

Differential Geometry

Thomas Brosnan

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“hokay” -Sergey Frolov

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1 Definition of a Manifold

1.1 Regions

- A *region* (“open set”) is a set of D points in \mathbb{R}^n such that together with each point p_0 , D also contains all points sufficiently closer to p_0 , i.e.:

$$\forall p_0 = (x_0^1, \dots, x_0^n) \in D \exists \epsilon > 0, \\ \text{st } p = (x^1, \dots, x^n) \in D, \text{ iff } |x^i - x_0^i| < \epsilon.$$

- A *region with out a boundary* is obtained from a region D by adjoining all boundary points to D . The *boundary* of a region is the set of all boundary points.

1.2 Differentiable Manifold

- A differentiable n -dimensional manifold is a set M together with the following structure on it. The set M is the union of a finite or countably infinite collection of subsets U_q with the following properties:
 - Each subset U_q has defined on it co-ords $x_q^\alpha, \alpha = 1, \dots, n$ called local co-ords by virtue of which U_q is identifiable with a region of Euclidean n -space \mathbb{R}^n with Euclidean co-ords x_q^α . The U_q with their co-ord systems are called *charts* or *local coordinate neighborhoods*.
 - Each non-empty intersection $U_q \cap U_p$ of a pair of charts thus has defined on it two co-ord systems, the restriction of x_p^α and x_q^α . It is required that under each of these coordinatizations the intersection $U_q \cap U_p$ is identifiable with a region of \mathbb{R}^n and that each of these co-ordinate systems be expressible in terms of the other in a one to one differentiable manner. Thus, if a *transition* functions from x_p^α to x_q^α and back are given by:

$$x_p^\alpha = x_p^\alpha(x_q^1, \dots, x_q^n), \quad \alpha = 1, \dots, n \\ x_q^\alpha = x_q^\alpha(x_p^1, \dots, x_p^n), \quad \alpha = 1, \dots, n$$

Then the *Jacobian* $J_{pq} = \det(\partial x_p^\alpha / \partial x_q^\alpha)$ is non-zero on $U_p \cap U_q$.

1.3 Abuse of notation

- Regular partial derivative do not have the same “canceling” that total derivative have ($dx * dy / dx = dy$) But we can restore this property through Einstein summation convention. That is that:

$$\sum_{\gamma=1}^n \frac{\partial x_p^\alpha}{\partial x_q^\gamma} \frac{\partial x_q^\gamma}{\partial x_q^\beta} = \frac{\partial x_p^\alpha}{\partial x_q^\gamma} \frac{\partial x_q^\gamma}{\partial x_q^\beta} = \delta_\beta^\alpha$$

2 Elements of Topology

2.1 Topological space

- A topological space is a set X of points of which certain subsets called *open sets* of the topological space, are distinguished, these open sets have to satisfy:
 - The intersection of any two (and hence of any finite collection) open sets should again be an open set.
 - The union of any collection of open sets must again be open.
 - The empty set and the whole set X must be open.
- The compliment of any open set is called a *closed* set of the topological space.

In Euclidean space \mathbb{R}^n the “Euclidean topology” is the usual one where the open sets are the open regions.

2.1.1 Induced topology

- Given any subset $A \in \mathbb{R}^n$, the *induced topology* on A is that where the open sets are the intersections $A \cap U$, where U ranges over all open sets of \mathbb{R}^n .

2.1.2 Continuity

- A map $f : X \rightarrow Y$ of one topological space to another is called *continuous* if the complete inverse image $f^{-1}(U)$ of every open set $U \subset Y$ is open in X .

2.1.3 Homeomorphic

- Two topological space are *topologically equivalent* or *homeomorphic* if there is a one to one and onto map (bijective) between them, such that it and its inverse are continuous.

2.1.4 Topology on a manifold

- The topology on a manifold M is given by the following specifications of the open sets. In every local co-ordinate neighborhood U_q the open regions are to be open in the topology on M ; the totality of open sets of M is then obtained by admitting as open, also arbitrary unions countable collections of such regions, i.e. by closing under countable unions.

2.2 Metric space

- A *metric space* is a set which comes equipped with a “distance function” i.e. a real-valued function $\rho(x, y)$, defined on pairs x, y of its elements and having the following properties:
 - Symmetry: $\rho(x, y) = \rho(y, x)$.
 - Positivity: $\rho(x, x) = 0$, $\rho(x, y) > 0$ if $x \neq y$.
 - The triangle inequality: $\rho(x, y) \leq \rho(x, z) + \rho(z, y)$.

2.2.1 Hausdorff

- A topological space is called *Hausdorff* if any two points are contained in disjoint open sets. Any metric space is Hausdorff because the open balls of radius $\rho(x, y)/3$ with centers at x, y do not intersect.

All topological spaces we consider will be Hausdorff.

2.2.2 Compact

- A topological space X is said to be compact if every countable collection of open sets covering X contains a finite sub-collection already covering X .

If X is a metric space the compactness is equivalent to the condition that from every sequence of points of X a convergent sub-sequence can be selected.

2.2.3 Connected

- A topological space is connected if any two points can be joined by a continuous path.

2.3 Orientation

- A manifold M is said to be *orientated* if one can choose its atlas (collection of all the charts) so that for every pair U_p, U_q of intersecting co-ordinate neighborhoods the Jacobian of the transition functions is positive.
- We say that the co-ordinate systems x and y define the *same orientation* if $J > 0$ and the *opposite orientation* if $J < 0$.

3 Mappings on Manifolds

3.1 Manifold mappings

- A mapping $f : M \rightarrow N$ is said to be smooth of smoothness class k if for all p, q for which f determines functions $y_q^b(x_p^1, \dots, x_p^m) = f(x_p^1, \dots, x_p^m)_p^b$, these functions are, where defined, smooth of smoothness class k (i.e. all their partial derivatives up to those of k -th order exist and are continuous).

the smoothness class of f cannot exceed the maximum class of the manifolds.

3.2 Equivalent manifolds

- The manifolds M and N are said to be *smoothly equivalent* or *diffeomorphic* if there is a one to one and onto map f such that both $f : M \rightarrow N$ and $f^{-1} : N \rightarrow M$ are smooth of some class $k \geq 1$.

Since f^{-1} exists then the Jacobian $J_{pq} \neq 0$ wherever it is defined.

3.3 Tangent vector

- A *tangent* vector to an m -dim manifold M at an arbitrary point x is represented in terms of local co-ords x_p^α by an m tuple ξ^α of components which are linked to the components in terms of any other system x_q^β of local co-ords by:

$$\xi_p^\alpha = \left(\frac{\partial x_p^\alpha}{\partial x_q^\beta} \right)_x \xi_q^\beta, \quad \forall \alpha \quad (3.1)$$

- The set of all tangent vectors to an m -dim manifold M at a point x forms an m -dim vector space $T_x = T_x M$, the *tangent space* to M at the point x .
- Thus, the velocity at x of any smooth curve M through x is a tangent vector to M at x .

3.4 Push forward

- A smooth map f from M to N gives rise for each x to a *push forward* or an *induced linear* map to tangent spaces:

$$f_* : T_x M \rightarrow T_{f(x)} N$$

defined as sending the velocity at x of any smooth curve $x = x(\tau)$ on M to the velocity vector at $f(x)$ of the curve $f(x(\tau))$ on N . If the map f is given by: $y^b = f^b(x^1, \dots, x^m)$ for $x \in M$ and $y \in N$, then the push forward map f_* is:

$$\xi^\alpha \rightarrow \eta^b = \frac{\partial f^b}{\partial x^\alpha} \xi^\alpha.$$

- For a real valued function $f : M \rightarrow \mathbb{R}$, the push-forward map f_* corresponding to each $x \in M$ is a real valued linear function on the tangent space to M at x :

$$\xi^\alpha \rightarrow \eta = \frac{\partial f}{\partial x^\alpha} \xi^\alpha$$

and it is represented by the gradient of f at x , and is a co-vector or one form. Thus f_* can be identified with the differential df , in particular:

$$dx_p^\alpha : \xi^\alpha \rightarrow \eta = \xi_p^\alpha$$

3.5 Directional derivative

- We can associate with each vector $\xi = (\xi^i)$ a linear differential operator as follows: Since the gradient $\frac{\partial f}{\partial x^i}$ of a function f is a co-vector, the quantity:

$$\partial_\xi f = \xi^i \frac{\partial f}{\partial x^i}$$

is a scalar called the directional derivative of f in the direction of ξ .

- Thus an arbitrary vector ξ corresponds to the operator:

$$\partial_\xi = \xi^i \frac{\partial}{\partial x^i}$$

So we can identify $\frac{\partial}{\partial x^i} \equiv e_i$ as the *Canonical basis of the tangent space*.

3.6 Riemann metric

- A *Riemann metric* on a manifold M is a point-dependent, positive-definite quadratic form on the tangent vectors at each point, depending smoothly on the local co-ords of the points.

Thus at each point $x = (x_p^1, \dots, x_p^m)$ of each chart U_p , the metric is given by a symmetric metric $g_{\alpha\beta}(x_p^1, \dots, x_p^m)$, and determines a symmetric scalar product of pairs of tangent vectors at the point x .

$$\langle \xi, \eta \rangle = g_{\alpha\beta}^{(p)} \xi_p^\alpha \eta_p^\beta = \langle \eta, \xi \rangle, \quad |\xi|^2 = \langle \xi, \xi \rangle$$

This scalar product is to be co-ordinate independent:

$$g_{\alpha\beta}^{(p)} \xi_p^\alpha \eta_p^\beta = g_{\alpha\beta}^{(q)} \xi_q^\alpha \eta_q^\beta$$

And therefor the coefficients $g_{\alpha\beta}^{(p)}$ of the quadratic form transform as:

$$g_{\gamma\delta}^{(q)} = \frac{\partial x_p^\alpha}{\partial x_q^\gamma} \frac{\partial x_p^\beta}{\partial x_q^\delta} g_{\alpha\beta}^{(p)} \quad (3.2)$$

For a *pseudo-Riemann* metric M one just requires the quadratic form to be *nondegenerate*. Note that 3.2 can be re-written as:

$$ds^2 = g_{\alpha\beta}^{(p)} dx_p^\alpha dx_p^\beta = g_{\alpha\beta}^{(q)} dx_q^\alpha dx_q^\beta$$

Where ds is called a line element, and it is chart-independent. ds is used to measure the distance between two infinitesimally close points.

4 Tensors

4.1 Tensor def

- A *tensor of type* (k, l) and rank $k + l$ on an m -dim manifold M is given each local co-ord system (x_p^i) by a family of functions:

$${}^{(p)}T_{j_1, \dots, j_l}^{i_1, \dots, i_k}(x) \text{ of the point } x.$$

In other local co-ord (x_q^i) the components ${}^{(p)}T_{j_1, \dots, j_l}^{i_1, \dots, i_k}(x)$ of the same tensor are:

$${}^{(p)}T_{t_1, \dots, t_l}^{s_1, \dots, s_k}(x) = \frac{\partial x_q^{s_1}}{\partial x_p^{i_1}} \dots \frac{\partial x_q^{s_k}}{\partial x_p^{i_k}} \frac{\partial x_p^{j_1}}{\partial x_q^{t_1}} \dots \frac{\partial x_p^{j_l}}{\partial x_q^{t_l}} \cdot {}^{(p)}T_{j_1, \dots, j_l}^{i_1, \dots, i_k}(x)$$

4.2 Operations on Tensors

4.2.1 Permutation of indices

- Let σ be some permutation of $1, 2, \dots, l$. σ acts on the ordered tuple (j_1, \dots, j_l) as $\sigma(j_1, \dots, j_l) = (j_{\sigma_1}, \dots, j_{\sigma_l})$. We say that a tensor $\tilde{T}_{j_1, \dots, j_l}^{i_1, \dots, i_k}(x)$ is obtained from a tensor $T_{j_1, \dots, j_l}^{i_1, \dots, i_k}(x)$ by means of a permutation σ of the lower indices if at each point of M :

$$\tilde{T}_{j_1, \dots, j_l}^{i_1, \dots, i_k}(x) = T_{\sigma(j_1, \dots, j_l)}^{i_1, \dots, i_k}(x)$$

Permutation of upper indicies is defined similarly.

4.2.2 Contraction of indicies

- By the contraction of a tensor $T_{j_1, \dots, j_l}^{i_1, \dots, i_k}(x)$ of type (k, l) with respect to the indicies i_a, j_a we mean the tensor (summation over n):

$$T_{j_1, \dots, j_{l-1}}^{i_1, \dots, i_{k-1}}(x) = T_{j_1, \dots, j_{a-1}, n, j_{a+1}, \dots, j_l}^{i_1, \dots, i_{a-1}, n, i_{a+1}, \dots, i_k}(x)$$

Of type $(k - 1, l - 1)$

4.2.3 Product of Tensors

- Given two tensors $T = (T_{j_1, \dots, j_l}^{i_1, \dots, i_k})$ of type (k, l) and $P = (P_{j_1, \dots, j_q}^{i_1, \dots, i_p})$ of type (p, q) , we define their product to be the tensor product $S = T \otimes P$ of type $(k + p, l + q)$ with components:

$$S_{j_1, \dots, j_{l+q}}^{i_1, \dots, i_{k+p}} = T_{j_1, \dots, j_l}^{i_1, \dots, i_k} P_{j_{l+1}, \dots, j_q}^{i_{k+1}, \dots, i_p}$$

This multiplication is *not commutative* but it is associative.

- The result of applying the above three operations to tensors are again tensors.

4.3 Co-Vectors

- Recall that the differential of a function f of x^1, \dots, x^n corresponding to the increments dx^i in the x^i is:

$$df = \frac{\partial f}{\partial x^i} dx^i$$

Since dx^i is a vector df has the same value in any co-ord system. In general, given any co-vector (T_i) , the differential form $T_i dx^i$ is invariant under change of chart. We can thus identify $dx^i \equiv e^i$ as the *canonical basis of co-vectors or cotangent space*.

4.4 Skew-Symmetric Tensor

- A *skew-symmetric tensor* of type $(0, k)$ is a tensor T_{i_1, \dots, i_k} satisfying:

$$T_{\sigma(i_1, \dots, i_k)} = \mathfrak{s}(\sigma) T_{i_1, \dots, i_k}$$

where for all permutations $\mathfrak{s}(\sigma)$ is the sign function. i.e. $\mathfrak{s}(\sigma) = +1(-1)$ for even(odd) permutation. If two indices of T_{i_1, \dots, i_k} are the same then the corresponding component of T_{i_1, \dots, i_k} is 0. This means if $k > n$ the tensor is automatically 0.

- The standard basis at a given point is:

$$dx^{i_1} \wedge \dots \wedge dx^{i_k}, \quad i_1 < i_2 < \dots < i_k$$

Where:

$$dx^{i_1} \wedge \dots \wedge dx^{i_k} = \sum_{\sigma \in S_k} \mathfrak{s}(\sigma) e^{i_{\sigma_1}} \otimes \dots \otimes e^{i_{\sigma_k}}$$

Here S_k is the symmetric group. i.e. the group of all permutations of k elements.

- The differential form of the skew-symmetric tensor (T_{i_1, \dots, i_k}) is:

$$\begin{aligned} T_{i_1, \dots, i_k} e^{i_1} \otimes \dots \otimes e^{i_k} &= \sum_{i_1 < i_2 < \dots < i_k} T_{i_1, \dots, i_k} dx^{i_1} \wedge \dots \wedge dx^{i_k} \\ &= \frac{1}{k!} T_{i_1, \dots, i_k} dx^{i_1} \wedge \dots \wedge dx^{i_k} \end{aligned}$$

Where the last step can be made as both $dx^{i_1} \wedge \dots \wedge dx^{i_k}$ and T_{i_1, \dots, i_k} are anti-symmetric.

4.5 Volume element

- A metric g_{ij} on a manifold is a tensor of type $(0, 2)$ and on an oriented manifold of $\dim(M) = n$ such a metric gives rise to a *volume element*:

$$T_{i_1, \dots, i_n} = \sqrt{|g|} \epsilon_{i_1, \dots, i_n}, \quad g = \det(g_{ij})$$

It is convenient to write the volume element in the notation of differential forms:

$$\Omega = \sqrt{|g|} dx^1 \wedge \dots \wedge dx^n$$

If g_{ij} is Riemann then the *volume* V of M is:

$$V = \int_M \Omega = \int_M \sqrt{|g|} dx^1 \wedge \dots \wedge dx^n$$

4.6 Generalized push forward

- We can generalize the push forward map we had on vectors earlier to the space of tensors $(k, 0)$:

$$f_* : \xi^{i_1, \dots, i_k} \rightarrow \eta^{a_1, \dots, a_k} = \frac{\partial f^{a_1}}{\partial x^{i_1}} \cdots \frac{\partial f^{a_k}}{\partial x^{i_k}} \xi^{i_1, \dots, i_k}$$

4.7 Pull back

- Let $T_x^{(0,k)}M$ denote the space of tensors of type $(0, k)$ at $x \in M$. Let f be a smooth map from M to N . It gives rise to a map:

$$f^* : T_{f(x)}^{(0,k)}N \rightarrow T_x^{(0,k)}M$$

which in terms of $x^i \in U \subset M$, and $y^a \in V \subset N$ is written as:

$$f^* : \eta_{a_1, \dots, a_k} \rightarrow \xi_{i_1, \dots, i_k} = \frac{\partial f^{a_1}}{\partial x^{i_1}} \cdots \frac{\partial f^{a_k}}{\partial x^{i_k}} \eta_{a_1, \dots, a_k}$$

The map f^* is called the *pullback*.

- We can then note the following relationship between pullbacks and push forwards. Let us denote the action of a vector on another vector as follows:

$$\zeta(\theta) \equiv \zeta_{i_1, \dots, i_k} \theta^{i_1, \dots, i_k}$$

Then we can write that:

$$(f^*\eta)(\xi) = \frac{\partial f^{a_1}}{\partial x^{i_1}} \cdots \frac{\partial f^{a_k}}{\partial x^{i_k}} \eta_{a_1, \dots, a_k} \xi^{i_1, \dots, i_k} = \eta(f_*\xi)$$

5 Manifolds and surfaces

5.1 Immersion

- A manifold M of dim m is said to be immersed in a manifold N of dim $n \geq m$ if \exists a smooth map $f : M \rightarrow N$ such that the push forward map f_* is at each point a one to one map of the tangent space.

The map f is called the *immersion* of M to N .

Since f_* is at each a point one to one map of the tangent space, in terms of local co-ords the Jacobian matrix of f at each point has rank equal to $m = \dim M$.

5.1.1 Embedding

- An immersion of M to N is called an *embedding* if it one to one. Then M is called a *sub-manifold* of N .
- To see the difference between these two definitions note that a Klein bottle is immersed in \mathbb{R}^3 but not embedded as its tangent spaces are distinct (intersecting points can have different tangent spaces) but the map of points is not one- to one as there are cross overs.

5.2 Manifold with boundary

- A closed region A of a manifold M defined by an inequality:

$$f(x) \leq 0, \quad (\text{or } f(x) \geq 0)$$

where f is a real-valued function on M . This region is a *Manifold with boundary*. It is assumed that the boundary ∂A given by $f(x) = 0$ is a non-singular sub-manifold of M i.e. $\nabla f \neq 0$ on ∂A .

5.2.1 Closed manifold

- A compact manifold without a boundary is called *closed*.

5.3 Surfaces as Manifolds

- A *Non-singular surface* M of dimension k in n -dim Euclidean space is given by a set of $n - k$ equations:

$$f_i(x^1, \dots, x^n) = 0, \quad i = 1, \dots, n - k$$

where $\forall x$ the matrix $\left(\frac{\partial f_i}{\partial x^\alpha} \right)$ has rank $n - k$.

5.4 Orientation of surfaces

5.4.1 Orientation class

- Consider a frame $\tau_1 = (e_1^{(1)}, \dots, e_n^{(1)})$ called an ordered basis and another frame $\tau_1 = (e_1^{(2)}, \dots, e_n^{(2)})$ then we say that they lie in the *same orientation class* if $\det A > 0$ and the *opposite orientation*

class if $\det A < 0$. Where A is defined as:

$$A : e_k^{(1)} \rightarrow e_k^{(2)}$$

5.4.2 Orientability

- A manifold is said to be *orientable* if it is possible to choose at every point of it a single orientation class depending continuously on the points.

A particular choice of such an orientation class for each point is called an orientation of the manifold, and a manifold equipped with a particular orientation is said to be *oriented*.

If no orientation exists the manifold is said to be *non-orientable*

5.5 Two-sided hyper-surface

- A connected $(n - 1)$ -dim sub-manifold of \mathbb{R}^n is called two sided if a single valued continuous field of unit normals can be defined on it.

such a sub-manifold is called a *two-sided hyper-surface*.

6 Lie Groups

6.1 Group

- A *group* is a non-empty set G on which there is defined a binary operation $(a, b) \rightarrow ab$ satisfying the following properties:
 - Closure: If a and b belong to G , then $ab \in G$.
 - Associativity: $\forall a, b, c \in G, \quad a(bc) = (ab)c$.
 - Identity: \exists an element $1 \in G$ st: $a1 = 1a = a, \quad \forall a \in G$
 - Inverse: If $a \in G$ then $\exists a^{-1} \in G$ st: $aa^{-1} = a^{-1}a = 1$.

6.2 Lie Group

- A manifold G is called a *Lie Group* if it has given on it a group operation with the properties that the maps $\varphi : G \rightarrow G$, defined by $\varphi(g) = g^{-1}$ and $\psi : G \times G \rightarrow G$ defined by $\psi(g, h) = gh$, are smooth maps.

6.3 Example of Lie groups

6.3.1 General Linear group

- This is $GL(n, \mathbb{R})$ consisting of all $n \times n$ real matrices with non zero determinant in a region \mathbb{R}^{n^2} .
 $\dim GL(n, \mathbb{R}) = n^2$.

6.3.2 Special Linear group

- This is $SL(n, \mathbb{R})$ consisting of all $n \times n$ real matrices with determinant equal to 1. It is a hyper-surface in \mathbb{R}^{n^2} .

$$\det A = 1, \quad A \in Mat(n, \mathbb{R})$$

$$\dim SL(n, \mathbb{R}) = n^2 - 1.$$

6.3.3 Orthogonal group

- This is $O(n, \mathbb{R})$ consisting of all $n \times n$ real matrices Satisfying:

$$A^T \cdot A = \mathbb{I}, \quad A \in Mat(n, \mathbb{R})$$

$$\dim O(n, \mathbb{R}) = \frac{1}{2}n(n-1).$$

6.3.4 Special Orthogonal group

- This is $SO(n, \mathbb{R})$ consisting of all $n \times n$ real matrices Satisfying:

$$A^T \cdot A = \mathbb{I}, \quad \det(A) = 1, \quad A \in Mat(n, \mathbb{R})$$

$$\dim SO(n, \mathbb{R}) = \frac{1}{2}n(n-1).$$

6.3.5 Pseudo Orthogonal group

- This is $O(p, q, n)$ consisting of all $n \times n$ real matrices Satisfying:

$$A^T \cdot \eta \cdot A = \eta, \quad \det(A) = 1, \quad \eta = \text{diag}\{\underbrace{1, \dots, 1}_p, \underbrace{-1, \dots, -1}_q\}$$

$$\dim O(p, q, n) = \frac{1}{2}n(n-1).$$

6.3.6 Unitary group

- This is $U(n)$ consisting of all $n \times n$ complex matrices Satisfying:

$$A^\dagger \cdot A = \mathbb{I}, \quad A \in \text{Mat}(n, \mathbb{C})$$

$$\dim U(n) = n^2.$$

6.3.7 Special Unitary group

- This is $SU(n)$ consisting of all $n \times n$ complex matrices Satisfying:

$$A^\dagger \cdot A = \mathbb{I}, \quad \det(A) = 1, \quad A \in \text{Mat}(n, \mathbb{C})$$

$$\dim U(n) = n^2 - 1.$$

7 Projective spaces

7.1 Real protective space

- The *real Projective space* $\mathbb{R}P^n$ is the set of all straight lines in \mathbb{R}^{n+1} passing through the origin. Equivalently it is the set of equivalence classes of non-zero vectors in \mathbb{R}^{n+1} where two non-zero vectors are equivalent if they are scalar multiples of one another.
- We may think of $\mathbb{R}P^n$ as obtained from S^n by gluing, that is identifying diametrically opposite points. This means we have the isomorphism $\mathbb{R}P^n \simeq S^n/Z_2$.

7.2 Quaternions

- The set \mathbb{H} of *Quaternions* consists of all linear combinations:

$$q \in \mathbb{H}, \quad q = a\mathbf{1} + b\mathbf{i} + c\mathbf{j} + d\mathbf{k}, \quad a, b, c, d \in \mathbb{R}$$

Where $\mathbf{1}, \mathbf{i}, \mathbf{j}, \mathbf{k}$ are linearly independent. Where these bases satisfy the following multiplications:

$$\begin{aligned} \mathbf{i} \cdot \mathbf{j} &= \mathbf{k} = -\mathbf{j} \cdot \mathbf{i}, & \mathbf{j} \cdot \mathbf{k} &= \mathbf{i} = -\mathbf{k} \cdot \mathbf{j}, & \mathbf{k} \cdot \mathbf{i} &= \mathbf{j} = -\mathbf{i} \cdot \mathbf{k}, \\ \mathbf{i} \cdot \mathbf{i} &\equiv \mathbf{i}^2 = -1, & \mathbf{j} \cdot \mathbf{j} &\equiv \mathbf{j}^2 = -1, & \mathbf{k} \cdot \mathbf{k} &\equiv \mathbf{k}^2 = -1, \\ \mathbf{i} \cdot \mathbf{1} &= \mathbf{i} = \mathbf{1} \cdot \mathbf{i}, & \mathbf{j} \cdot \mathbf{1} &= \mathbf{j} = \mathbf{1} \cdot \mathbf{j}, & \mathbf{k} \cdot \mathbf{1} &= \mathbf{k} = \mathbf{1} \cdot \mathbf{k}, & \mathbf{1} \cdot \mathbf{1} &= \mathbf{1}. \end{aligned}$$

This makes \mathbb{H} an associative algebra over the field of real numbers.

7.3 Complex Projective spaces

