5^6)^14911 ] ]
gap> UnderlyingField(d);
GF(5^2)
gap> Zero(d);
<Hermitian divisor with support of length 0 over indeterminates [ Y1, Y2 ]>
gap> Characteristic(d);
5
gap>
gap> Valuation(d,p);
-4
gap> Valuation(d,[1,2]);
0
gap>
gap> fr:=FrobeniusAutomorphismOfHermitian_Curve(Hq);
AC_FrobeniusAutomorphism(5^2)
gap> d^fr;
<Hermitian divisor with support of length 2 over indeterminates [ Y1, Y2 ]>
gap> Support(d^fr);
[ [ infinity ], [ Z(5^6)^3194, Z(5^6)^13423 ] ]
gap> Support(d);
[ [ infinity ], [ Z(5^6)^12002, Z(5^6)^14911 ] ]
```

3.4 Hermitian Riemann-Roch spaces

3.4.1 Hermitian_RiemannRochSpaceBasis

▷ Hermitian_RiemannRochSpaceBasis(D)

(function)

Returns: A BASIS of the Riemann-Roch space of the Hermitian divisor D , which is defined by $\{f \in K[Y] \mid \text{Div}(f) \geq -D\}$.

Example

```
gap> a:=RandomPlaceOfGivenDegreeOfHermitian_Curve(Hq,3);
<Hermitian place [ Z(5^6)^5885, Z(5^6)^13071 ] over indeterminates [ Y1, Y2 ]>
gap> fr:=FrobeniusAutomorphismOfHermitian_Curve(Hq);
AC_FrobeniusAutomorphism(5^2)
gap> d:=Sum(AC_FrobeniusAutomorphismOrbit(fr,a));
<Hermitian divisor with support of length 3 over indeterminates [ Y1, Y2 ]>
gap> IsRationalHermitian_Divisor(d);
true
gap>
gap> bb:=Hermitian_RiemannRochSpaceBasis(5*d);
[ (Y1^3+Z(5^2)*Y1^2+Z(5^2)^17)/(Z(5^2)*Y1^3+Z(5^2)^17*Y1*Y2^2-Y2^3+Z(5^2)^14*Y1*Y2+Z(5^2)^11*Y2^2
```

```

15),
  (Z(5^2)^16*Y1^2+Z(5^2)^23*Y1+Y2+Z(5^2)^5)/(Z(5^2)*Y1^3+Z(5^2)^17*Y1*Y2^2-Y2^3+Z(5^2)^14*Y1*Y2+Z(5^2)^7*Y2+Z(5^2)^15),
  (Z(5^2)^17*Y1^2+Y1*Y2+Z(5^2)^5*Y1+Z(5^2)^21)/(Z(5^2)*Y1^3+Z(5^2)^17*Y1*Y2^2-Y2^3+Z(5^2)^14*Y1*Y2+Z(5^2)^7*Y2+Z(5^2)^15),
  (Y1^2*Y2+Z(5^2)^3*Y1^2+Z(5^2)^21*Y1+Z(5^2)^22)/(Z(5^2)*Y1^3+Z(5^2)^17*Y1*Y2^2-Y2^3+Z(5^2)^14*Y1*Y2+Z(5^2)^7*Y2+Z(5^2)^15),
  (Z(5^2)^23*Y1^2+Y2^2+Z(5^2)^8*Y1+Z(5^2)^13)/(Z(5^2)*Y1^3+Z(5^2)^17*Y1*Y2^2-Y2^3+Z(5^2)^14*Y1*Y2+Z(5^2)^7*Y2+Z(5^2)^15),
  (Y1*Y2^2+Z(5^2)^7*Y1^2+Z(5^2)^13*Y1+Z(5^2)^4)/(Z(5^2)*Y1^3+Z(5^2)^17*Y1*Y2^2-Y2^3+Z(5^2)^14*Y1*Y2+Z(5^2)^7*Y2+Z(5^2)^15),
  (Y2^3+Z(5^2)^5*Y1^2+Z(5^2)^11*Y1+Z(5^2)^14)/(Z(5^2)*Y1^3+Z(5^2)^17*Y1*Y2^2-Y2^3+Z(5^2)^14*Y1*Y2+Z(5^2)^7*Y2+Z(5^2)^15) ]
gap> Size(bb);
7
gap> ForAll(bb,x->x=x^fr);
true
gap> ForAll(bb,x->PrincipalHermitian_Divisor(Hq,x)>=-5*d);
true

```

3.5 Hermitian AG-codes

The following functions are available:

3.5.1 IsHermitian_Code

- ▷ IsHermitian_Code(obj) (Category)
- ▷ IsHermitian_FunctionalCode(obj) (Category)
- ▷ IsHermitian_DifferentialCode(obj) (Category)

A Hermitian code is an algebraic-geometric (AG) code defined on the Hermitian curve of equation $X^{q+1} = Y^q + Y$. AG-codes are either of functional or of differential type.

3.5.2 GeneratorMatrixOfFunctionalHermitian_CodeNC

- ▷ GeneratorMatrixOfFunctionalHermitian_CodeNC(G , pls) (function)

Returns: The generator matrix of the functional AG code $C_L(D, G)$, where D is the sum of the degree one places in the list pls . The support of G must be disjoint from pls .

3.5.3 Hermitian_FunctionalCode

- ▷ Hermitian_FunctionalCode(G , D) (operation)
- ▷ Hermitian_FunctionalCode(G) (operation)

Returns: The functional AG code $C_L(D, G) = \{(f(P_1), \dots, f(P_n)) \mid f \in L(G)\}$. D and G are rational divisors of the Hermitian curve $H(q)$. $D = P_1 + \dots + P_n$, where P_1, \dots, P_n are degree one places of $H(q)$. The supports of D and G are disjoint. If D is not given then it is the sum of affine rational places of $H(q)$, not contained in the support of G . By the Riemann-Roch theorem, functional codes have dimension at least $\deg(G) + 1 - g$, with equality if $\deg(G) > 2g - 2$.

3.5.4 Hermitian_DifferentialCode

- ▷ `Hermitian_DifferentialCode(G , D)` (operation)
 ▷ `Hermitian_DifferentialCode(G)` (operation)

Returns: The differential AG code $C_\Omega(D, G) = \{res_{P_1}(\omega), \dots, res_{P_n}(\omega) \mid \omega \in \Omega(G - D)\}$. D and G are rational divisors of the Hermitian curve $H(q)$. $D = P_1 + \dots + P_n$, where P_1, \dots, P_n are degree one places of $H(q)$. The supports of D and G are disjoint. If D is not given then it is the sum of affine rational places of $H(q)$, not contained in the support of G . By the Riemann-Roch theorem, functional codes have dimension $\deg(G) + 1 - g$. The differential code is the dual of the corresponding functional code. By the Riemann-Roch theorem, differential codes have dimension at least $n - \deg(G) - 1 + g$, with equality if $\deg(G) > 2g - 2$.

3.5.5 UnderlyingCurveOfHermitian_Code

- ▷ `UnderlyingCurveOfHermitian_Code(C)` (function)
Returns: The underlying Hermitian curve of the AG code C .

3.5.6 UnderlyingField

- ▷ `UnderlyingField(C)` (attribute)

The underlying field of an AG code is its left acting domain.

3.5.7 Length

- ▷ `Length(C)` (attribute)
Returns: The length of the AG code C .

3.5.8 GeneratorMatrixOfHermitian_Code

- ▷ `GeneratorMatrixOfHermitian_Code(C)` (attribute)
Returns: The generator matrix of the AG code C in CVEC matrix format.

3.5.9 DesignedMinimumDistance

- ▷ `DesignedMinimumDistance(C)` (attribute)
Returns: The designed minimum distance δ of the Hermitian AG code C . When $\deg(G) \geq 2g - 2$, then the general formulas for δ are as follows. For the functional code $C_L(D, G)$, $\delta = n - \deg(G)$, and for the differential code $C_\Omega(D, G)$, $\delta = \deg(G) - (2g - 2)$.

Example

```
gap> Hermitian_FunctionalCode(5*d);
<[125,7] Hermitian AG-code over GF(5^2)>
gap> a:=Sum(AllRationalAffinePlacesOfHermitian_Curve(Hq));
<Hermitian divisor with support of length 125 over indeterminates [ Y1, Y2 ]>
gap> code:=Hermitian_FunctionalCode(8*d,a);
<[125,15] Hermitian AG-code over GF(5^2)>
gap> Print(code);
Hermitian_FunctionalCode(Hermitian_Divisor(Hermitian_Curve(Y1),[ [ Z(5^6)^5885, Z(5^6)^13071 ], [
  [ Z(5^6)^6509, Z(5^6)^14295 ] ],[ 8, 8, 8 ]),Hermitian_Divisor(Hermitian_Curve(Y1),[ [ 0*Z(5),
```

3.5.10 Hermitian DecodeToCodeword

The decoding algorithm is from [Hoholdt-Pellikaan 1995]. The function `Hermitian_DECODER_DATA` precomputes two matrices which are stored as attributes of the AG code. The decoding consists of solving linear equations.

```
gap> q:=4;
4
gap> # construct the curve and the divisors
gap> Y:=HermitianIndeterminates(GF(q^2),"Y1","Y2");
[ Y1, Y2 ]
gap> Hq:=Hermitian_Curve(Y[1]);
```

```

<Hermitian curve over GF(16) with indeterminates [ Y1, Y2 ]>
gap> P_infty:=Hermitian_Place(Hq,[infinity]);
<Hermitian place [ infinity ] over indeterminates [ Y1, Y2 ]>
gap>
gap> fr:=FrobeniusAutomorphismOfHermitian_Curve(Hq);
AC_FrobeniusAutomorphism(2^4)
gap> P4:=RandomPlaceOfGivenDegreeOfHermitian_Curve(Hq,5);
<Hermitian place [ Z(2,20)+Z(2,20)^3+Z(2,20)^4+Z(2,20)^6+Z(2,20)^11+Z(2,20)^13+Z(2,20)^15+Z(2,20)^19 ] c
Z(2,20)+Z(2,20)^4+Z(2,20)^5+Z(2,20)^7+Z(2,20)^8+Z(2,20)^12+Z(2,20)^13+Z(2,20)^15+Z(2,20)^19 ] c
gap> P4:=Sum(AC_FrobeniusAutomorphismOrbit(fr,P4));
<Hermitian divisor with support of length 5 over indeterminates [ Y1, Y2 ]>
gap> G:=5*P4+7*P_infty;
<Hermitian divisor with support of length 6 over indeterminates [ Y1, Y2 ]>
gap> Degree(G);
32
gap>
gap> len:=50;
50
gap> affpts:=AllRationalAffinePlacesOfHermitian_Curve(Hq);
gap> D:=Sum(affpts{[1..len]});
<Hermitian divisor with support of length 50 over indeterminates [ Y1, Y2 ]>
gap>
gap> # construct the AG differential code
gap> Hermitian_DifferentialCode(G);
<[64,37] Hermitian AG-code over GF(2^4)>
gap> agcode:=Hermitian_DifferentialCode(G,D);
<[50,23] Hermitian AG-code over GF(2^4)>
gap> DesignedMinimumDistance(agcode);
22
gap> Length(agcode)-Degree(G)-1;
17
gap>
gap> # test codeword generation
gap> t:=Int((DesignedMinimumDistance(agcode)-1-Genus(G!.curve))/2);
7
gap> sent:=Random(agcode);
gap> err:=RandomVectorOfGivenWeight(GF(q),Length(agcode),t);
gap> received:=sent+err;
gap>
gap> # decoding
gap> sent_decoded:=Hermitian_DecodeToCodeword(agcode,received);
<cvec over GF(2,4) of length 50>
gap> sent=sent_decoded;
true

```

3.6 Utilities for Hermitian AG-codes

3.6.1 InfoHermitian

▷ InfoHermitian

(info class)

An infoclass for the package. Its default value is 0. With `SetInfoLevel(InfoHermitian, 2)` one can get some additional messages about the ongoing computation of Hermitian curves and their codes.

3.6.2 RestrictVectorSpace

▷ `RestrictVectorSpace(V, F)` (function)

Let K be a field and V a linear subspace of K^n . The restriction of V to the field F is the intersection $V \cap F^n$.

3.6.3 UPolCoeffsToSmallFieldNC

▷ `UPolCoeffsToSmallFieldNC(f, q)` (function)

This non-checking function returns the same polynomial as f , making sure that the coefficients are in $GF(q)$.

3.6.4 RandomVectorOfGivenWeight

▷ `RandomVectorOfGivenWeight(F, n, k)` (function)

Returns: A random vector of F^n of Hamming weight k .

▷ `RandomVectorOfGivenDensity(F, n, delta)` (function)

Returns: A random vector of F^n in which the density of nonzero elements is approximatively δ .

▷ `RandomBinaryVectorOfGivenWeight(n, k)` (function)

Returns: A random vector of $GF(2)^n$ of Hamming weight k .

▷ `RandomBinaryVectorOfGivenDensity(n, delta)` (function)

Returns: A random vector of $GF(2)^n$ in which the density of nonzero elements is approximatively δ .

Chapter 4

An example: Parameters of subfield subcodes of 1-point Hermitian codes

The following example computes the parameters of subfield subcodes of 1-point Hermitian codes.

Example

```
gap> q:=4; r:=2;
4
2
gap> Y:=HermitianIndeterminates(GF(q^2),"Y1","Y2");
[ Y1, Y2 ]
gap> Hq:=Hermitian_Curve(Y[1]);
<Hermitian curve over GF(16) with indeterminates [ Y1, Y2 ]>
gap> P_infty:=Hermitian_Place(Hq,[infinity]);
<Hermitian place [ 0*Z(2), Z(2)^0, 0*Z(2) ] over indeterminates [ Y1, Y2 ]>
gap>
gap> for s in [q^3/r..q^3] do
>   hcode:=Hermitian_FunctionalCode(s*P_infty);
>   rcode:=RestrictVectorSpace(hcode,GF(r));
>   n:=Length(hcode);
>   delta:=DesignedMinimumDistance(hcode);
>   if delta<=1 then break; fi;
>   kappa:=Dimension(rcode);
>   if kappa>1 then
>     gamma:=(kappa+delta)/(n+1);
>     Print(
>       "s=",s," ",Int(gamma*100+1/2)*0.01,"\t",
>       "[",n,"",Dimension(hcode),"",delta,"]_",q," ---> ",
>       "[",n,"",kappa,"",delta,"]_",r,
>       "\n");
>   fi;
> od;
s=32 0.57 [64,27,32]_4 ---> [64,5,32]_2
s=33 0.55 [64,28,31]_4 ---> [64,5,31]_2
s=34 0.54 [64,29,30]_4 ---> [64,5,30]_2
s=35 0.52 [64,30,29]_4 ---> [64,5,29]_2
s=36 0.51 [64,31,28]_4 ---> [64,5,28]_2
s=37 0.49 [64,32,27]_4 ---> [64,5,27]_2
s=38 0.48 [64,33,26]_4 ---> [64,5,26]_2
s=39 0.46 [64,34,25]_4 ---> [64,5,25]_2
```

s=40	0.51	[64,35,24]_4	--->	[64,9,24]_2
s=41	0.49	[64,36,23]_4	--->	[64,9,23]_2
s=42	0.54	[64,37,22]_4	--->	[64,13,22]_2
s=43	0.52	[64,38,21]_4	--->	[64,13,21]_2
s=44	0.51	[64,39,20]_4	--->	[64,13,20]_2
s=45	0.49	[64,40,19]_4	--->	[64,13,19]_2
s=46	0.48	[64,41,18]_4	--->	[64,13,18]_2
s=47	0.46	[64,42,17]_4	--->	[64,13,17]_2
s=48	0.51	[64,43,16]_4	--->	[64,17,16]_2
s=49	0.49	[64,44,15]_4	--->	[64,17,15]_2
s=50	0.51	[64,45,14]_4	--->	[64,19,14]_2
s=51	0.49	[64,46,13]_4	--->	[64,19,13]_2
s=52	0.54	[64,47,12]_4	--->	[64,23,12]_2
s=53	0.58	[64,48,11]_4	--->	[64,27,11]_2
s=54	0.57	[64,49,10]_4	--->	[64,27,10]_2
s=55	0.55	[64,50,9]_4	--->	[64,27,9]_2
s=56	0.60	[64,51,8]_4	--->	[64,31,8]_2
s=57	0.58	[64,52,7]_4	--->	[64,31,7]_2
s=58	0.63	[64,53,6]_4	--->	[64,35,6]_2
s=59	0.62	[64,54,5]_4	--->	[64,35,5]_2
s=60	0.66	[64,55,4]_4	--->	[64,39,4]_2
s=61	0.71	[64,56,3]_4	--->	[64,43,3]_2
s=62	0.75	[64,57,2]_4	--->	[64,47,2]_2

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