

Fibre Bundles and Gauge Theory

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1. Introduction

Let us start considering a linear system of differential equations of order 1 on an interval $I \subseteq \mathbb{R}$.

$$\frac{dx}{dt} = -Ax, \quad t \in I \tag{1.1}$$

where $x = (x_1, \dots, x_n) \in \mathbb{R}^n$ and $A = A(t)$ is an $n \times n$ real matrix.

It is well-known that given $x_0 = (x_{10}, \dots, x_{n0}) \in \mathbb{R}^n$ and $t_0 \in I$, there is a unique solution $x(t) = (x_1(t), \dots, x_n(t))$ to (1.1) such that $x(t_0) = x_0$. The simplest case is of course if $A \equiv 0$ and in fact we can change (1.1) into this by *change of gauge*

$$y = gx \tag{1.2}$$

where $g = g(t) \in \text{GL}(n, \mathbb{R})$. To see this notice that we want to find g such that

$$\frac{dy}{dt} = \frac{dg}{dt} \cdot x + g \cdot \frac{dx}{dt} = \frac{dg}{dt} \cdot x - gAx = 0.$$

That is we want

$$\frac{dg}{dt} = gA \tag{1.3}$$

or by transposing

$$\frac{dg^t}{dt} = A^t g^t.$$

That is, the rows of g are solutions to (1.1) with A replaced by $-A^t$. Hence we just choose $g_0 = g(t_0) \in \text{GL}(n, \mathbb{R})$ arbitrarily and find the unique solution corresponding to each row, i.e., we find the unique solution to (1.3)

with $g(t_0) = g_0$. To see that g is in fact invertible we solve similarly the equation of matrices

$$\frac{dh}{dt} = -Ah$$

with $h(t_0) = g_0^{-1}$ and observe that

$$\frac{d}{dt}(gh) = \frac{dg}{dt} \cdot h + g \cdot \frac{dh}{dt} = gAh - gAh = 0,$$

thus by uniqueness $g \cdot h = 1$. Hence we have proved the following proposition.

Proposition 1.1. *Consider a system of equations (1.1) on an interval $I \subseteq \mathbb{R}$. Let $t_0 \in \mathbb{R}$ and $g_0 \in \text{GL}(n, \mathbb{R})$. Then there is a unique gauge transformation $g = g(t)$, such that (1.1) is equivalent to*

$$\frac{dy}{dt} = 0, \quad \text{for } y = gx \text{ and } g(t_0) = g_0.$$

Remark. We shall think of g as a family of linear transformations parametrised by I , i.e. given by a map \bar{g} in the commutative diagram

$$\begin{array}{ccc} I \times \mathbb{R}^n & \xrightarrow{\bar{g}} & I \times \mathbb{R}^n \\ & \searrow \text{proj} & \swarrow \text{proj} \\ & & I \end{array}$$

with $\bar{g}(t, x) = (t, g(t)x)$.

We want to generalise this to the case where I is replaced by an open set $U \subseteq \mathbb{R}^m$ or more generally by any *differentiable manifold* $M = M^m$. For that purpose it is convenient to rewrite (1.1) as an equation of differential forms:

$$dx = -(Adt)x.$$

Absorbing dt into the matrix we shall in general consider a matrix A of differential 1-forms on M and we want to solve the equation

$$dx = -Ax \tag{1.4}$$

for $x = (x_1, \dots, x_n)$ a vector of functions on M . Again a gauge transformation is a smooth family of non-singular linear maps $g = g(t) \in \text{GL}(n, \mathbb{R})$, $t \in M$, or equivalently, a smooth map \bar{g} in the commutative diagram

$$\begin{array}{ccc} M \times \mathbb{R}^n & \xrightarrow{\bar{g}} & M \times \mathbb{R}^n \\ \text{proj} \searrow & & \swarrow \text{proj} \\ & M & \end{array}$$

such that $\bar{g}(t, x) = (t, g(t)x)$ defines a non-singular linear map $g(t)$ for each $t \in M$. Again putting $y = gx$ the equation (1.4) changes into the *gauge equivalent* equation

$$dy = -A^g y$$

with $A^g = gAg^{-1} - (dg)g^{-1}$. In particular we can transform the equation into the *trivial equation*

$$dy = 0$$

(which has the obvious solution $y = \text{constant}$) if and only if we can find g satisfying

$$dg = gA \quad \text{or} \quad g^{-1}dg = A. \quad (1.5)$$

Example 1.2. Let $M = \mathbb{R}^2$ with variables (t^1, t^2) . Consider the equation (1.4) with $A = -t^2 dt^1$, that is

$$dx = (t^2 dt^1)x,$$

or equivalently, the partial differential equations

$$\frac{\partial x}{\partial t^1} = t^2 x, \quad \frac{\partial x}{\partial t^2} = 0. \quad (1.6)$$

But this implies

$$0 = \frac{\partial^2 x}{\partial t^1 \partial t^2} = \frac{\partial}{\partial t^2}(t^2 x) = x.$$

Hence only $x \equiv 0$ is a solution to (1.6) whereas the equation $dy = 0$ has other (constant) solutions as well. Therefore they are *not* gauge equivalent.

More systematically let us find a necessary condition for solving (1.5): Suppose g is a solution; then

$$0 = ddg = d(gA) = (dg) \wedge A + g dA = gA \wedge A + gdA$$

and since g is invertible we obtain

$$F_A = A \wedge A + dA = 0. \tag{1.7}$$

This is called the *integrability condition* for the equation (1.4) and F_A is called the *curvature*. We have thus proved the first statement of the following proposition.

Proposition 1.3. *For the equation (1.4) to be gauge equivalent to the trivial equation $dy = 0$ a necessary condition is that the curvature $F_A = 0$. Locally this is also sufficient.*

Proof. For the proof of the second statement it suffices to take $M = B^m \subseteq \mathbb{R}^m$ the open ball of radius 1, that is $B^m = \{u = (u_1, \dots, u_n) \mid |u| < 1\}$. Let S^{m-1} be the sphere $S^{m-1} = \{u \mid |u| = 1\}$ and define $g: B^m \rightarrow \text{GL}(n, \mathbb{R})$ by solving the equation

$$\frac{\partial g}{\partial r} = gA \left(\frac{\partial}{\partial r} \right), \quad g(0) = 1,$$

along the radial lines $\{ru \mid 0 \leq r \leq 1\}$ for each $u \in S^{m-1}$. Now choose a local coordinate system (v^1, \dots, v^{m-1}) for S^{m-1} so that we get polar coordinates (r, v^1, \dots, v^{m-1}) on B^m . By construction the equation (1.5) holds when evaluated on the tangent vector $\partial/\partial r$. We need to evaluate on $\partial/\partial v^i$, $i = 1, \dots, m-1$, as well, that is, we must prove

$$\frac{\partial g}{\partial v^i} = gA \left(\frac{\partial}{\partial v^i} \right), \quad i = 1, \dots, m-1. \tag{1.8}$$

Notice that by construction (1.5) and hence also (1.8) holds at $u = 0$. Let

us calculate $\partial/\partial r$ of the difference using the assumption

$$\begin{aligned} 0 &= F_A \left(\frac{\partial}{\partial r}, \frac{\partial}{\partial v^i} \right) \\ &= \frac{\partial}{\partial r} A \left(\frac{\partial}{\partial v^i} \right) - \frac{\partial}{\partial v^i} A \left(\frac{\partial}{\partial r} \right) \\ &\quad + A \left(\frac{\partial}{\partial r} \right) A \left(\frac{\partial}{\partial v^i} \right) - A \left(\frac{\partial}{\partial v^i} \right) A \left(\frac{\partial}{\partial r} \right). \end{aligned}$$

Then

$$\begin{aligned} &\frac{\partial}{\partial r} \left(\frac{\partial g}{\partial v^i} - g A \left(\frac{\partial}{\partial v^i} \right) \right) \\ &= \frac{\partial^2 g}{\partial r \partial v^i} - \frac{\partial g}{\partial r} \cdot A \left(\frac{\partial}{\partial v^i} \right) - g \frac{\partial}{\partial r} A \left(\frac{\partial}{\partial v^i} \right) \\ &= \frac{\partial g}{\partial v^i} A \left(\frac{\partial}{\partial r} \right) + g \frac{\partial}{\partial v^i} A \left(\frac{\partial}{\partial r} \right) - g A \left(\frac{\partial}{\partial r} \right) A \left(\frac{\partial}{\partial v^i} \right) - g \frac{\partial}{\partial r} A \left(\frac{\partial}{\partial v^i} \right) \\ &= \frac{\partial g}{\partial v^i} A \left(\frac{\partial}{\partial r} \right) - g A \left(\frac{\partial}{\partial v^i} \right) A \left(\frac{\partial}{\partial r} \right) \\ &= \left(\frac{\partial g}{\partial v^i} - g A \left(\frac{\partial}{\partial v^i} \right) \right) A \left(\frac{\partial}{\partial r} \right). \end{aligned}$$

By uniqueness of the solution to the equation

$$\frac{\partial x}{\partial r} = x A \left(\frac{\partial}{\partial r} \right)$$

along a radial we conclude that

$$\frac{\partial g}{\partial v^i} - g A \left(\frac{\partial}{\partial v^i} \right) \equiv 0$$

which was to be proven. \square

In the global case there are obvious difficulties even for M of dimension 1.

Example 1.4. Let $M = S^1 = \{(\cos 2\pi t, \sin 2\pi t) \mid t \in [0, 1]\}$ and suppose $A = A_0 dt$ for a constant matrix A_0 . Then, on the interval $[0, 1)$, the unique gauge transformation to the trivial equation with $g(0) = 1$ is given by

$$g(t) = \exp(tA_0) = \sum_{n=0}^{\infty} \frac{t^n A_0^n}{n!}$$

so that $g(1) = \exp(A_0)$. Hence we have a globally defined gauge transformation to the trivial equation if and only if $g_1 = \exp(A_0) = 1$. If $g_1 \neq 1$, on the other hand, we can overcome this difficulty if we replace $S^1 \times \mathbb{R}^n$ with the vector bundle obtained from $[0, 1] \times \mathbb{R}^n$ by identifying $(1, v)$ with $(0, g_1 v)$.

This example suggests that we should (and will) generalize the problem to vector bundles (real or complex). However, as seen above, it is really the Lie group $G = \text{GL}(n, \mathbb{R})$ (or $G = \text{GL}(n, \mathbb{C})$) which enters in the question of gauge transformations. This gives rise to the notion of a *principal G -bundle* with a *connection* where locally the connection is given by the matrix A of 1-forms occurring in the equation (1.4). Again we will encounter the notion of *curvature* as in (1.7) which is the starting point for the definition of *characteristic forms* and *characteristic classes*.

2. Vector Bundles and Frame Bundles

In this chapter we shall introduce the notion of a vector bundle and the associated frame bundle. Unless otherwise specified all vector spaces are real, but we could of course use complex vector spaces instead.

Definition 2.1. An n -dimensional differentiable (real) vector bundle is a triple (V, π, M) where $\pi: V \rightarrow M$ is a differentiable mapping of smooth manifolds with the following extra structure:

- (1) For every $p \in M$, $V_p = \pi^{-1}(p)$ has the structure of a real vector space of dimension n , and satisfying the following condition:
- (2) Every point in M has an open neighborhood U with a diffeomorphism

$$f: \pi^{-1}(U) \rightarrow U \times \mathbb{R}^n$$

such that the diagram

$$\begin{array}{ccc}
 \pi^{-1}(U) & \xrightarrow{f} & U \times \mathbb{R}^n \\
 \searrow \pi & & \swarrow \text{proj} \\
 & U &
 \end{array}$$

commutes, i.e., $f(V_p) \subseteq p \times \mathbb{R}^n$ for all $p \in U$; and $f_p = f|_{V_p}: V_p \rightarrow p \times \mathbb{R}^n$ is an isomorphism of vector spaces for each $p \in U$.

Notation. (V, π, M) is called a vector bundle over M , V is called the *total space*, M is the *base space*, and π is the projection. We shall often write V instead of (V, π, M) . The diffeomorphism f in definition 2.1 is called a *local trivialization* of V over U . If f exists over all of M then we call V a *trivial bundle*.

Remark. If (V, π, M) is an n -dimensional vector bundle, then the total space V is a manifold of dimension $n + m$, where $m = \dim M$.

Example 2.2. The product bundle $M \times \mathbb{R}^n$ with $\pi = \text{proj}: M \times \mathbb{R}^n \rightarrow M$ is obviously a trivial vector bundle.

Exercise 2.3. For $g \in \text{GL}(n, \mathbb{R})$ show that the quotient space of $\mathbb{R} \times \mathbb{R}^n$ by the identification $(t, x) \sim (t + 1, gx)$ where $(t, x) \in \mathbb{R} \times \mathbb{R}^n$, defines an n -dimensional vector bundle over $\mathbb{R}/\mathbb{Z} \cong S^1$.

Example 2.4. The tangent bundle of a differentiable manifold $M = M^m$, that is, the disjoint union of tangent spaces

$$TM = \bigsqcup_{p \in M} T_p M$$

is in a natural way the total space in a m -dimensional vector bundle with the projection $\pi: TM \rightarrow M$ given by $\pi(v) = p$ for $v \in T_p M$. If $(U, x) = (U, x^1, \dots, x^m)$ is a local coordinate system for M then

$$\pi^{-1}(U) = \bigsqcup_{p \in U} T_p M$$

and we have a local trivialization

$$x_*: \pi^{-1}(U) \rightarrow U \times \mathbb{R}^m$$

defined by

$$x_* \left(\sum_{i=1}^m v^i \cdot \frac{\partial}{\partial x^i} \Big|_p \right) = (p, v^1, \dots, v^m).$$

Sections

For a vector bundle (V, π, M) it is useful to study its sections.

Definition 2.5. A (differentiable) *section* σ in (V, π, M) is a differentiable mapping

$$\sigma: M \rightarrow V$$

such that $\pi \circ \sigma = \text{id}_M$, that is, $\sigma(p) \in V_p = \pi^{-1}(p)$ for all $p \in M$.

Notation. The set of differentiable sections in V is often denoted $\Gamma(V)$.

Example 2.6. Every vector bundle V has a zero section, i.e., the section $\sigma(p) = 0 \in V_p$, for all $p \in M$. The zero section is differentiable and in fact $\Gamma(V)$ is in a natural way a vector space with the zero section as the zero vector.

Example 2.7. A (differentiable) section in the tangent bundle of a manifold M is the same thing as a (differentiable) vector field on M .

Example 2.8. For the product bundle $V = M \times \mathbb{R}^n$ (example 2.2) a section σ in V has the form

$$\sigma(p) = (p, s^1(p), \dots, s^n(p)) = (p, s(p))$$

and σ is differentiable if and only if $s: M \rightarrow \mathbb{R}^n$ is differentiable. Thus we have a 1-1 correspondence between differentiable sections in V and differentiable functions $s: M \rightarrow \mathbb{R}^n$.

The Frame Bundle

By the last example the notion of a section in a vector bundle V generalizes the notion of a function on it. But we can actually do even better: We can consider a section of V as a function defined on a different manifold, the so-called frame bundle $F(V)$ for V .

First consider a single n -dimensional real vector space V and define

$$F(V) = \text{Iso}(\mathbb{R}^n, V) = \{\text{linear isomorphisms } x: \mathbb{R}^n \rightarrow V\}.$$

An element $x \in F(V)$ is determined by the n linear independent vectors

$$x_1 = x(e_1), \dots, x_n = x(e_n)$$

where $\{e_1, \dots, e_n\}$ is the standard basis in \mathbb{R}^n . The element $x \in F(V)$ is called a n -frame in V . Notice that a choice of basis in V gives an identification of $F(V)$ with

$$\text{Iso}(\mathbb{R}^n, \mathbb{R}^n) = \text{GL}(n, \mathbb{R})$$

which is an open set in the set $M(n, \mathbb{R}) = \mathbb{R}^{n^2}$ of all $n \times n$ matrices.

Now let us return to (V, π, M) a differentiable vector bundle over the manifold M . We shall make the disjoint union

$$F(V) = \bigsqcup_{p \in M} F(V_p) = \bigsqcup_{p \in M} \text{Iso}(\mathbb{R}^n, V_p)$$

into a differentiable manifold such that $\bar{\pi}: F(V) \rightarrow M$ given by $\bar{\pi}(x) = p$ for $x \in F(V_p)$ is differentiable. Thus suppose we have a local trivialization of V

$$f: \pi^{-1}(U) \rightarrow U \times \mathbb{R}^n.$$

Then there is a natural bijection

$$\bar{f}: \bar{\pi}^{-1}(U) \rightarrow U \times \text{GL}(n, \mathbb{R}) \quad (2.1)$$

defined by

$$x \mapsto (p, f_p \circ x), \quad \text{for } x \in F(V_p).$$

where $f_p: V_p \rightarrow \mathbb{R}^n$ is the restriction of f to V_p .

Proposition 2.9. *There is a natural topology and differentiable structure on $F(V)$ satisfying:*

- (1) $F(V)$ is a differentiable manifold of dimension $m + n^2$.
- (2) The bijections \bar{f} defined by (2.1) are diffeomorphisms for all local trivializations f .
- (3) The mapping $\bar{\pi}$ is differentiable and locally we have a commutative diagram

$$\begin{array}{ccc} \bar{\pi}^{-1}(U) & \xrightarrow{\bar{f}} & U \times \text{GL}(n, \mathbb{R}) \\ & \searrow \bar{\pi} & \swarrow \text{proj} \\ & & U \end{array}$$

- (4) We have a differentiable right group action

$$F(V) \times \text{GL}(n, \mathbb{R}) \rightarrow F(V) \quad (2.2)$$

given by

$$x \cdot g = x \circ g, \quad \text{for } x \in F(V_p), g \in \text{GL}(n, \mathbb{R}).$$

Exercise 2.10. Prove proposition 2.9.

Remark. (1) The proof of the first statement is similar to the construction of the differentiable structure on the tangent bundle of a manifold.

(2) That the mapping in (2.2) is a differentiable right group action means that it is given by a differentiable mapping and that it satisfies

$$(x \cdot g) \cdot g' = x \cdot (gg') \quad \text{for all } x \in F(V), g, g' \in \text{GL}(n, \mathbb{R}),$$

and

$$x \cdot 1 = x \quad \text{for all } x \in F(V).$$

Notice also that each $F(V_p)$ is an orbit, that is $F(V_p) = x \cdot \text{GL}(n, \mathbb{R})$ for any $x \in F(V_p)$, and we can identify M with the orbit space $F(V)/\text{GL}(n, \mathbb{R})$.

Notation. The triple $(F(V), \bar{\pi}, M)$ is called the bundle of n -frames of V or for short, the frame bundle of V .

Now we can interpret the set of sections of V in the following way:

Proposition 2.11. *There is a natural 1-1 correspondence between the vector space $\Gamma(V)$ and the space of equivariant functions on $F(V)$ with values in \mathbb{R}^n , i.e., the set of differentiable functions $\tilde{s}: F(V) \rightarrow \mathbb{R}^n$ satisfying*

$$\tilde{s}(x \cdot g) = g^{-1}\tilde{s}(x), \quad \text{for all } x \in F(V), g \in \text{GL}(n, \mathbb{R}). \quad (2.3)$$

Proof. Let $s \in \Gamma(V)$ and define \tilde{s} by

$$\tilde{s}(x) = x^{-1}(s(p)), \quad \text{for } x \in F(V_p) = \text{Iso}(\mathbb{R}^n, V_p).$$

Then it is straightforward to check that \tilde{s} satisfies (2.3). Also, using the local triviality in (2.1), it follows that \tilde{s} is differentiable if and only if s is. On the other hand given $\tilde{s}: F(V) \rightarrow \mathbb{R}^n$ satisfying (2.3) it is easy to see that $\bar{s}: F(V) \rightarrow V$ given by

$$\bar{s}(x) = x(\tilde{s}(x))$$

is constant on every orbit $F(V_p)$, and so \bar{s} defines an function $s: M \rightarrow V$ such that the diagram

$$\begin{array}{ccc}
 F(V) & \xrightarrow{\tilde{s}} & V \\
 \downarrow \tilde{\pi} & \nearrow s & \\
 M & &
 \end{array}$$

commutes. Again s is seen to be differentiable (provided \tilde{s} is) using the local trivialization in (2.1). \square

We next study homomorphisms between vector bundles with the same base M , that is, vector bundles (V, π, M) and (V', π', M) .

Definition 2.12. A *homomorphism* $\varphi: V \rightarrow V'$ is a differentiable mapping of total spaces such that the following holds:

(1) The diagram

$$\begin{array}{ccc}
 V & \xrightarrow{\varphi} & V' \\
 \pi \searrow & & \nearrow \pi' \\
 & M &
 \end{array}$$

commutes, that is, $\varphi_p = \varphi|_{V_p}$ maps V_p to V'_p .

(2) $\varphi_p: V_p \rightarrow V'_p$ is a linear mapping for each $p \in M$.

An *isomorphism* $\varphi: V \rightarrow V'$ is a bijective map where both φ and φ^{-1} are homomorphisms.

Example 2.13. A trivialization $f: V \rightarrow M \times \mathbb{R}^n$ is an isomorphism to the product bundle.

Remark. It follows from the definition that a homomorphism $\varphi: V \rightarrow V'$ is an isomorphism if and only if φ is a diffeomorphism of total spaces such that $\varphi_p: V_p \rightarrow V'_p$ is an isomorphism of vector spaces for every $p \in M$. We can improve this:

Proposition 2.14. A homomorphism $\varphi: V \rightarrow V'$ is an isomorphism if and only if $\varphi_p: V_p \rightarrow V'_p$ is an isomorphism of vector spaces for every $p \in M$.

Proof. (\Rightarrow) Obvious.

(\Leftarrow) We must show that φ is a diffeomorphism. Since φ is clearly bijective it suffices to show that φ^{-1} is differentiable. This however is a local problem, so we can assume $V = M \times \mathbb{R}^n$, $V' = M \times \mathbb{R}^n$. In that case $\varphi: M \times \mathbb{R}^n \rightarrow M \times \mathbb{R}^n$ has the form

$$\varphi(p, v) = (p, \varphi_p(v))$$

where $\varphi_p: \mathbb{R}^n \rightarrow \mathbb{R}^n$ is a linear isomorphism. It is easy to see using local coordinates for M that the Jacobi matrix for φ at every point (p, v) has the form

$$\begin{bmatrix} I & 0 \\ X & \varphi_p \end{bmatrix} \quad (2.4)$$

where φ_p is the matrix for $\varphi_p: \mathbb{R}^n \rightarrow \mathbb{R}^n$. Since φ_p is an isomorphism the matrix (2.4) is clearly invertible and hence the proposition follows from the Inverse Function Theorem. \square

Corollary 2.15. *A vector bundle (V, π, M) is trivial if and only if the associated frame bundle $(F(V), \bar{\pi}, M)$ has a section; i.e., if there is a differentiable mapping $\sigma: M \rightarrow F(V)$ such that $\bar{\pi} \circ \sigma = \text{id}_M$.*

Proof. (\Rightarrow) Let $f: V \rightarrow M \times \mathbb{R}^n$ be a trivialization. Then we define

$$\sigma: M \rightarrow F(V) \quad \text{by} \quad \sigma(p) = f_p^{-1} \in \text{Iso}(\mathbb{R}^n, V_p).$$

By the definition of the differentiable structure in $F(V)$ σ is differentiable since

$$f \circ \sigma(p) = (p, 1) \in M \times \text{GL}(n, \mathbb{R}^n).$$

(\Leftarrow) Let $\sigma: M \rightarrow F(V)$ be a differentiable section. Then we define a homeomorphism $\varphi: M \times \mathbb{R}^n \rightarrow V$ by

$$\varphi(p, v) = \sigma(p)(v), \quad \text{for } (p, v) \in M \times \mathbb{R}^n.$$

(here $\sigma(p) \in \text{Iso}(\mathbb{R}^n, V_p)$). It follows from proposition 2.14 that φ is an isomorphism, hence $f = \varphi^{-1}: V \rightarrow M \times \mathbb{R}^n$ is a trivialization. \square

Remark. A section σ in $F(V)$ is equivalent to a set of n sections $\{\sigma_1, \dots, \sigma_n\}$ in V such that $\{\sigma_1(p), \dots, \sigma_n(p)\} \subseteq V_p$ is a basis for V_p for every $p \in M$ (cf. the definition of $F(V_p)$). A section in $F(V)$ is also called a *moving frame* for V . Since every vector bundle is locally trivial it always has a local moving frame.

Riemannian Metrics

For the remainder of this chapter we shall study vector bundles with a Riemannian metric: First recall that on a single vector space V an inner product $\langle \cdot, \cdot \rangle$ is a symmetric, positive definite, bilinear form on V , that is, a function $\langle \cdot, \cdot \rangle: V \times V \rightarrow \mathbb{R}$ such that

- (1) $\langle v, w \rangle$, $v, w \in V$, is linear in both v and w ,
- (2) $\langle v, w \rangle = \langle w, v \rangle$, for all $v, w \in V$,
- (3) $\langle v, v \rangle \geq 0$, for all $v \in V$, and
- (4) $\langle v, v \rangle = 0$ if and only if $v = 0$.

Now return to V a vector bundle over M .

Definition 2.16. A *Riemannian metric* on a vector bundle V over M is a collection of inner products $\langle \cdot, \cdot \rangle_p$ on V_p , $p \in M$, which is differentiable in the following sense: For $s_1, s_2 \in \Gamma(V)$ the function $\langle s_1, s_2 \rangle$ given by $\langle s_1, s_2 \rangle(p) = \langle s_1(p), s_2(p) \rangle_p$ is differentiable.

Notation. We shall often just write $\langle v_1, v_2 \rangle = \langle v_1, v_2 \rangle_p$ for $v_1, v_2 \in V_p$.

Example 2.17. The product bundle $V = M \times \mathbb{R}^n$ has the standard inner product given by the usual inner product in \mathbb{R}^n :

$$\langle v, w \rangle = \sum_{i=1}^n v^i w^i, \quad \text{for } v = (v^1, \dots, v^n), w = (w^1, \dots, w^n).$$

Proposition 2.18. *Every vector bundle has a Riemannian metric.*

Exercise 2.19. Prove proposition 2.18. Hint: Use a partition of unity.

Now suppose (V, π, M) is an n -dimensional vector bundle with Riemannian metric $\langle \cdot, \cdot \rangle$.

Proposition 2.20. *Every point in M has a neighborhood U and a trivialization $f: \pi^{-1}(U) \rightarrow U \times \mathbb{R}^n$ such that $f_p: V_p \rightarrow \mathbb{R}^n$ is a linear isometry for every $p \in U$ (with the metric in $U \times \mathbb{R}^n$ given by example 2.17).*

Proof. By the remark following corollary 2.15 every point in M has a neighborhood U with a local *moving frame*, i.e. a set of sections $\{s_1, \dots, s_n\}$ of $(\pi^{-1}(U), \pi, U)$ such that $\{s_1(p), \dots, s_n(p)\}$ is a linear independent set for each $p \in U$. By means of the Gram-Schmidt process we can replace this set by $\{\sigma_1, \dots, \sigma_n\}$ such that $\{\sigma_1(p), \dots, \sigma_n(p)\}$ is an orthonormal basis for V_p for every $p \in U$. Again $\sigma_1, \dots, \sigma_n$ are all differentiable. As in the proof of corollary 2.15 we consider $\{\sigma_1, \dots, \sigma_n\}$ as a section of the frame bundle $F(V)$ over U , i.e. we obtain an isomorphism $\varphi: U \times \mathbb{R}^n \rightarrow \pi^{-1}(U)$ given by

$$\varphi(p, v) = \sigma(p)(v), \quad \text{for } (p, v) \in U \times \mathbb{R}^n.$$

Since $\varphi_p(e_i) = \sigma(p)(e_i) = \sigma_i(p)$ and since $\{\sigma_1(p), \dots, \sigma_n(p)\}$ is an orthonormal basis for V_p , it follows that $\varphi_p: \mathbb{R}^n \rightarrow V_p$ is a linear isometry for each $p \in U$. Hence $f = \varphi^{-1}: \pi^{-1}(U) \rightarrow U \times \mathbb{R}^n$ has the desired properties. \square

We can now define the orthogonal frame bundle for a vector bundle with a Riemannian metric. For a single vector space V with inner product $\langle \cdot, \cdot \rangle$ we let $F_O(V) \subseteq F(V)$ be the set

$$F_O(V) = \text{Isom}(\mathbb{R}^n, V) = \{\text{linear isometries } x: \mathbb{R}^n \rightarrow V\},$$

that is, $x \in F_O(V)$ if and only if the vectors

$$x_1 = x(e_1), \dots, x_n = x(e_n)$$

constitutes an orthonormal basis for $(V, \langle \cdot, \cdot \rangle)$. We will call x an *orthogonal n -frame* in V . With respect to a given orthonormal basis for V we get an identification of $F_O(V)$ with the orthogonal group $O(n) \subseteq \text{GL}(n, \mathbb{R})$, which is an $n(n-1)/2$ -dimensional submanifold in $\text{GL}(n, \mathbb{R})$.

Now return to (V, π, M) a vector bundle with a Riemannian metric $\langle \cdot, \cdot \rangle$ and we define the *orthogonal frame bundle* as the subset

$$F_O(V) = \bigsqcup_{p \in M} F_O(V_p) \subseteq F(V).$$

Proposition 2.21. (1) $F_O(V) \subseteq F(V)$ is a submanifold and

$$\bar{\pi}|_{F_O(V)}: F_O(V) \longrightarrow M$$

is differentiable.

(2) There is a differentiable right $O(n)$ -action

$$F_O(V) \times O(n) \longrightarrow F_O(V)$$

such that the orbits are the sets $F_O(V_p)$, $p \in M$.

(3) There are local diffeomorphisms

$$\bar{f}: \bar{\pi}^{-1}(U) \cap F_O(V) \longrightarrow U \times O(n)$$

such that $\bar{f}_p = f|_{F_O(V_p)}$ maps $F_O(V_p)$ to $p \times O(n)$ for every $p \in U$, and also

$$\bar{f}(x \cdot g) = \bar{f}(x) \cdot g, \quad \text{for all } x \in F_O(V_p), g \in O(n).$$

Proof. Choose a local trivialization

$$\bar{f}: \bar{\pi}^{-1}(U) \longrightarrow U \times \text{GL}(n, \mathbb{R})$$

as in proposition 2.20. Then the corresponding local diffeomorphism for the frame bundle $(F(V), \bar{\pi}, M)$

$$\bar{f}: \bar{\pi}^{-1}(U) \longrightarrow U \times \text{GL}(n, \mathbb{R})$$

is given on $F_p(V)$ by

$$\bar{f}(x) = (p, f_p \circ x), \quad x \in F_p(V)$$

where f_p is the restriction of f to V_p . Since $f_p: V_p \rightarrow \mathbb{R}^n$ is an isometry it follows that \bar{f} maps $F_O(V_p)$ to $p \times O(n)$, that is,

$$\bar{f}: \bar{\pi}^{-1}(U) \cap F_O(V) \longrightarrow U \times O(n)$$

is a bijection. Since $O(n) \subseteq \text{GL}(n, \mathbb{R})$ is a submanifold it follows that $F_O(V) \subseteq F(V)$ is also a submanifold and all the statements in the proposition are now straightforward. We leave the details to the reader. \square

Example 2.22. The real projective n -space $\mathbb{R}P^n$ is defined as the quotient space $(\mathbb{R}^{n+1} \setminus \{0\})/(\mathbb{R} \setminus \{0\})$, that is, $x = (x_1, \dots, x_n)$ is equivalent to $y = (y_1, \dots, y_n)$ if and only if $y = tx$ for some $t \in \mathbb{R} \setminus \{0\}$. Let $\eta: (\mathbb{R}^{n+1} \setminus \{0\}) \rightarrow \mathbb{R}P^n$ be the natural projection, that is,

$$\eta(x) = [x] = [x_1 : \dots : x_{n+1}]$$

and these $(n+1)$ -tuples are called the *homogenous coordinates*. $\mathbb{R}P^n$ is an n -dimensional differentiable manifold with coordinate systems (U_i, ζ_i) , $i = 1, \dots, n+1$, given by

$$U_i = \{[x] \in \mathbb{R}P^n \mid x_i \neq 0\}$$

and $\zeta_i: U_i \rightarrow \mathbb{R}^n$ defined by

$$\zeta_i[x_1, \dots, x_{n+1}] = \left(\frac{x_1}{x_i}, \dots, \frac{x_{i-1}}{x_i}, \frac{x_{i+1}}{x_i}, \dots, \frac{x_{n+1}}{x_i} \right).$$

Notice that the inclusion of the unit n -sphere $i: S^n \subseteq (\mathbb{R}^{n+1} \setminus \{0\})$ gives rise to a commutative diagram

$$\begin{array}{ccc} S^n & \xrightarrow{i} & \mathbb{R}^{n+1} \setminus \{0\} \\ \downarrow & & \downarrow \eta \\ S^n / \{\pm 1\} & \xrightarrow[\cong]{\bar{i}} & \mathbb{R}P^n \end{array}$$

Here \bar{i} is a homeomorphism; hence $\mathbb{R}P^n$ is compact.

We shall now construct a 1-dimensional vector bundle with $\mathbb{R}P^n$ as basis. This is called the *real Hopf-bundle* or the *canonical line bundle*. The total space $H \subseteq \mathbb{R}P^n \times \mathbb{R}^{n+1}$ is the subset

$$H = \{([x], v) \mid v \in \text{span}\{x\}\}$$

and the projection $\pi: H \rightarrow \mathbb{R}P^n$ is the restriction of the projection onto the first component. There are local trivializations

$$h_i: \pi^{-1} \rightarrow U_i \times \mathbb{R}, \quad i = 1, \dots, n+1,$$

given by

$$h_i([x], v) = ([x], v_i).$$

Theorem 2.23. (1) $H \subseteq \mathbb{R}P^n \times \mathbb{R}^{n+1}$ is an embedded submanifold and $\pi: H \rightarrow \mathbb{R}P^n$ is a 1-dimensional vector bundle with local trivializations h_i as above.

(2) The associated frame bundle is $\eta: (\mathbb{R}^{n+1} \setminus \{0\}) \rightarrow \mathbb{R}P^n$. Here the action by $\mathrm{GL}(1, \mathbb{R}) = \mathbb{R} \setminus \{0\}$ is just given by the usual scalar multiplication.

Proof. (1) As before $\langle \cdot, \cdot \rangle$ denotes the usual inner product in \mathbb{R}^{n+1} , that is, $\langle x, y \rangle = \sum_{i=1}^{n+1} x_i y_i$ for $x, y \in \mathbb{R}^{n+1}$. For $x \in \mathbb{R}^{n+1} \setminus \{0\}$ let P_x denote the orthogonal projection onto $\mathrm{span}\{x\}$, that is,

$$P_x(y) = \frac{\langle y, x \rangle}{\langle x, x \rangle} x$$

and denote the projection onto the orthogonal complement by $P_x^\perp = \mathrm{id} - P_x$. Similarly, for $i = 1, \dots, n+1$, let

$$P_i: \mathbb{R}^{n+1} \rightarrow \mathbb{R}, \quad P_i^\perp: \mathbb{R}^{n+1} \rightarrow \mathbb{R}^n$$

be the projections

$$P_i(x) = x_i, \quad P_i^\perp(x) = (x_1, \dots, \hat{x}_i, \dots, x_n)$$

where the hat indicates that the term is left out. For $i = 1, \dots, n+1$, define $k_i: U_i \times \mathbb{R}^{n+1} \rightarrow U_i \times \mathbb{R} \times \mathbb{R}^n$ by

$$k_i([x], v) = ([x], P_i \circ P_x(v), P_i^\perp \circ P_x^\perp(v)).$$

It is easy to see that k_i is a homomorphism between the two product bundles and that it is injective (and hence bijective) on each fibre. By Proposition 2.14 k_i is therefore an isomorphism, hence in particular a diffeomorphism. Since

$$k_i(H \cap \pi^{-1}(U_i)) = U_i \times \mathbb{R} \times 0$$

it follows that H is embedded in $\mathbb{R}P^n \times \mathbb{R}P^n$, and since $k_i|_{H \cap \pi^{-1}(U_i)} = h_i \times 0$ we have shown (1).

(2) By definition the frame bundle for H is given by

$$F(H) = H_0 = \{([x], v) \mid v \in \mathrm{span}\{x\}, v \neq 0\}$$

and $\bar{\pi} = \pi|_{H_0}$. Now projecting on the second component in $H_0 \subseteq \mathbb{R}P^n \times (\mathbb{R}^{n+1} \setminus \{0\})$ gives a diffeomorphism l in the commutative diagram

$$\begin{array}{ccc}
 M_0 & \xrightarrow[l \cong]{} & \mathbb{R}^{n+1} \setminus \{0\} \\
 \searrow \pi & & \swarrow \eta \\
 & \mathbb{R}P^n &
 \end{array}$$

In fact the inverse l^{-1} is given by

$$l^{-1} = ([v], v), \quad \text{for } v \in \mathbb{R}^{n+1} \setminus \{0\}.$$

Also l clearly respects the action of $\text{GL}(1, \mathbb{R}) = \mathbb{R} \setminus \{0\}$ since in both cases it is given by the scalar multiplication. \square

Corollary 2.24. *H is a non-trivial vector bundle for $n > 0$.*

Proof. If H is trivial then by Corollary 2.15 the frame bundle $F(H) \rightarrow \mathbb{R}P^n$ has a section. That is we have a differentiable map

$$\sigma: \mathbb{R}P^n \rightarrow \mathbb{R}^{n+1} \setminus 0,$$

such that $\eta \circ \sigma = \text{id}$. For $x \in S^n \subseteq \mathbb{R}^{n+1}$ define $f(x) \in \mathbb{R}$ by

$$\sigma([x]) = f(x)x, \quad x \in S^n \subseteq \mathbb{R}^{n+1} \setminus 0.$$

Then $f: S^n \rightarrow \mathbb{R} \setminus 0$ is differentiable. But $f(-x)(-x) = \sigma([-x]) = \sigma([x]) = f(x)x$, which implies that $f(-x) = -f(x)$. Hence f takes both values in \mathbb{R}_+ and \mathbb{R}_- . Since f is continuous and S^n is connected this is a contradiction. \square

3. Principal G-bundles

The frame bundle for a vector bundle is the special case of a principal G -bundle for the Lie group $G = \text{GL}(n, \mathbb{R})$. In the following G denotes an arbitrary Lie group.

Definition 3.1. A *principal G -bundle* is a triple (E, π, M) in which $\pi: E \rightarrow M$ is a differentiable mapping of differentiable manifolds. Furthermore E is given a differentiable right G -action $E \times G \rightarrow E$ such that the following holds.

- (1) $E_p = \pi^{-1}(p)$, $p \in M$ are the orbits for the G -action.
- (2) (Local trivialization) Every point in M has a neighborhood U and a diffeomorphism $\varphi: \pi^{-1}(U) \rightarrow U \times G$ such that the diagram

$$\begin{array}{ccc}
 \pi^{-1}(U) & \xrightarrow{\varphi} & U \times G \\
 \pi \searrow & & \swarrow \text{proj} \\
 & U &
 \end{array}$$

commutes, i.e. $\varphi_p = \varphi|_{E_p}$ maps E_p to $p \times G$; and φ is *equivariant*, i.e.,

$$\varphi(xg) = \varphi(x)g \quad \forall x \in \pi^{-1}(U), g \in G$$

where G acts on $U \times G$ by $(p, g')g = (p, g'g)$

Notation. E is called the *total space*, M the *base space* and $E_p = \pi^{-1}(p)$ the *fiber* at $p \in M$. Often we shall just denote the G -bundle (E, π, M) by E .

- Remark.* (1) π is surjective and *open*.
 (2) The orbit space E/G is homeomorphic to M .

(3) The G -action is *free*, i.e.,

$$xg = x \quad \text{implies} \quad g = 1 \quad \text{for all } x \in E, g \in G.$$

(4) For each $x \in E$ the mapping $G \rightarrow E_p$ given by $g \mapsto x \cdot g$, is a diffeomorphism.

(5) If $N \subseteq M$ is a submanifold (e.g. if N is an open subset) then the *restriction to N*

$$E|_N = (\pi^{-1}(N), \pi, N)$$

is again a principal G -bundle with base space N .

Example 3.2. (1) For (V, π, M) an n -dimensional vector bundle the associated frame bundle $(F(V), \bar{\pi}, M)$ is a principal $\text{GL}(n, \mathbb{R})$ -bundle.

(2) If V is equipped with a Riemannian metric then $(F_O(V), \bar{\pi}, M)$ is a principal $O(n)$ -bundle.

(3) Let G be any Lie group and M a manifold. Then $(M \times G, \pi, M)$, with π the projection onto the first factor, is a principal G -bundle called the *product bundle*.

Definition 3.3. Let $(E, \pi, M), (F, \pi', M)$ be two principal G -bundles over the same base space M . An *isomorphism* $\varphi: E \rightarrow F$ is a diffeomorphism of the total spaces such that

(1) The diagram

$$\begin{array}{ccc} E & \xrightarrow{\varphi} & F \\ \pi \searrow & & \swarrow \pi' \\ & M & \end{array}$$

commutes, i.e. $\varphi_p = \varphi|_{E_p}$ maps E_p to F_p .

(2) φ is *equivariant*, i.e.

$$\varphi(xg) = \varphi(x)g \quad \text{for all } x \in E, g \in G.$$

Remark. In this case $\varphi_p: E_p \rightarrow F_p$ is also a diffeomorphism for each $p \in M$.

Definition 3.4. A principal G -bundle (E, π, M) is called *trivial* if there is an isomorphism $\varphi: E \rightarrow M \times G$ and φ is called a *trivialization*.

Remark. It follows from definition 3.1 that every principal G -bundle E has *local trivializations*

$$\varphi: E|_U \xrightarrow{\cong} U \times G.$$

Lemma 3.5. *Every isomorphism $\varphi: M \times G \rightarrow M \times G$ has the form*

$$\varphi(p, a) = (p, g(p) \cdot a) \quad p \in M, a \in G \quad (3.1)$$

where $g: M \rightarrow G$ is a differentiable mapping.

Proof. It is easy to see that φ defined by (3.1) is an isomorphism with inverse φ^{-1} given by

$$\varphi^{-1}(p, b) = (p, g(p)^{-1} \cdot b) \quad p \in M, b \in G. \quad (3.2)$$

conversely let $\varphi: M \times G \rightarrow M \times G$ be an arbitrary isomorphism and let $g: M \rightarrow G$ be the mapping defined by

$$\varphi(p, 1) = (p, g(p)) \quad p \in M.$$

then g is clearly differentiable and since φ is equivariant we obtain for $p \in M, a \in G$:

$$\varphi(p, a) = \varphi((p, 1)a) = (\varphi(p, 1))a = (p, g(p) \cdot a)$$

that is, (3.1) holds. □

Now for an arbitrary G -bundle (E, π, M) choose an open covering of $M, \mathcal{U} = \{U_\alpha\}_{\alpha \in \Sigma}$, and trivializations

$$\varphi_\alpha: E|_{U_\alpha} \xrightarrow{\cong} U_\alpha \times G.$$

For $U_\alpha \cap U_\beta \neq \emptyset$ we consider the isomorphism

$$\varphi_\beta \circ \varphi_\alpha^{-1}: U_\alpha \cap U_\beta \times G \rightarrow U_\alpha \cap U_\beta \times G$$

and by lemma 3.5 this has the form

$$\varphi_\beta \circ \varphi_\alpha^{-1}(p, a) = (p, g_{\beta\alpha}(p) \cdot a) \quad (3.3)$$

where $a \in G, p \in U_\alpha \cap U_\beta$ and $g_{\beta\alpha}: U_\alpha \cap U_\beta \rightarrow G$ is a differentiable mapping.

Notation. The collection $\{g_{\beta\alpha}\}_{\alpha,\beta\in\Sigma}$ are called the *transition functions* for E with respect to the covering \mathcal{U} (and trivialisations $\{\varphi_\alpha\}_{\alpha\in\Sigma}$).

Remark. For $\alpha, \beta, \gamma \in \Sigma$ such that $U_\alpha \cap U_\beta \cap U_\gamma \neq \emptyset$ the following *cocycle condition* holds

$$\begin{aligned} g_{\gamma\beta}(p) \cdot g_{\beta\alpha}(p) &= g_{\gamma\alpha}(p) & \text{for all } p \in U_\alpha \cap U_\beta \cap U_\gamma, \\ g_{\alpha\alpha}(p) &= 1 & \text{for all } p \in U_\alpha. \end{aligned} \quad (3.4)$$

Conversely we have the following proposition.

Proposition 3.6. *Let $\mathcal{U} = \{U_\alpha\}_{\alpha\in\Sigma}$ be an open covering of a manifold M and suppose $\{g_{\alpha\beta}\}_{\alpha,\beta\in\Sigma}$ is a system of differentiable mappings $g_{\alpha\beta}: U_\alpha \cap U_\beta \rightarrow G$ satisfying the cocycle condition. Then there is a principal G -bundle (E, π, M) and trivialisations $\varphi_\alpha: E|_{U_\alpha} \rightarrow U_\alpha \times G$, $\alpha \in \Sigma$, such that $\{g_{\alpha\beta}\}_{\alpha,\beta\in\Sigma}$ is the associated system of transition functions.*

Proof. The total space E is the quotient space

$$E = \left(\bigsqcup_{\alpha \in \Sigma} U_\alpha \times G \right) / \sim$$

of the disjoint union of all $U_\alpha \times G$, $\alpha \in \Sigma$, for the equivalence relation \sim defined by

$$(p, a)_\alpha \sim (q, b)_\beta \quad \text{if and only if} \quad p = q \text{ and } b = g_{\beta\alpha}(p)a$$

where $(p, a)_\alpha \in U_\alpha \times G$ and $(q, b)_\beta \in U_\beta \times G$. The cocycle condition ensures that \sim is an equivalence relation. Furthermore the projections $U_\alpha \times G \rightarrow U_\alpha$ gives a well-defined continuous mapping $\pi: E \rightarrow M$ and we also have obvious bijections

$$\varphi_\alpha: \pi^{-1}(U_\alpha) \rightarrow U_\alpha \times G$$

given by $\varphi_\alpha((p, a)_\alpha) = (p, a)$. It is now straight forward to define a differentiable structure on E such that the maps φ_α becomes diffeomorphisms. Furthermore one checks that (E, π, M) is a principal G -bundle and by construction $\{\varphi_\alpha\}_{\alpha\in\Sigma}$ are trivialisations with $\{g_{\alpha\beta}\}_{\alpha,\beta\in\Sigma}$ the associated system of transition functions. \square

Exercise 3.7. Show that the bundle constructed in proposition 3.6 is trivial if and only if there is a system of differentiable mappings

$$h_\alpha: U_\alpha \longrightarrow G, \quad \alpha \in \Sigma,$$

such that

$$g_{\beta\alpha}(p) = h_\beta(p)h_\alpha(p)^{-1}, \quad \text{for all } p \in U_\alpha \cap U_\beta.$$

In the previous chapter we associated to a vector bundle (V, π, M) the frame bundle $(F(V), \bar{\pi}, M)$ which is a principal $\text{GL}(n, \mathbb{R})$ -bundle. We shall now show how to reconstruct the vector bundle V from the principal bundle using the natural action of $\text{GL}(n, \mathbb{R})$ on \mathbb{R}^n . In general for a Lie group G and a principal G -bundle (E, π, M) we consider a manifold N with a left G -action $G \times N \longrightarrow N$ and we shall associate to this a fiber bundle (E_N, π_N, M) with fiber N . For this we define the total space E_N as the orbit space

$$E_N = E \times_G N = (E \times N)/G$$

for the G -action on $E \times N$ given by

$$(x, u) \cdot g = (xg, g^{-1}u), \quad x \in E, u \in N, g \in G$$

so that E_N is the quotient space for the equivalence relation \sim , where $(x, u) \sim (y, v)$ if and only if there exists $g \in G$ such that $y = xg$ and $u = gv$. Furthermore let $\pi_N: E_N \longrightarrow M$ be induced by the composite mapping

$$E \times N \xrightarrow{\text{proj}} E \xrightarrow{\pi} M.$$

Then we have the following proposition.

Proposition 3.8. (1) E_N is in a natural way a differentiable manifold and $\pi_N: E_N \longrightarrow M$ is differentiable.

(2) There are local trivializations, i.e. every point in M has a neighborhood U and a diffeomorphism $f: \pi_N^{-1}(U) \longrightarrow U \times N$ such that the diagram

$$\begin{array}{ccc} \pi_N^{-1}(U) & \xrightarrow{f} & U \times N \\ \pi_N \searrow & & \swarrow \text{proj} \\ & U & \end{array}$$

commutes.

Exercise 3.9. Prove proposition 3.8.

Notation. The triple (E_N, π_N, M) is called the *fiber bundle with fiber N associated* to the principal G -bundle (E, π, M) .

Example 3.10. Let (V, π, M) be a vector bundle and $(F(V), \bar{\pi}, M)$ the corresponding frame bundle. Then the associated fiber bundle with fiber \mathbb{R}^n $(F(V)_{\mathbb{R}^n}, \bar{\pi}_{\mathbb{R}^n}, M)$ is in a natural way a vector bundle isomorphic to (V, π, M) . In fact there is a natural isomorphism φ

$$\begin{array}{ccc} F(V) \times_{\text{GL}(n, \mathbb{R})} \mathbb{R}^n & \xrightarrow{\varphi} & U \times G \\ & \searrow \bar{\pi}_{\mathbb{R}^n} & \swarrow \pi \\ & U & \end{array}$$

given by

$$\varphi(x, v) = x(v), \quad x \in F_p(V) = \text{Iso}(\mathbb{R}^n, V_p).$$

Exercise 3.11. Let $(E, \tilde{\pi}, M)$ be a principal $\text{GL}(n, \mathbb{R})$ bundle and let (V, π, M) be the associated fiber bundle with fiber \mathbb{R}^n using the natural action of $\text{GL}(n, \mathbb{R})$ on \mathbb{R}^n . Show that V is in a natural way a vector bundle and that the corresponding frame bundle $(F(V), \bar{\pi}, M)$ is isomorphic to $(E, \tilde{\pi}, M)$.

Finally let us consider bundles over different base spaces: Suppose (E', π', M') and (E, π, M) are principal G -bundles.

Definition 3.12. A *bundle map* from E' to E is a pair of differentiable mappings (\bar{f}, f) in the commutative diagram

$$\begin{array}{ccc} E' & \xrightarrow{\bar{f}} & E \\ \pi' \downarrow & & \downarrow \pi \\ M' & \xrightarrow{f} & M \end{array}$$

such that \bar{f} is G -equivariant, i.e.

$$\bar{f}(x \cdot g) = \bar{f}(x) \cdot g, \quad \text{for all } x \in E', g \in G.$$

Example 3.13. (1) A bundle isomorphism is by definition a bundle map of the form

$$\begin{array}{ccc} E' & \xrightarrow{\bar{f}} & E \\ \pi' \downarrow & & \downarrow \pi \\ M & \xrightarrow{\text{id}} & M \end{array}$$

(2) If $N \subseteq M$ is a submanifold and (E, π, M) is a principal G -bundle, then the inclusion maps in the diagram

$$\begin{array}{ccc} E|_N & \hookrightarrow & E \\ \pi|_{E|_N} \downarrow & & \downarrow \pi \\ N & \hookrightarrow & M \end{array}$$

is a bundle map.

(3) In the product bundle $M \times G$ the projection π_2 on the second factor defines a bundle map of the form

$$\begin{array}{ccc} M \times G & \xrightarrow{\pi_2} & G \\ \pi_1 \downarrow & & \downarrow \\ M & \longrightarrow & \text{pt} \end{array}$$

Given a differentiable mapping $f: M' \rightarrow M$ and a principal G -bundle (E, π, M) we can construct a G -bundle called the *pull-back* of E by f over M' , denoted $f^*(E) = (f^*(E), \pi', M')$, and a bundle map $(\bar{f}, f): f^*(E) \rightarrow E$. That is, we construct a commutative diagram

$$\begin{array}{ccc}
 f^*(E) & \xrightarrow{\bar{f}} & E \\
 \pi' \downarrow & & \downarrow \pi \\
 M' & \xrightarrow{f} & M
 \end{array}$$

To do this we let $f^*(E) \subseteq M' \times E$ be the subset

$$f^*(E) = \{(p, x) \in M' \times E \mid f(p) = \pi(x)\}$$

and let π' and \bar{f} be defined by the restriction of the projections to M' and E respectively. Then we have

Proposition 3.14. $f^*(E) = (f^*(E), \pi', M')$ is in a natural way a principal G -bundle and (\bar{f}, f) is a bundle map.

Proof. G clearly acts on $f^*(E)$, and for each $p \in M'$

$$(\pi')^{-1}(p) = \{(p, x) \mid x \in E_{f(p)}\}$$

is mapped bijectively by \bar{f} to $E_f(p)$ which is a G -orbit. Hence it suffices to show locally that $f^*(E)$ is a locally trivial G -bundle. for this we can assume E to be a product bundle $E = M \times G$. In this case

$$f^*(E) = \{(p, q, g) \in M' \times M \times G \mid f(p) = q\} \cong M' \times G$$

by the map $(p, q, g) \mapsto (p, g)$. Via this isomorphism \bar{f} is furthermore given by the map $(p, g) \mapsto (f(p), g)$ which shows that \bar{f} is a bundle map. \square

Exercise 3.15. (1) Show that if $(\tilde{f}, f): (E', \pi', M') \rightarrow (E, \pi, M)$ is a bundle map then there is a canonical factorization $\tilde{f} = \bar{f} \circ \varphi$, where $\varphi: E' \rightarrow f^*(E)$ is an isomorphism and (\bar{f}, f) is the bundle map in proposition 3.14.

(2) Show that this provides a 1-1 correspondence between the set of bundle maps with fixed map $f: M' \rightarrow M$ of base spaces, and the set of isomorphisms $E' \rightarrow f^*(E)$.

(3) In particular there is a 1-1 correspondence between the set of trivializations of a bundle (E, π, M) and the set of bundle maps to the trivial G -bundle over a point (G, π, pt) .

(4) Show that if $f: M' \rightarrow M$ is a differentiable map and if $\{g_{\alpha\beta}\}_{\alpha,\beta \in \Sigma}$ is a cocycle of transition functions for a G -bundle E over M with covering $\{U_\alpha\}_{\alpha \in \Sigma}$ then $\{g_{\alpha\beta} \circ f\}$ is a cocycle of transition functions for $f^*(E)$ over M' with covering $\{f^{-1}(U_\alpha)\}_{\alpha \in \Sigma}$.

4. Extension and reduction of principal bundles

We will now examine the relation between principal bundles with different structure groups. In the following let G and H be two Lie groups and $\alpha: H \rightarrow G$ a Lie group homomorphism. Typically α is the inclusion of a closed Lie subgroup. Now suppose (F, π, M) is a principal H -bundle and (E, ξ, M) is a principal G -bundle.

Definition 4.1. Let $\varphi: F \rightarrow E$ be a differentiable mapping of the total spaces such that the following holds.

(1) The diagram

$$\begin{array}{ccc}
 F & \xrightarrow{\varphi} & E \\
 \pi \searrow & & \swarrow \xi \\
 & M &
 \end{array}$$

commutes, i.e. $\varphi_p = \varphi|_{F_p}$ maps F_p into E_p for all $p \in M$.

(2) The map φ is α -equivariant, i.e.,

$$\varphi(x \cdot h) = \varphi(x) \cdot \alpha(h) \quad \text{for all } x \in F, h \in H.$$

Then $\varphi: F \rightarrow E$ is called an *extension* of F to G relative to α and is also called a *reduction* of E to H relative to α .

Notation. (1) We will often omit the term “relative to α ” if α is clear from the context, e.g. when α is the inclusion of a Lie subgroup.

(2) When α is surjective with non-trivial kernel one usually calls a reduction a *lifting* of the bundle E to H .

(3) Often the extension is just denoted by the target E and similarly a reduction is denoted by the domain F . But it should be kept in mind that φ is part of the structure. This is important when talking about equivalences of extensions resp. reductions (liftings).

Definition 4.2. (1) Two extensions $\varphi_1: F \rightarrow E_1$ and $\varphi_2: F \rightarrow E_2$ are equivalent if there is an isomorphism ψ in the commutative diagram

$$\begin{array}{ccc} & & E_1 \\ & \nearrow \varphi_1 & \downarrow \psi \\ F & & \\ & \searrow \varphi_2 & E_2 \end{array}$$

(2) Two reductions (liftings) $\varphi_1: F_1 \rightarrow E$ and $\varphi_2: F_2 \rightarrow E$ are equivalent if there is an isomorphism ψ in the commutative diagram

$$\begin{array}{ccc} F_1 & & \\ \downarrow \psi & \searrow \varphi_1 & \\ & & E \\ & \nearrow \varphi_2 & \\ F_2 & & \end{array}$$

Example 4.3. (1) Let (V, π, M) be a vector bundle with a Riemannian metric. Then the inclusion $F_O(V) \subset F(V)$ of the orthogonal frame bundle into the frame bundle is an extension relative to the inclusion $O(n) \subseteq GL(n, \mathbb{R})$. Thus the Riemannian metric defines a reduction of the principal $GL(n, \mathbb{R})$ -bundle $F(V)$ to $O(n)$. Furthermore there is an 1-1 correspondence between the set of Riemannian metrics on V and the set of equivalence classes of reductions.

(2) Let $GL(n, \mathbb{R})^+ \subseteq GL(n, \mathbb{R})$ be the subgroup of non-singular matrices with positive determinant. By definition a vector bundle (V, π, M) is called *orientable* if the frame bundle $F(V)$ has a reduction to $GL(n, \mathbb{R})^+$ and a choice of equivalence class of reductions is called an *orientation* of V (if orientable).

Proposition 4.4. Let $\alpha: H \rightarrow G$ be a Lie group homomorphism and let (F, π, M) be a principal H -bundle. Then there is an extension of F to G relative to α and any two extensions are equivalent.

Proof. There is a left H -action on G defined by $h \cdot g = \alpha(h)g$ for $h \in H$ and $g \in G$. Consider the associated fibre bundle with fiber G , i.e. the bundle (F_G, π_G, M) where $F_G = F \times_G G$ and $\pi_G(x, g) = \pi(x)$ for $x \in F, g \in G$. Here F_G has a natural right G -action given by

$$(x, g)g' = (x, gg'), \quad x \in F, g, g' \in G.$$

It now follows from Proposition 3.8 that (F_G, π_G, M) is a principal G -bundle. Furthermore the natural mapping $\varphi: F \rightarrow F \times_G G$ defined by $\varphi(x) = (x, 1)$ makes F_G an extension of F to G . If $\varphi': F \rightarrow E'$ is any other extension then there is a natural isomorphism $\psi: F_G \rightarrow E'$ given by

$$\psi(x, g) = \varphi'(x) \cdot g, \quad x \in F, g \in G$$

and clearly the diagram

$$\begin{array}{ccc} & & F_G \\ & \nearrow \varphi & \downarrow \psi \\ F & & E' \\ & \searrow \varphi' & \end{array}$$

commutes. Hence $\varphi': F \rightarrow E'$ is equivalent to $\varphi: F \rightarrow F_G$. \square

Hence extensions exist and are unique up to equivalence. Reductions (or liftings) do however not always exist, and if they do, they are usually not unique.

Exercise 4.5. Let $\alpha: H \rightarrow G$ be a Lie group homomorphism and (E, π, M) a principal G -bundle.

(1) Show that E has a reduction to H if and only if there is a covering $\mathcal{U} = \{U_\alpha\}_{\alpha \in \Sigma}$ of M and a set of transition functions for E of the form $\{\alpha \circ h_{\alpha\beta}\}_{\alpha, \beta \in \Sigma}$, where $h_{\alpha\beta}: U_\alpha \cap U_\beta \rightarrow H$ are smooth functions satisfying the cocycle condition (3.4)

(2) If $H \subseteq G$ is a closed embedded Lie subgroup and α is the inclusion, show that E has a reduction to H if and only if there is a covering $\mathcal{U} = \{U_\alpha\}_{\alpha \in \Sigma}$ of M and a set of transition functions $\{g_{\alpha\beta}\}_{\alpha, \beta \in \Sigma}$ for E with $\{g_{\alpha\beta}\}$ mapping into H .

Let us now restrict to the case where $H \subseteq G$ is a closed embedded Lie subgroup and α is the inclusion.

We need the following lemma.

Lemma 4.6. *The natural projection $\pi: G \rightarrow G/H$ defines a principal H -bundle $(G, \pi, G/H)$.*

Proof. Let $U \subseteq G$ be a local cross section, that is, U is an embedded submanifold of G containing the identity element e , such that $\pi(U) = W$ is open in G/H and $\pi: U \rightarrow W$ is a diffeomorphism. Let $s: W \rightarrow U$ be the inverse. We now get a local trivialisation $f: \pi^{-1}(W) \rightarrow W \times H$ defined by

$$f(a) = (\pi(a), s(\pi(a))^{-1}a).$$

This is clearly smooth and so is the inverse

$$f^{-1}(w, h) = s(w) \cdot h.$$

Also f and f^{-1} are H -equivariant, hence f is a local trivialisation. Similarly over the neighborhood gW we have the trivialisation

$$f_g: \pi^{-1}(gW) \rightarrow gW \times H$$

given by

$$f_g(a) = (\pi(a), s(\pi(g^{-1}a))^{-1}g^{-1}a),$$

with inverse

$$f_g^{-1}(u, h) = g \cdot s(g^{-1}u) \cdot h.$$

This shows that $(G, \pi, G/H)$ is a principal H -bundle. □

More generally we can now prove:

Theorem 4.7. *Let $H \subseteq G$ be a closed embedded Lie-subgroup and let (E, π, M) be a principal G -bundle.*

(1) *There is a natural homeomorphism k in the commutative diagram*

$$\begin{array}{ccc}
 E/H & \xrightarrow{k} & E \times_G (G/H) \\
 & \cong & \\
 & \searrow \bar{\pi} & \swarrow \pi_{G/H} \\
 & & M
 \end{array}$$

where $\bar{\pi}$ is induced by π . In particular E/H has a natural differentiable structure induced by k .

(2) Let $\tilde{\pi}: E \rightarrow E/H$ be the natural projection. Then $(E, \tilde{\pi}, E/H)$ is a principal H -bundle.

(3) There is a 1-1 correspondence between the set of sections of the bundle $(E/H, \bar{\pi}, M)$ with fibre G/H and the set of equivalence classes of reductions of E to H .

Proof. (1) The map k is just induced by the natural inclusion $E \rightarrow E \times (G/H)$ sending x to $(x, [H])$ and the inverse is induced by the map $E \times G/H \rightarrow E/H$ given by $k^{-1}(x, gH) = xgH$. Since $E \times_G (G/H) = E_{G/H}$ is the total space in the associated fibre bundle with fibre G/H , it has a differentiable structure as noted in Proposition 3.8.

(2) Since the differentiable structure on E/H is given via the homeomorphism k we have local trivialisations of $(E/H, \bar{\pi}, M)$, that is, over suitable neighborhoods $U \subseteq M$ we have a commutative diagram

$$\begin{array}{ccc}
 \pi^{-1}(U) & \xrightarrow{\cong} & U \times G \\
 \bar{\pi} \downarrow & & \downarrow \\
 \bar{\pi}^{-1}(U) & \xrightarrow{\cong} & U \times G/H \\
 \downarrow & & \downarrow \text{proj} \\
 U & \xrightarrow{=} & U
 \end{array}$$

with the horizontal maps being diffeomorphisms.

By Lemma 4.6 $G \rightarrow G/H$ is a locally trivial H -bundle; hence by the upper part of the diagram above $(E, \tilde{\pi}, E/H)$ is also locally trivial.

(3) Suppose we have a reduction $\varphi: F \rightarrow E$, where (F, π_0, M) is a principal H -bundle. Then φ induces a natural map

$$s_\varphi: M = F/H \rightarrow E/H$$

which is easily checked to be a smooth section of $(E/H, \bar{\pi}, M)$ using local trivializations. Also if $\varphi_1: F_1 \rightarrow E$ and $\varphi_2: F_2 \rightarrow E$ are equivalent reductions then clearly $s_{\varphi_1} = s_{\varphi_2}$.

On the other hand if $s: M \rightarrow E/H$ is a section then we get a bundle map of H -bundles

$$\begin{array}{ccc} s^*(E) & \xrightarrow{\bar{s}} & E \\ \downarrow & & \downarrow \\ M & \xrightarrow{s} & E/H \end{array}$$

and it follows that $\bar{s}: s^*(E) \rightarrow E$ is a reduction of E to H . □

Remark. (1) In particular E has a reduction to H if and only if $(E/H, \bar{\pi}, M)$ has a section.

(2) For $H = \{e\}$ Theorem 4.7 gives a 1-1 correspondence between trivializations of E and sections of E .

Exercise 4.8. (1) Let $G = H \cdot K$ be a semi-direct product of the two closed embedded Lie subgroups H and K , that is, H is invariant and the natural map $K \hookrightarrow G \rightarrow G/H$ is an isomorphism of Lie groups. show that if (E, π, M) is a principal G -bundle then $(E/H, \bar{\pi}, M)$ is a principal K -bundle.

(2) For $k \leq n$ let $W_{n,k}$ be the manifold of k linearly independent vectors in \mathbb{R}^n , let

$$G_k(\mathbb{R}^n) = W_{n,k}/\text{GL}(k, \mathbb{R})$$

be the *Grassmann manifold* of k -planes in \mathbb{R}^n , and let $\gamma_{n,k}: W_{n,k} \rightarrow G_k(\mathbb{R}^n)$ be the natural projection. Show that $(W_{n,k}, \gamma_{n,k}, G_k(\mathbb{R}^n))$ is a principal $\text{GL}(k, \mathbb{R})$ -bundle.

(3) Similarly let $V_{n,k} \subseteq W_{n,k}$ be the *Stiefel manifold* of k orthogonal vectors in \mathbb{R}^n with the usual inner product. Show that the inclusion $V_{n,k} \subseteq W_{n,k}$ defines a reduction of the bundle defined in (2) to the group $O(k) \subseteq GL(k, \mathbb{R})$

(4) Show that the natural map

$$l: W_k(\mathbb{R}^n) \times_{GL(k, \mathbb{R})} \mathbb{R}^n \longrightarrow G_k(\mathbb{R}^n) \times \mathbb{R}^n$$

defined by

$$l(X, v) = ([X], Xv)$$

is an embedding. (Here $[X] = \gamma_{n,k}(X)$ is the subspace spanned by the column vectors in the matrix X , and Xv denotes usual matrix multiplication. Notice that l identifies the total space of the associated bundle with fibre \mathbb{R}^k with the submanifold of $G_k(\mathbb{R}^n) \times \mathbb{R}^n$ consisting of pairs $([X], w)$ where $w \in [X]$.)

5. Differential Forms with Values in a Vector Space

In the following M denotes a differentiable manifold and V a finite dimensional vector space. We shall consider differential forms with values in V , generalizing the usual real valued differential forms.

Definition 5.1. A differential form ω on M with values in V associates to k differentiable vector fields X_1, \dots, X_k on M a differentiable function

$$\omega(X_1, \dots, X_k): M \rightarrow V$$

such that

- (1) ω is multilinear and alternating.
- (2) ω has the tensor property, ie.,

$$\omega(X_1, \dots, fX_i, \dots, X_k) = f\omega(X_1, \dots, X_k)$$

for all vector fields X_1, \dots, X_k on M , $f \in C^\infty(M)$ and $i = 1, \dots, k$.

Remark. Alternatively ω is defined as a family ω_x , $x \in M$ of k -linear alternating maps

$$\omega_x: T_x(M) \times \dots \times T_x(M) \rightarrow V$$

such that for all k -tuples of differentiable vector fields X_1, \dots, X_k the mapping

$$x \mapsto \omega_x(X_1(x), \dots, X_k(x))$$

is differentiable.

Remark. If we choose a basis $\{e_1, \dots, e_n\}$ for V then we can write ω uniquely in the form

$$\omega = \omega_1 e_1 + \dots + \omega_n e_n$$

where $\omega_1, \dots, \omega_n$ are usual differential forms on M . Hence relative to a choice of basis $\{e_1, \dots, e_n\}$, there is a 1-1 correspondence between differential forms with values in V and n -tuples of usual differential forms $\{\omega_1, \dots, \omega_n\}$. Note that we tacitly did so already in the introduction in the case of $V = \mathbb{R}^n$ or $V = M(n, \mathbb{R})$.

Notation. The set of differential k -forms on M with values in V is denoted by $\Omega^k(M, V)$. For $V = \mathbb{R}$ we have $\Omega^k(M) = \Omega^k(M, \mathbb{R})$.

Similar to the usual case we have an exterior differential

$$d: \Omega^k(M, V) \longrightarrow \Omega^{k+1}(M, V).$$

Relative to a choice of basis $\{e_1, \dots, e_n\}$ for V it is just defined for $\omega = \omega_1 e_1 + \dots + \omega_n e_n$ by

$$d\omega = (d\omega_1)e_1 + \dots + (d\omega_n)e_n$$

and it is easy to see that this equation is independent of basis. Furthermore we have the usual identities

$$\begin{aligned} d(d\omega) &= 0, & \text{for all } \omega \in \Omega^k(M, V), k \in \mathbb{N}, \\ (d\omega)(X_1, \dots, X_{k+1}) &= \sum_{i=1}^{k+1} (-1)^{i+1} X_i \omega(X_1, \dots, \widehat{X}_i, \dots, X_{k+1}) \\ &\quad + \sum_{i < j} (-1)^{i+j} \omega([X_i, X_j], \dots, \widehat{X}_i, \dots, \widehat{X}_j, \dots, X_{k+1}) \end{aligned} \tag{5.1}$$

for all differentiable vector fields X_1, \dots, X_{k+1} . These formulas follow easily from the corresponding ones for usual differential forms.

In order to generalize the wedge product of two differential forms we need the notion of the tensor product $V \otimes W$ of two finite dimensional vector spaces V and W . First let $\text{Hom}^2(V \times W, \mathbb{R})$ denote the vector space

of bilinear maps $V \times W \rightarrow \mathbb{R}$ and then define $V \otimes W$ as the dual vector space

$$V \otimes W = \text{Hom}(\text{Hom}^2(V \times W, \mathbb{R}), \mathbb{R}).$$

For $v \in V$ and $w \in W$ we define $v \otimes w \in V \otimes W$ by

$$\langle \varphi, v \otimes w \rangle = \varphi(v, w), \quad \varphi \in \text{Hom}^2(V \times W, \mathbb{R}).$$

We now have the following proposition.

Proposition 5.2. (1) *The mapping $\otimes: V \times W \rightarrow V \otimes W$ given by $(v, w) \mapsto v \otimes w$ is bilinear.*

(2) *There is a bijection for any vector space U*

$$\text{Hom}(V \otimes W, U) \xrightarrow{\cong} \text{Hom}^2(V \times W, U)$$

given by $\varphi \mapsto \varphi \circ \otimes$.

(3) *$V \otimes W$ is generated by the set of vectors of the form $v \otimes w$, where $v \in V$ and $w \in W$.*

(4) *If $\{e_1, \dots, e_n\}$ and $\{f_1, \dots, f_m\}$ are bases for V resp. W then $\{e_i \otimes f_j\}$ is a basis for $V \otimes W$. In particular*

$$\dim(V \otimes W) = \dim(V) \cdot \dim(W).$$

Exercise 5.3. Prove proposition 5.2.

For $\omega_1 \in \Omega^k(M, V)$ and $\omega_2 \in \Omega^l(M, W)$ we can now define the wedge product $\omega_1 \wedge \omega_2 \in \Omega^{l+k}(M, V \otimes W)$ by the usual formula

$$\begin{aligned} & (\omega_1 \wedge \omega_2)(X_1, \dots, X_{k+l}) \\ &= \sum_{\sigma} \text{sign}(\sigma) \omega_1(X_{\sigma(1)}, \dots, X_{\sigma(k)}) \otimes \omega_2(X_{\sigma(k+1)}, \dots, X_{\sigma(k+l)}) \end{aligned}$$

where σ runs over all (k, l) -shuffles of $1, \dots, k+l$. As usual one has the formulas

$$\omega_1 \wedge (\omega_2 \wedge \omega_3) = (\omega_1 \wedge \omega_2) \wedge \omega_3,$$

for all $\omega_1 \in \Omega^k(M, U)$, $\omega_2 \in \Omega^l(M, V)$, $\omega_3 \in \Omega^m(M, W)$,

$$d(\omega_1 \wedge \omega_2) = (d\omega_1) \wedge \omega_2 + (-1)^k \omega_1 \wedge (d\omega_2)$$

for all $\omega_1 \in \Omega^k(M, U)$, $\omega_2 \in \Omega^l(M, W)$. Furthermore for a linear mapping $P: V \rightarrow W$ there is an induced mapping $P: \Omega^k(M, V) \rightarrow \Omega^k(M, W)$ defined by

$$(P\omega)(X_1, \dots, X_k) = P \circ \omega(X_1, \dots, X_k)$$

and it is easy to see that

$$d(P\omega) = P(d\omega), \quad \omega \in \Omega^k(M, V).$$

In particular let $T: V \otimes W \rightarrow W \otimes V$ be the linear mapping given by $T(v \otimes w) = w \otimes v$. Then one has

$$\omega_2 \wedge \omega_1 = (-1)^{kl} T(\omega_1 \wedge \omega_2) \tag{5.2}$$

for all $\omega_1 \in \Omega^k(M, V)$, $\omega_2 \in \Omega^l(M, W)$. Finally for $f: M \rightarrow N$ a differentiable mapping of differentiable manifolds we get as usual an induced mapping $f^*: \Omega^k(N, V) \rightarrow \Omega^k(M, V)$, where for $\omega \in \Omega^k(N, V)$, $f^*(\omega)$ is defined pointwise by

$$f^*(\omega)_x(X_1, \dots, X_k) = \omega_{f(x)}(f_*(X_1), \dots, f_*(X_k))$$

for $X_1, \dots, X_k \in T_x(M)$. Then one also has the formulas

$$f^*(\omega_1 \wedge \omega_2) = (f^*\omega_1) \wedge (f^*\omega_2),$$

$$d(f^*(\omega)) = f^*(d\omega),$$

$$f^*(P(\omega)) = P(f^*(\omega))$$

for $P: V \rightarrow W$ a linear mapping and for all $\omega \in \Omega^k(N, V)$, $\omega_1 \in \Omega^k(N, V)$ and $\omega_2 \in \Omega^l(N, W)$.

Exercise 5.4. Show all unproven statements in the above.

6. Connections in Principal G-bundles

We now come to our main topic which, as we shall see later, generalizes the differential systems considered in the introduction. This is the notion of a *connection*.

In general we consider a Lie group G with Lie algebra $\mathfrak{g} = T_e G$, and we let $\text{Ad}: G \rightarrow \text{GL}(\mathfrak{g})$ be the adjoint representation, i.e., for $g \in G$ $\text{Ad}(g)$ is the differential at the identity element e of the mapping $x \mapsto gxg^{-1}$, $x \in G$.

Let (E, π, M) be a principal G -bundle. For a fixed $x \in E$ the mapping $G \rightarrow E$ given by $g \mapsto xg$, $g \in G$, induces an injective map $v_x: \mathfrak{g} \rightarrow T_x E$ and the quotient space by the image of v_x is mapped isomorphically onto $T_{\pi(x)} M$ by the differential π_* of π . That is, we have an exact sequence of vector spaces

$$0 \longrightarrow \mathfrak{g} \xrightarrow{v_x} T_x E \xrightarrow{\pi_*} T_{\pi(x)} M \longrightarrow 0$$

The vectors in $v_x(\mathfrak{g}) \subseteq T_x E$ are called *vertical tangent vectors* of E and we want to choose a complementary subspace $H_x \subseteq T_x E$ of *horizontal vectors*, i.e., H_x is mapped isomorphically onto $T_{\pi(x)} M$ by π_* . This choice is equivalent to a choice of linear mapping $\omega_x: T_x E \rightarrow \mathfrak{g}$, such that

$$\omega_x \circ v_x = \text{id}_{\mathfrak{g}} \tag{6.1}$$

and such that $H_x = \ker \omega_x$. Furthermore we shall require ω_x to vary differentially, i.e., $\{\omega_x \mid x \in E\}$ defines a differential 1-form with values in \mathfrak{g} , hence, $\omega \in \Omega^1(E, \mathfrak{g})$.

Example 6.1. Consider the trivial bundle $E = M \times G$, $\pi: M \times G \rightarrow M$ the natural projection. We define $\omega_{\text{MC}} \in \Omega^1(E, \mathfrak{g})$ as follows:

$$(\omega_{\text{MC}})_{(p,g)} = (L_{g^{-1}} \circ \pi_2)_*, \quad p \in M, g \in G \tag{6.2}$$

where $\pi_2: M \times G \rightarrow G$ is the projection onto the second factor and $L_{g^{-1}}: G \rightarrow G$ is left translation by g^{-1} . Let us show that $\omega_{\text{MC}} \in \Omega^1(E, \mathfrak{g})$, that is, we shall show that ω_{MC} is differentiable. First notice that $\omega_{\text{MC}} = \pi_2^* \circ \omega_0$ where $\omega_0 \in \Omega^1(G, \mathfrak{g})$ is defined by

$$(\omega_0)_g = (L_{g^{-1}})_*. \quad (6.3)$$

Hence it suffices to show that ω_0 is differentiable. For this notice that if $X \in \mathfrak{g} = T_e G$ and \tilde{X} is the corresponding left invariant vector field then

$$\omega_0(\tilde{X}) = X$$

is constant and hence differentiable. Since every differentiable vector field Y on G is a linear combination of left invariant ones with differentiable coefficients it follows that $\omega_0(Y)$ is differentiable, hence ω_0 is differentiable. Furthermore ω_{MC} satisfies (6.1): In fact for $x = (p, g)$, v_x is the differential of the map $G \rightarrow M \times G$ given by $a \mapsto (p, ga)$, and hence $(\omega_{\text{MC}})_x \circ v_x = \text{id}_* = \text{id}$.

Remark. The form ω_0 on G is called the *Maurer-Cartan form*. For $G = \text{GL}(n, \mathbb{R})$ it is just the form

$$\omega_0 = g^{-1} dg, \quad g \in G.$$

The form ω_{MC} in example 6.1 satisfies another identity: For $g \in G$ let $R_g: E \rightarrow E$ denote the right multiplication by g , that is $R_g(x) = xg$, $x \in E$. In the case $E = M \times G$ we just have

$$R_g(p, a) = (p, ag) \quad p \in M, a \in G.$$

Lemma 6.2. *In $E = M \times G$ the form ω_{MC} defined by (6.2) satisfies*

$$R_g^* \omega_{\text{MC}} = \text{Ad}(g^{-1}) \circ \omega_{\text{MC}}, \quad \text{for all } g \in G, \quad (6.4)$$

where $\text{Ad}(g^{-1}) \circ: \Omega^1(E, \mathfrak{g}) \rightarrow \Omega^1(E, \mathfrak{g})$ is induced by the linear map

$$\text{Ad}(g^{-1}): \mathfrak{g} \rightarrow \mathfrak{g}.$$

Proof. Since $\omega_{\text{MC}} = \pi_2^* \omega_0$, for ω_0 given by (6.3), and since

$$R_g^* \omega_{\text{MC}} = R_g^* \circ \pi_2^* \omega_0 = \pi_2^* \circ R_g^* \omega_0$$

it suffices to prove (6.4) for $\omega = \omega_0$ on G . But here we have for $a \in G$:

$$\begin{aligned} R_g^*(\omega)_a &= \omega_{ag} \circ (R_g)_* \\ &= (L_{(ag)^{-1}})_* \circ (R_g)_* \\ &= (L_{g^{-1}})_* \circ (L_{a^{-1}})_* \circ (R_g)_* \\ &= \text{Ad}(g^{-1}) \circ (L_{a^{-1}})_* \\ &= \text{Ad}(g^{-1}) \circ \omega_a, \end{aligned}$$

completing the proof. \square

With this as motivation we now make the following definition.

Definition 6.3. A *connection* in a principal G -bundle (E, π, M) is a 1-form $\omega \in \Omega^1(E, \mathfrak{g})$ satisfying

- (1) $\omega_x \circ v_x = \text{id}$ where $v_x: \mathfrak{g} \rightarrow T_x E$ is the differential of the mapping $g \mapsto xg$.
- (2) $R_g^* \omega = \text{Ad}(g^{-1}) \circ \omega$, for all $g \in G$, where $R_g: E \rightarrow E$ is given by $R_g(x) = xg$.

There is a more geometric formulation of (2): For a 1-form $\omega \in \Omega^1(E, \mathfrak{g})$ satisfying (1) in definition 6.3 let $H_x \subseteq T_x E$, $x \in E$, be the subspace

$$H_x = \ker \omega_x.$$

Then as noted above $\pi_*: H_x \rightarrow T_x E$ is an isomorphism. Therefore $H_x \subseteq T_x E$ is called the *horizontal subspace* at x given by ω , and a vector in H_x is called a *horizontal tangent vector* in E .

Proposition 6.4. For $\omega \in \Omega^1(E, \mathfrak{g})$ satisfying definition 6.3 (1), the requirement (2) is equivalent to

- (2') $(R_g)_* H_x = H_{xg}$, for all $x \in E$ and $g \in G$.

That is, the horizontal vector spaces are permuted by the right action of G on TE .

Proof. (2) \Rightarrow (2'). If $X \in H_x$, then we obtain

$$\omega_{xg}(R_{g*} X) = (R_g^* \omega)(X) = \text{Ad}(g^{-1})(\omega(X)) = 0;$$

hence $R_{g*}X \in H_{xg}$.

(2') \Rightarrow (2). To prove (2) notice that both sides are zero when evaluated on horizontal vectors. Hence it is enough to verify (2) when evaluated on a vertical vector $v_x(X)$, $X \in \mathfrak{g}$. But for $g \in G$ we have

$$R_{g*} \circ v_x = v_{xg} \circ \text{Ad}(g^{-1})$$

since both sides are the differential of the mapping $G \rightarrow E$ given by

$$a \mapsto xag = xg(g^{-1}ag).$$

Hence by (1)

$$R_g^*(\omega)(v_x(X)) = \omega_{xg}(v_{xg} \circ \text{Ad}(g^{-1})(X)) = \text{Ad}(g^{-1})(X),$$

completing the proof. \square

Remark. By lemma 6.2 the form $\omega_{\text{MC}} \in \Omega^1(M \times G)$ defined in example 6.1 is a connection in $M \times G$. This is often called the *Maurer-Cartan connection*, the *trivial connection* or the *flat connection*. Notice that in this case the horizontal subspace at $x = (p, g)$ is the tangent space to the submanifold $M \times \{g\} \subseteq M \times G$.

Proposition 6.5. (1) Let $(\bar{f}, f): (E', \pi', M') \rightarrow (E, \pi, M)$ be a bundle map of principal G -bundles and let $\omega \in \Omega^1(E, \mathfrak{g})$ be a connection in E . Then $\bar{f}^*\omega$ is a connection in E' .

(2) In particular if $\varphi: F \rightarrow E$ is an isomorphism of principal G -bundles over M and $\omega \in \Omega^1(E, \mathfrak{g})$ is a connection in E then $\omega^\varphi = \varphi^*\omega$ is a connection on F .

(3) Suppose $\omega_1, \dots, \omega_k \in \Omega^1(E, \mathfrak{g})$ are connections on the bundle (E, π, M) and $\lambda_1, \dots, \lambda_k \in C^\infty(M)$ satisfy $\sum_i \lambda_i = 1$ then the sum

$$\omega = \sum_i \lambda_i \omega_i$$

is also a connection on E .

Exercise 6.6. Prove Proposition 6.5.

Corollary 6.7. Every principal G -bundle has a connection.

Proof. Let $\mathcal{U} = \{U_\alpha\}_{\alpha \in \Sigma}$ be a covering of M with trivializations $\varphi_\alpha: E|_{U_\alpha} \xrightarrow{\cong} U_\alpha \times G$. By Proposition 6.5 the Maurer-Cartan connection in $U_\alpha \times G$ pulls back to a connection ω_α in $E|_{U_\alpha}$. Now choose a partition of unity $\{\lambda_\alpha\}_{\alpha \in \Sigma}$ and put

$$\omega = \sum_{\alpha} \lambda_\alpha \omega_\alpha.$$

Then ω is a well-defined 1-form on E , and, by Proposition 6.5 c), it satisfies the requirements for a connection (since these are local conditions). \square

Next let us look at a *local description* of a connection, i.e., let us look at a general connection ω in a product bundle:

Proposition 6.8. *Let $E = M \times G$ be the product bundle with projection $\pi: E \rightarrow M$, and let $i: M \rightarrow E$ be the inclusion $i(p) = (p, e)$.*

(1) *The induced map $i^*: \Omega^1(E, \mathfrak{g}) \rightarrow \Omega^1(M, \mathfrak{g})$ gives a 1-1 correspondence between connections in E and \mathfrak{g} -valued 1-forms on M .*

(2) *Let $\varphi: E \rightarrow E$ be an isomorphism of the form $\varphi(p, a) = (p, g(p)a)$ for $g: M \rightarrow G$ a differential map, and let $\omega \in \Omega^1(E, \mathfrak{g})$ be a connection on E with $i^*\omega = A \in \Omega^1(M, \mathfrak{g})$. Then $\omega^\varphi = \varphi^*\omega$ satisfies*

$$i^*\omega^\varphi = A^\varphi = \text{Ad}(g^{-1}) \circ A + g^*(\omega_0) \tag{6.5}$$

where $\omega_0 \in \Omega^1(G, \mathfrak{g})$ is the Maurer-Cartan form on G .

Proof. (1) First notice that given $A \in \Omega^1(M, \mathfrak{g})$ there is a unique form $\tilde{A} \in \Omega^1(E, \mathfrak{g})$ with $i^*\tilde{A} = A$ such that

- (i) $\tilde{A}(X) = 0$ for $X \in T_x E$ a vertical vector.
- (ii) $R_g^*\tilde{A} = \text{Ad}(g^{-1}) \circ \tilde{A}$ for all $g \in G$.

In fact, for $x = (p, e)$ \tilde{A} is determined by A and (i) since

$$T_x E = \ker(\pi_*) \oplus i_*(T_p M),$$

and for $y = (p, g) = R_g(x)$, (ii) implies that

$$\tilde{A}_y = \text{Ad}(g^{-1}) \circ \tilde{A}_x$$

which proves uniqueness. On the other hand the form \tilde{A} given by

$$\tilde{A}_{(p,g)} = \text{Ad}(g^{-1}) \circ A_p \circ \pi_* \quad (6.6)$$

defines a form satisfying (i) and (ii). Now if ω_{MC} denotes the Maurer-Cartan connection on E then the correspondence

$$\tilde{A} \longleftrightarrow \omega_{\text{MC}} + \tilde{A}$$

gives a 1-1 correspondence between 1-forms satisfying (i) and (ii), and the set of connections in E .

(2) As above we write

$$\omega = \omega_{\text{MC}} + \tilde{A}$$

where $A = i^*\omega$. Then

$$\omega^\varphi = \varphi^*\omega_{\text{MC}} + \varphi^*\tilde{A}$$

gives

$$A^\varphi = i^*\omega^\varphi = i^*\varphi^*\omega_{\text{MC}} + i^*\varphi^*\tilde{A}$$

where $\omega_{\text{MC}} = \pi_2^*\omega_0$ with $\pi_2: M \times G \rightarrow G$ the projection. Now $\pi_2 \circ g \circ i = g$ so that

$$i^*\varphi^*\omega_{\text{MC}} = i^*\varphi^*\pi_2^*\omega_0 = g^*\omega_0.$$

Also by (6.6)

$$\begin{aligned} (i^*\varphi^*\tilde{A})_p &= \tilde{A}_{(p,g(p))} \circ (\varphi \circ i)_* \\ &= \text{Ad}(g^{-1}) \circ A_p \circ \pi_* \circ (\varphi \circ i)_* \\ &= \text{Ad}(g^{-1}) \circ A_p \end{aligned}$$

since $\pi \circ \varphi \circ i = \text{id}$. □

Remark. Notice that for the Maurer-Cartan connection ω_{MC} , $A = i^*\omega_{\text{MC}} = 0$.

Corollary 6.9. *Let (E, π, M) be a principal G -bundle and let $\mathcal{U} = \{U_\alpha\}_{\alpha \in \Sigma}$ be a covering of M with trivializations $\{\varphi_\alpha\}_{\alpha \in \Sigma}$ and transition functions $\{g_{\alpha\beta}\}_{\alpha, \beta \in \Sigma}$. Then there is a 1-1 correspondence between connections in E and collections of 1-forms $\{A_\alpha \in \Omega^1(U_\alpha, \mathfrak{g})\}_{\alpha \in \Sigma}$ satisfying*

$$A_\beta = \text{Ad}(g_{\alpha\beta}^{-1}) \circ A_\alpha + g_{\alpha\beta}^* \omega_0 \quad (6.7)$$

on $U_\alpha \cap U_\beta$.

Proof. If ω is a connection in E the trivialization $\varphi_\alpha: E|_{U_\alpha} \rightarrow U_\alpha \times G$ defines a connection in $U_\alpha \times G$ by

$$\omega_\alpha = (\varphi_\alpha^{-1})^* \omega.$$

For $\beta \in \Sigma$ we then have over $U_\alpha \cap U_\beta$ that

$$\omega_\beta = \psi_{\alpha\beta}^* \omega_\alpha \quad (6.8)$$

where $\psi_{\alpha\beta}: (U_\alpha \cap U_\beta) \times G \rightarrow (U_\alpha \cap U_\beta) \times G$ is the isomorphism $\psi_{\alpha\beta} = \varphi_\alpha \circ \varphi_\beta^{-1}$, so that

$$\psi_{\alpha\beta}(p, a) = (p, g_{\alpha\beta}(p)a).$$

Hence (6.7) follows from (6.8) and Proposition 6.8, (2).

On the other hand suppose $\{A_\alpha\}_{\alpha \in \Sigma}$ is given. Then there are corresponding connections $\{\omega_\alpha\}$ in $U_\alpha \times G$ as in Proposition 6.8, (1) and by Proposition 6.8, (2), (6.7) implies (6.8) or equivalently

$$\varphi_\alpha^* \omega_\alpha = \varphi_\beta^* \omega_\beta$$

on $E|_{U_\alpha \cap U_\beta}$. Hence we get a well-defined connection ω on E such that the restriction to $E|_{U_\alpha}$ is $\varphi_\alpha^* \omega_\alpha$. \square

Notation. Often a connection is identified with the collection $\{A_\alpha\}_{\alpha \in \Sigma}$ of local connection forms. It is then denoted by A .

In the proof of Proposition 6.8 we encountered two important conditions ((i) and (ii)) on differential 1-forms on the total space E of a principal G -bundle (E, π, M) . Let us state these for general k -forms on E with values in a finite dimensional vector space V .

Definition 6.10. (1) A differential k -form $\omega \in \Omega^k(E, V)$ is called *horizontal* if $\omega_X(X_1, \dots, X_k) = 0$ for all k -tuples of tangent vectors $X_1, \dots, X_k \in T_x E$ for which at least one is vertical.

(2) Let $\rho: G \rightarrow \text{GL}(V)$ be a representation of G on V . Then $\omega \in \Omega^k(E, V)$ is called ρ -*equivariant* if

$$R_g^* \omega = \rho(g^{-1}) \circ \omega, \quad \text{for all } g \in G.$$

(3) if ρ in (2) is the trivial representation then a ρ -equivariant form is called *invariant*.

(4) If ω is both invariant and horizontal then it is called *basic*.

Proposition 6.11. Let (E, π, M) be a principal G -bundle and let $\mathcal{U} = \{U_\alpha\}_{\alpha \in \Sigma}$ be a covering of M with trivializations $\{\varphi_\alpha\}_{\alpha \in \Sigma}$ and transition functions $\{g_{\alpha\beta}\}_{\alpha, \beta \in \Sigma}$. Let $\rho: G \rightarrow \text{GL}(V)$ be a representation. Then there is a 1-1 correspondence between horizontal ρ -equivariant k -forms $\tilde{\omega}$ on E and collections of k -forms $\{\omega_\alpha \in \Omega^k(U_\alpha, V)\}_{\alpha \in \Sigma}$ satisfying

$$\omega_\beta = \rho(g_{\alpha\beta}) \circ \omega_\alpha \quad \text{on } U_\alpha \cap U_\beta. \quad (6.9)$$

Here ω_α is the pull-back of ω by the local section $U_\alpha \rightarrow E|_{U_\alpha}$ sending $p \in U_\alpha$ to $\varphi_\alpha^{-1}(p, e)$.

Proof. This is proved exactly as in the proof of Corollary 6.9 using the following lemma. The details are left to the reader. \square

Lemma 6.12. Let $E = M \times G$ be the product bundle with projection $\pi: E \rightarrow M$, and let $i: M \rightarrow E$ be the inclusion $i(p) = (p, e)$. Let $\rho: G \rightarrow \text{GL}(V)$ be a representation.

(1) The induced map $i^*: \Omega^k(E, V) \rightarrow \Omega^k(M, V)$ gives a 1-1 correspondence between horizontal ρ -equivariant k -forms on E and all V -valued k -forms on M .

(2) Let $\varphi: E \rightarrow E$ be an isomorphism of the form $\varphi(p, a) = (p, g(p)a)$ for $g: M \rightarrow G$ a differentiable map. If $\tilde{\omega} \in \Omega^k(E, V)$ is horizontal and equivariant and if we put $\omega = i^* \tilde{\omega}$ then

$$i^*(\varphi^* \tilde{\omega}) = \rho(g^{-1}) \circ \omega. \quad (6.10)$$

Proof. Again the proof is similar to the proof of Proposition 6.8 and the details are left to the reader. We only note that given $\omega \in \Omega^k(M, V)$ the corresponding ρ -equivariant horizontal k -form $\tilde{\omega}$ on E is given by

$$\tilde{\omega}_{(p,g)}(X_1, \dots, X_k) = \rho(g^{-1})(\omega_p(\pi_*X_1, \dots, \pi_*X_k)) \quad (6.11)$$

for $X_1, \dots, X_k \in T_{(p,g)}(E)$, $p \in M$, $g \in G$. \square

Corollary 6.13. *Let (E, π, M) be any principal G -bundle and let V be a vector space. Then $\pi^*: \Omega^k(M, V) \rightarrow \Omega^k(E, V)$ gives an isomorphism onto the basic forms on E .*

Proof. This follows immediately from Proposition 6.11 since the collection $\{\omega_\alpha\}_{\alpha \in \Sigma}$ in that case defines a well-defined form ω on M and since by (6.11) the corresponding horizontal invariant form $\tilde{\omega}$ on E is just the pull-back by π . \square

Remark. Let $\rho: G \rightarrow \text{GL}(V)$ be any representation, and for (E, π, M) a principal G -bundle let (E_V, π_V, M) be the *associated vector bundle*, i.e., the associated fibre bundle with fibre V using the left action of G on V given by $gv = \rho(g)v$, $g \in G$, $v \in V$ (cf. exercise 3.11). Then Proposition 6.11 states in particular for $k = 0$ that there is a 1-1 correspondence between the set of ρ -equivariant functions $\tilde{s}: E \rightarrow V$ and the set of sections s of the vectorbundle E_V . This set is often denoted $\Gamma(M, E_V)$ (cf. Proposition 2.11). We shall denote the set of ρ -equivariant horizontal k -forms on E by $\Omega^k(M, E_V)$, so that in particular $\Omega^0(M, E_V) = \Gamma(M, E_V)$. Notice that $\Omega^k(M, E_V)$ is a real vector space.

Corollary 6.14. *Let (E, π, M) be a principal G -bundle. Then the set of connections in E is an affine space for the vector space $\Omega^1(M, E_{\mathfrak{g}})$. That is, given one connection ω_0 any other connection ω_1 has the form $\omega_0 + A$ for some $A \in \Omega^1(M, E_{\mathfrak{g}})$.*

Notation. The set of connections in (E, π, M) is denoted $\mathcal{A}(E)$ or just \mathcal{A} when E is clear from the context.

Definition 6.15. (1) A *gauge transformation* φ of the principal G -bundle (E, π, M) is an automorphism of E , that is, a bundle isomorphism $\varphi: E \rightarrow E$.

(2) Two connections $\omega_1, \omega_2 \in \mathcal{A}(E)$ are called *gauge-equivalent* if there exists a gauge transformation φ such that

$$\omega_2 = \omega_1^\varphi = \varphi^* \omega_1. \quad (6.12)$$

Remark. Notice that the set of gauge transformations $\mathcal{G} = \mathcal{G}(E)$ is a group and that

$$\begin{aligned} (\omega^\varphi)^\psi &= \omega^{\varphi \circ \psi}, & \text{for all } \varphi, \psi \in \mathcal{G}, \\ \omega^{\text{id}} &= \omega. \end{aligned} \quad (6.13)$$

That is, \mathcal{G} acts from the right on the set \mathcal{A} and the set of gauge equivalence classes is just the orbit space \mathcal{A}/\mathcal{G} .

Exercise 6.16. (1) Show that there is a 1-1 correspondence between \mathcal{G} and each of the following 3 sets.

(1.a) The set of differentiable maps $\tilde{\sigma}: E \rightarrow G$ satisfying $\tilde{\sigma}(x, g) = g^{-1} \tilde{\sigma}(x) g$, $x \in E, g \in G$.

(1.b) The set of sections of the fibre bundle (E_{iG}, π_{iG}, M) associated to the action of G on itself by inner conjugation (that is, $g(a) = gag^{-1}$).

(1.c) Given $\{U_\alpha\}_{\alpha \in \Sigma}$ a covering of M and trivializations with transition functions $\{g_{\alpha\beta}\}_{\alpha, \beta \in \Sigma}$, the set of families of differentiable maps $\{\sigma_\alpha: U_\alpha \rightarrow G\}_{\alpha \in \Sigma}$ satisfying

$$g_{\alpha\beta} \sigma_\beta = \sigma_\alpha g_{\alpha\beta} \quad \text{on } U_\alpha \cap U_\beta. \quad (6.14)$$

(2) In the above notation let $\varphi \in \mathcal{G}$ correspond to the family $\{\sigma_\alpha\}_{\alpha \in \Sigma}$ and let ω be a connection in E with corresponding local connection forms $\{A_\alpha\}_{\alpha \in \Sigma}$. Show that ω^φ has local connection forms $\{A_\alpha^{\sigma_\alpha}\}_{\alpha \in \Sigma}$ where

$$A_\alpha^{\sigma_\alpha} = \text{Ad}(\sigma_\alpha^{-1}) \circ A_\alpha + \sigma_\alpha^* \omega_0 \quad (6.15)$$

an ω_0 is the Maurer-Cartan form.

Finally let us consider extension and reduction of connections.

Definition 6.17. Let $\alpha: H \rightarrow G$ be a Lie group homomorphism and let F be an H -bundle and $\varphi: F \rightarrow E$ an extension of F to G . Furthermore let ω_F be a connection in F and ω_E be a connection in E . Then ω_E is called an *extension* of ω_F (and ω_F a *reduction* of ω_E) if

$$\varphi^* \omega_E = \alpha_* \circ \omega_F. \quad (6.16)$$

Exercise 6.18. Let $\alpha: H \rightarrow G$ and $\varphi: F \rightarrow E$ be as above.

(1) Show that if ω_F is a connection in F and ω_E is an extension in E then φ_* maps the horizontal vector spaces in F isomorphically to the horizontal vector spaces in E .

(2) Show that if ω_F is a connection in F then there is a unique extension ω_E to E .

(3) Let $\{U_\alpha\}_{\alpha \in \Sigma}$ be a covering of M with transitions of F respectively of E such that the transition functions are $\{h_{\alpha\beta}\}_{\alpha, \beta \in \Sigma}$ for F respectively $\{\alpha \circ h_{\alpha\beta}\}_{\alpha, \beta \in \Sigma}$ for E . Show that if ω_F has local connection forms $\{A_\alpha\}_{\alpha \in \Sigma}$ then the extension ω_E has local connection forms $\{\alpha_* \circ A_\alpha\}_{\alpha \in \Sigma}$.

Remark. In particular if H is a Lie subgroup and α is the inclusion then ω_F and ω_E have the same local connection form.

7. The Curvature Form

As before let G be a Lie group with Lie algebra \mathfrak{g} and let (E, π, M) be a principal G -bundle with connection ω . We will now define the *curvature form* generalizing the form F_A in (1.7). Since $\omega \in \Omega^1(E, \mathfrak{g})$ we have $\omega \wedge \omega \in \Omega^2(E, \mathfrak{g} \otimes \mathfrak{g})$ and we define $[\omega, \omega] \in \Omega^2(E, \mathfrak{g})$ to be the image of $\omega \wedge \omega$ by the linear mapping

$$[-, -]: \mathfrak{g} \otimes \mathfrak{g} \longrightarrow \mathfrak{g}$$

determined by the Lie bracket, i.e. the mapping sending $X \otimes Y$ to $[X, Y]$, $X, Y \in \mathfrak{g}$.

Definition 7.1. The *curvature form* $F_\omega \in \Omega^2(E, \mathfrak{g})$ for the connection ω is defined by the equation (the structural equation)

$$d\omega = -\frac{1}{2}[\omega, \omega] + F_\omega. \quad (7.1)$$

In the above notation we have the following theorem.

Theorem 7.2. (1) *If $E = M \times G$ and $\omega = \omega_{\text{MC}}$ is the Maurer-Cartan connection then $F_{\omega_{\text{MC}}} = 0$, that is,*

$$d\omega_{\text{MC}} = -\frac{1}{2}[\omega_{\text{MC}}, \omega_{\text{MC}}]. \quad (7.2)$$

(2) *In general F_ω is horizontal and Ad-equivariant, i.e. defines a 2-form (also denoted) $F_\omega \in \Omega^2(M, E_{\mathfrak{g}})$.*

(3) *(The Bianchi identity) Furthermore*

$$dF_\omega = [F_\omega, \omega]. \quad (7.3)$$

In particular dF_ω vanishes on triples of horizontal vectors.

(4) *Suppose $\{U_\alpha\}_{\alpha \in \Sigma}$ is a covering of M with trivializations $\{\varphi_\alpha\}_{\alpha \in \Sigma}$ of $E|_{U_\alpha}$ and transition functions $\{g_{\alpha\beta}\}_{\alpha, \beta \in \Sigma}$. Suppose ω has local connection*

forms $\{A_\alpha\}_{\alpha \in \Sigma}$. Then the curvature form F_ω corresponds to the family $F_{A_\alpha} \in \Omega^2(U_\alpha, \mathfrak{g})$ given by

$$F_{A_\alpha} = dA_\alpha + \frac{1}{2}[A_\alpha, A_\alpha]. \quad (7.4)$$

Notation. We will often denote the connection by $A = \{A_\alpha\}_{\alpha \in \Sigma}$ and in that case identify the curvature form with the collection $F_A = \{F_{A_\alpha}\}_{\alpha \in \Sigma}$ given by (7.4).

For the proof of Theorem 7.2 we need a few preparations. First note that given $A \in \mathfrak{g}$ there is an associated vector field A^* on E defined by $A_x^* = v_x(A)$, $x \in E$. Here as usual v_x is the differential of the map $G \rightarrow E$ given by $g \mapsto xg$, $g \in G$. Notice that for $A, B \in \mathfrak{g}$ we have

$$[A, B]^* = [A^*, B^*]. \quad (7.5)$$

To see this we observe that it is enough to show (7.5) locally, and hence we can assume that E is a product bundle $E = M \times G$. If $\pi_1: M \times G \rightarrow M$ and $\pi_2: M \times G \rightarrow G$ are the two projections then for $A \in \mathfrak{g}$, the vector field A^* is the unique vector field on E which is π_1 -related to the zero vector field on M and is π_2 -related to the left invariant vector field \tilde{A} on G . Since $[A, B] = [\tilde{A}, \tilde{B}]$ for $A, B \in \mathfrak{g}$ it follows that $[A^*, B^*]$ is again π_1 -related to zero and π_2 -related to $[A, B]$, hence (7.5) follows.

Next we observe that the vector field A^* generates a 1-parameter group of diffeomorphisms of E given by $t \mapsto R_{g_t}$, $t \in \mathbb{R}$, with $g_t = \exp(tA)$. That is, we claim that for each $x \in E$, the curve $t \mapsto xg_t$, $t \in \mathbb{R}$, is an integral curve for the vector field A^* , i.e. it satisfies the differential equation

$$\frac{\partial}{\partial t} R_{g_t}(x) = A_{R_{g_t}(x)}^*. \quad (7.6)$$

For $t = 0$ this follows from the definition of A^* and hence we have for t arbitrary:

$$\frac{\partial}{\partial t} R_{g_t}(x) = \frac{\partial}{\partial s} R_{g_{s+t}}(x)|_{s=0} = \frac{\partial}{\partial s} R_{g_s}(R_{g_t}(x))|_{s=0} = A_{R_{g_t}(x)}^*.$$

We now have the following lemma.

Lemma 7.3. *Let Y be a differentiable vectorfield on E and let $A \in \mathfrak{g}$ as above. Then*

$$[A^*, Y] = \lim_{t \rightarrow 0} \frac{Y_x - Y_x^{g_t}}{t}$$

where $Y_x^{g_t} = (R_{g_t})_*(Y_{R_{g_t}^{-1}(x)}) \in T_x E$.

Proof. (For a more general result see e.g. Spivak ch. V, Thm. 10; or Warner, prop. 2.25 (b).)

Since E is locally trivial we can take $E = U \times G$ where $U \subseteq M$ has a local coordinate system (x^1, \dots, x^n) . Also choose a basis A_1, \dots, A_k for \mathfrak{g} . Then every vector field Y on E has the form

$$Y = \sum_{i=1}^n a^i \frac{\partial}{\partial x^i} + \sum_{j=1}^k b^j A_j^*$$

where $a^i, b^j \in C^\infty(E)$. Also, since A^* is constant in the x^i -direction we have $[A^*, \partial/\partial x^i] = 0$, $i = 1, \dots, n$, so that

$$[A^*, Y] = \sum_{i=1}^n A^*(a^i) \frac{\partial}{\partial x^i} + \sum_{j=1}^k (A^*(b^j) A_j^* + b^j [A, A_j]^*). \quad (7.7)$$

On the other hand

$$\begin{aligned} Y_x - Y_x^{g_t} &= \sum_{i=1}^n (a^i(x) - a^i(xg_t^{-1})) \frac{\partial}{\partial x^i} + \\ &+ \sum_{j=1}^k ((b^j(x) A_j^*(x) - b^j(xg_t^{-1}) A_j^*(x))) + \\ &+ \sum_{j=1}^k ((b^j(xg_t^{-1}) A_j^*(x) - b^j(xg_t^{-1}) R_{g_t*} A_j^*(xg_t^{-1}))). \end{aligned}$$

Hence, using (7.6), we have

$$\begin{aligned}
 \lim_{t \rightarrow 0} \frac{Y_x - Y_x^{g_t}}{t} &= \sum_{i=1}^n A_x^*(a^i) \frac{\partial}{\partial x^i} + \sum_{j=1}^k A^*(b^j) A_j^*(x) + \\
 &+ \sum_{j=1}^k b^j(x) \lim_{t \rightarrow 0} \frac{1}{t} (A_j^*(x) - R_{g_t*} A_j^*(xg_t^{-1})).
 \end{aligned} \tag{7.8}$$

Here

$$R_{g_t*} A_j^*(xg_t^{-1}) = v_x(\text{Ad}(g_t^{-1})(A_j));$$

hence

$$\lim_{t \rightarrow 0} \frac{1}{t} (A_j^*(x) - R_{g_t*} A_j^*(xg_t^{-1})) = v_x(B_j)$$

with

$$B_j = \lim_{t \rightarrow 0} \frac{1}{t} (A_j - \text{Ad}(g_t^{-1})(A)) = -\text{ad}(-A)(A_j) = [A, A_j].$$

Inserting this in (7.8) and comparing with (7.7) we obtain the formula in Lemma 7.3 \square

Proof of Theorem 7.2. First notice that (1) follows from (2). In fact, as in the proof of Lemma 6.2, $\omega_{\text{MC}} = \pi_2^* \omega_0$, where ω_0 is the Maurer-Cartan connection on the bundle $G \rightarrow \text{pt}$, that is, $F_{\omega_{\text{MC}}} = \pi_2^* F_{\omega_0}$. But if F_{ω_0} is horizontal then it is clearly 0, and hence also $F_{\omega_{\text{MC}}} = 0$.

(2) Since ω is Ad-equivariant also $F_\omega = d\omega + \frac{1}{2}[\omega, \omega]$ is Ad-equivariant. We shall just show that it is horizontal, that is, for $X, Y \in T_x E$ we must show that if X is vertical then

$$(d\omega)(X, Y) = -\frac{1}{2} [\omega, \omega](X, Y). \tag{7.9}$$

Since

$$[\omega, \omega](X, Y) = [\omega(X), \omega(Y)] - [\omega(Y), \omega(X)] = 2[\omega(X), \omega(Y)]$$

(7.9) is equivalent to

$$(d\omega)(X, Y) = -[\omega(X), \omega(Y)]. \quad (7.10)$$

We have two cases: (1) Y is vertical; (2) Y is horizontal.

Case (1). Y is vertical. To show (7.10) for X and Y vertical we now take $X = A_x^*$, $Y = B_x^*$ for $A, B \in \mathfrak{g}$ and compute using (5.1):

$$\begin{aligned} (d\omega)(A^*, B^*) &= A^*(\omega(B^*)) - B^*(\omega(A^*)) - \omega([A^*, B^*]) \\ &= A^*(B) - B^*(A) - \omega([A, B]^*) \\ &= -[A, B] \\ &= -[\omega(A^*), \omega(B^*)] \end{aligned} \quad (7.11)$$

which is (7.10) in this case.

Case (2). Y is horizontal. Again we take $X = A_x^*$ for A^* the vector field associated to $A \in \mathfrak{g}$ as above. Also we extend Y to a vector field of horizontal vectors (also denoted by Y). This is possible since for an arbitrary vector field Z on E extending Y the vector field defined by

$$Y_y = Z_y - v_y \circ \omega_y(Z_y), \quad y \in E$$

is horizontal. For the proof of (7.10) we thus have to prove for $A \in \mathfrak{g}$ and Y a horizontal vector field:

$$(d\omega)(A^*, Y) = 0. \quad (7.12)$$

Since $\omega(A^*) = A$ is constant and since $\omega(Y) = 0$ we get using (5.1):

$$(d\omega)(A^*, Y) = -\omega([A^*, Y]). \quad (7.13)$$

Since Y is horizontal we get

$$\omega(Y_x^{g_t}) = (R_{g_t}^* \omega)(Y_{R_{g_t}^{-1}(x)}) = \text{Ad}(g_t^{-1}) \circ \omega(Y_{R_{g_t}^{-1}(x)}) = 0.$$

Hence

$$\omega([A^*, Y_x]) = \lim_{t \rightarrow 0} \frac{Y_x - Y_x^{g_t}}{t} = 0,$$

and by (7.12) we conclude

$$(d\omega)(A^*, Y) = 0$$

which proves (7.12) and hence (7.10) in case (2). This finishes the proof of Theorem 7.2 (2) and hence also of (1).

(3) Let us differentiate the equation (7.1):

$$\begin{aligned} 0 &= -\frac{1}{2}[d\omega, \omega] + \frac{1}{2}[\omega, d\omega] + dF_\omega \\ &= -[d\omega, \omega] + dF_\omega \\ &= \frac{1}{2}[[\omega, \omega], \omega] - [F_\omega, \omega] + dF_\omega \end{aligned} \tag{7.14}$$

where we have used (5.2) and (7.1). But

$$[[\omega, \omega], \omega] = 0 \tag{7.15}$$

since

$$\begin{aligned} &[[\omega, \omega], \omega](X, Y, Z) \\ &= [[\omega, \omega](X, Y), \omega(Z)] - [[\omega, \omega](X, Z), \omega(Y)] + \\ &\quad + [[\omega, \omega](Y, Z), \omega(X)] \\ &= 2([[\omega(X), \omega(Y)], \omega(Z)] - [[\omega(X), \omega(Z)], \omega(Y)] + \\ &\quad + [[\omega(Y), \omega(Z)], \omega(X)]) \\ &= 0, \end{aligned}$$

by the Jacobi identity. By (7.14) and (7.15) we clearly have proved (7.3).

(4) This follows directly from (7.1) \square

Remark. Let X and Y be two horizontal vector fields on E . Then by (7.1) we get

$$F_\omega = -\omega([X, Y]). \tag{7.16}$$

Remark. Suppose $(f, \bar{f}): (E', \pi', M') \rightarrow (E, \pi, M)$ is bundle map and ω is a connection in E with curvature form F_ω . Then $\bar{f}^*\omega$ is a connection in E' with curvature form \bar{f}^*F_ω . In particular if $\varphi: E' \rightarrow E$ is bundle isomorphism and ω connection in E then $\omega^\varphi = \varphi^*\omega$ has curvature $F_{\omega^\varphi} = \varphi^*F_\omega$.

Definition 7.4. A connection ω in a principal G -bundle is called *flat* if the curvature form vanishes identically, that is if $F_\omega \equiv 0$.

Theorem 7.5. Let (E, π, M) be a principal G -bundle with connection ω . Then ω is flat if and only if around every point in M there is a neighborhood U with trivialization $\varphi: \pi^{-1}(U) \rightarrow U \times G$ such that ω restricted to $E|_U$ is induced by the Maurer-Cartan connection in $U \times G$, that is $\omega|_{E|_U} = \varphi^* \omega_{\text{MC}}$.

Proof. (\Leftarrow) This follows clearly from theorem 7.2 and the above remark.

(\Rightarrow) Assume $F_\omega \equiv 0$. For $x \in E$ let $H_x \subseteq T_x E$ be the subspace of horizontal vectors, that is $H_x = \ker \omega_x$, $x \in E$. This defines a distribution which is integrable; in fact, if X, Y are horizontal vector fields then by (7.16) we have

$$0 = F_\omega(X, Y) = \omega([X, Y])$$

so that $[X, Y]$ is again a horizontal vector field. By the Frobenius Integrability Theorem there is a foliation $\mathcal{F} = \{\mathcal{F}_\alpha\}_{\alpha \in I}$ of E such that for each $x \in E$ H_x is the tangent space to the leaf through x . For $g \in G$ the diffeomorphism $R_g: E \rightarrow E$ satisfies $R_{g*} H_x = H_{xg}$, $\forall x \in E$, by Proposition 6.4; hence R_g maps the leaf through x diffeomorphically to the leaf through xg . Now fix $p \in M$, $x \in \pi^{-1}(p)$ and let $\mathcal{F}_\alpha \subseteq E$ be the leaf through x . Since $T_x \mathcal{F}_\alpha = H_x$ and $\pi_*: H_x \rightarrow T_p M$ is an isomorphism we can apply the Inverse Function Theorem and we can choose neighborhoods U of p and $V \subseteq \mathcal{F}_\alpha$ of x such that $\pi: V \rightarrow U$ is a diffeomorphism. The inverse mapping $s: U \rightarrow V \subseteq \pi^{-1}(U)$ defines a differentiable section in the bundle $E|_U$ and hence a trivialization $\varphi = \psi: \pi^{-1}(U) \rightarrow U \times G$ whose inverse is defined by $\psi(q, g) = s(q)g$, $q \in U$, $g \in G$. The fact that φ is differentiable follows from the Inverse Function Theorem. Now let ω' be the connection in $E|_U$ induced by the Maurer-Cartan connection in $U \times G$, that is $\omega' = \varphi^* \omega_{\text{MC}}$. By the remark following Proposition 6.4 the horizontal vector space at a point of the form yg , $y \in V$, $g \in G$ is

$$(R_g)_*(T_y(V)) = (R_g)_* H_y = H_{yg}$$

which is also the horizontal vector space for ω . Hence $\omega|_{E|_U}$ and ω' has the same horizontal subspaces and therefore they agree. \square

Corollary 7.6. Let (E, π, M) be a principal G -bundle. Then the following are equivalent:

- (1) E has a flat connection.
- (2) There is an open covering $\{U_\alpha\}_{\alpha \in \Sigma}$ and trivializations $\{\varphi_\alpha\}_{\alpha \in \Sigma}$ such that all transition functions $g_{\alpha\beta}: U_\alpha \cap U_\beta \rightarrow G$ are constant.

Proof. (2) \Rightarrow (1). Since $g_{\alpha\beta}$ is constant $g_{\alpha\beta}^* \omega_0 = 0$. Hence the collection $\{A_\alpha \in \Omega^1(U_\alpha, \mathfrak{g}) \mid A_\alpha \equiv 0, \alpha \in \Sigma\}$ satisfies (6.7), and thus defines a connection ω in E by Corollary 6.9. For this $F_\omega = 0$ by Theorem 7.2 d) since clearly $F_{A_\alpha} = 0, \forall \alpha \in \Sigma$.

(1) \Rightarrow (2). By Theorem 7.5 we can choose a covering $\{U_\alpha\}_{\alpha \in \Sigma}$ and trivializations $\{\varphi_\alpha\}_{\alpha \in \Sigma}$ of M such that the given flat connection ω restricted to $E|_{U_\alpha}$ is induced by the Maurer-Cartan connection, ω_{MC} in $U_\alpha \times G, \alpha \in \Sigma$. Furthermore we can arrange that all intersections are connected (e.g. by choosing a Riemannian metric on M and choosing all U_α to be geodesically convex sets). Now by construction the local connection forms $\{A_\alpha\}_{\alpha \in \Sigma}$ for ω are all zero, hence by Corollary 6.9 we have $g_{\alpha\beta}^* \omega_0 = 0$ on $U_\alpha \cap U_\beta$ where ω_0 is the Maurer-Cartan connection on G . It follows that $g_{\alpha\beta}: U_\alpha \cap U_\beta \rightarrow G$ has zero differential and since $U_\alpha \cap U_\beta$ is connected $g_{\alpha\beta}$ is constant. \square

Exercise 7.7. Let (E, π, M) be a principal G -bundle and let $\{U_\alpha\}_{\alpha \in \Sigma}$ be an open covering of M with trivializations $\{\varphi_\alpha\}_{\alpha \in \Sigma}$ and transition functions $\{g_{\alpha\beta}\}_{\alpha, \beta \in \Sigma}$. Let $\varphi: E \rightarrow E$ be a gauge transformation corresponding to the family of differentiable maps $\sigma_\alpha: U_\alpha \rightarrow G$ satisfying (6.14). Let ω be a connection in E with local connection forms $\{A_\alpha\}_{\alpha \in \Sigma}$.

- (1) Show that the curvature form F_{ω^φ} for the connection $\omega^\varphi = \varphi^* \omega$ is given locally by

$$F_{A_\alpha^{\sigma_\alpha}} = \text{Ad}(\sigma_\alpha^{-1}) \circ F_{A_\alpha}, \quad \text{for all } \alpha \in \Sigma$$

where F_ω is given locally by $\{F_{A_\alpha}\}_{\alpha \in \Sigma}$.

- (2) Let $H \subseteq G$ be a Lie subgroup with Lie algebra $\mathfrak{h} \subseteq \mathfrak{g}$. Show that if there is a reduction of E and ω to H then F_ω satisfies the following: For all $x \in E$ there is a $g \in G$ such that $\text{Ad}(g)(\mathfrak{h})$ contains the set $\{F_\omega(X, Y) \mid X, Y \in T_x E\}$.

- (3) The connection is called irreducible if for all $x \in E, \mathfrak{g}$ is generated as a Lie algebra by the set $\{F_\omega(X, Y) \mid X, Y \in T_x E\}$, i.e., is spanned by all iterated Lie brackets of such elements. Show, that if G is connected, ω is irreducible and if $\varphi: E \rightarrow E$ is a gauge transformation given by $\{\sigma_\alpha\}_{\alpha \in \Sigma}$

as above then $\omega^\varphi = \omega$ if and only if $\sigma_\alpha(p) \in Z(G)$, for all $p \in U_\alpha$, $\alpha \in \Sigma$, where $Z(G)$ is the center of G .

8. Linear Connections

Let us study in particular the case where $G = \text{GL}(n, \mathbb{R})$. As usual the Lie algebra is $M(n, \mathbb{R})$, the set of $n \times n$ real matrices with Lie bracket

$$[A, B] = AB - BA, \quad A, B \in M(n, \mathbb{R}), \quad (8.1)$$

and the adjoint representation

$$\text{Ad}(g)(A) = gAg^{-1}, \quad A \in M(n, \mathbb{R}), g \in \text{GL}(n, \mathbb{R}). \quad (8.2)$$

Now consider an n -dimensional vector bundle V on a manifold M and let $E = F(V)$ be the frame bundle. A connection in this is therefore a 1-form $\omega \in \Omega^1(E, M(n))$, ie. a matrix of ordinary 1-forms

$$\omega = \begin{bmatrix} \omega_{11} & \dots & \omega_{1n} \\ \vdots & & \vdots \\ \omega_{n1} & \dots & \omega_{nn} \end{bmatrix}, \quad \omega_{ij} \in \Omega^1(E).$$

Matrix multiplication defines a linear map

$$M(n) \otimes M(n) \longrightarrow M(n)$$

sending $A \otimes B \mapsto AB$, and this induces a map

$$\Omega^2(E, M(n) \otimes M(n)) \longrightarrow \Omega^2(E, M(n)).$$

The image of $\omega \wedge \omega$ by this is also denoted $\omega \wedge \omega$; that is,

$$(\omega \wedge \omega)(X, Y) = \omega(X)\omega(Y) - \omega(Y)\omega(X) \quad (8.3)$$

and the components are given by

$$(\omega \wedge \omega)_{ij} = \sum_k \omega_{ik} \wedge \omega_{kj} \quad (8.4)$$

It follows from (8.1) and (8.4) that

$$\begin{aligned} [\omega, \omega](X, Y) &= 2[\omega(X), \omega(Y)] = 2(\omega \wedge \omega)(X, Y), \\ \frac{1}{2} [\omega, \omega] &= \omega \wedge \omega. \end{aligned} \tag{8.5}$$

Hence the structural equation (7.1) becomes

$$d\omega = -\omega \wedge \omega + F_\omega, \tag{8.6}$$

where F_ω is a matrix of 2-forms on E , i.e.,

$$F_\omega = \begin{bmatrix} F_{11} & \dots & F_{1n} \\ \vdots & & \vdots \\ F_{n1} & \dots & F_{nn} \end{bmatrix}, \quad F_{ij} \in \Omega^2(E).$$

Given a covering $\{U_\alpha\}_{\alpha \in \Sigma}$ and local trivializations of V we get corresponding local trivializations for E , and hence for each α the local connection form $A_\alpha \in \Omega^1(U_\alpha, M(n))$ is just a matrix of one forms as in (1.4) and the corresponding curvature form

$$F_{A_\alpha} = A_\alpha \wedge A_\alpha + dA_\alpha$$

is just the formula (1.7). We shall now interpret the connection and curvature in terms of a differential operator on the bundle V .

First observe that there is a natural isomorphism of V with the vector bundle $E_{\mathbb{R}^n}$ associated with E via ι , the identity representation (cf. 3.10). This gives another interpretation of $\Omega^k(M, V)$:

Lemma 8.1. *Let $\tilde{\omega} \in \Omega^k(E, \mathbb{R}^n)$ be a horizontal and ι -equivariant k -form. Then $\tilde{\omega}$ defines for each $p \in M$ a k -linear map $\omega_p: T_p M \times \dots \times T_p M \rightarrow V_p$, which is differentiable in the following sense: For X_1, \dots, X_k differentiable vector fields on M $\omega(X_1, \dots, X_k)$ gives a differentiable section of V .*

Proof. Let $\pi: E \rightarrow M$ be the projection in the frame bundle for V and for $p \in M$ choose $x \in E$ with $\pi(x) = p$. For $X_1, \dots, X_k \in T_p M$ choose $\tilde{X}_1, \dots, \tilde{X}_k \in T_x E$ with $\pi_* \tilde{X}_i = X_i$, $i = 1, \dots, k$, and put

$$\omega_p(X_1, \dots, X_k) = x \circ \tilde{\omega}_x(\tilde{X}_1, \dots, \tilde{X}_k) \tag{8.7}$$

where we recall that $x \in \text{Iso}(\mathbb{R}^n, V)$. This is well-defined since $\tilde{\omega}$ is horizontal and since for $g \in \text{GL}(n, \mathbb{R})$, $R_{g_*} \tilde{X}_1, \dots, R_{g_*} \tilde{X}_k \in T_{xg}E$ also maps to X_1, \dots, X_k such that

$$\begin{aligned} xg(\tilde{\omega}_{xg} R_{g_*} \tilde{X}_1, \dots, R_{g_*} \tilde{X}_k) &= xg(R_{g_*}^* \tilde{\omega})(\tilde{X}_1, \dots, \tilde{X}_k) \\ &= xg(g^{-1} \tilde{\omega}(\tilde{X}_1, \dots, \tilde{X}_k)) \\ &= x(\tilde{\omega}(\tilde{X}_1, \dots, \tilde{X}_k)). \end{aligned}$$

We leave it to the reader to check differentiability. \square

Remark. Conversely if $\omega_p: T_p M \times \dots \times T_p M \rightarrow V_p$ satisfies the conditions of the lemma then $\tilde{\omega}$ defined by (8.7) defines a horizontal and ι -equivariant k -form on E . Hence $\Omega^k(M, V)$ is the set of such ω 's.

Now suppose $\omega \in \Omega^1(E, M(n))$ is a connection. We shall construct a differential operator called the covariant derivative

$$\nabla: \Gamma(M, V) \rightarrow \Omega^1(E, M(n)). \quad (8.8)$$

For this consider $s \in \Gamma(M, V)$ and let $\tilde{s}: E \rightarrow \mathbb{R}^n$ be the corresponding ι -equivariant map. Then we define $\tilde{\nabla}(\tilde{s}) \in \Omega^1(E, M(n))$ by the formula

$$\tilde{\nabla}(\tilde{s}) = d\tilde{s} + \omega\tilde{s}, \quad (8.9)$$

where the multiplication is the usual matrix multiplication of the matrix ω and the column vector \tilde{s} .

Proposition 8.2. *For $s \in \Gamma(M, V)$ corresponding to the ι -equivariant map $\tilde{s}: E \rightarrow \mathbb{R}^n$, the 1-form $\tilde{\nabla}(\tilde{s}) \in \Omega^1(E, \mathbb{R}^n)$ is also ι -equivariant and horizontal, hence defines a form $\nabla(s) \in \Omega^1(M, V)$.*

Proof. Let us first show ι -equivariance:

$$\begin{aligned} R_g^* \tilde{\nabla}(\tilde{s}) &= R_g^* d\tilde{s} + R_g^*(\omega)(\tilde{s} \circ R_g) \\ &= d(\tilde{s} \circ R_g) + (\text{Ad}(g^{-1}) \circ \omega)\tilde{s} \circ R_g \\ &= d(g^{-1}\tilde{s}) + (g^{-1}\omega g)g^{-1}\tilde{s} \\ &= g^{-1}d\tilde{s} + g^{-1}\omega\tilde{s} \\ &= g^{-1}\tilde{\nabla}(\tilde{s}). \end{aligned}$$

Next let us show that $\tilde{\nabla}(\tilde{s})$ is horizontal. For this we first show that for $x \in E$ we have

$$(d\tilde{s})(v_x A) = -A\tilde{s}, \quad A \in M(n). \quad (8.10)$$

In fact $(d\tilde{s}) \circ v_x$ is the differential of the map $G \rightarrow E$ sending g to $\tilde{s}(xg) = g^{-1}\tilde{s}(x)$, hence (8.10) follows from the fact that the differential of $g \mapsto g^{-1}$ is given by multiplication by -1 . It follows that for $A \in M(n)$ we have

$$\begin{aligned} \tilde{\nabla}(\tilde{s})(v_x A) &= (d\tilde{s})(v_x A) + \omega_x(v_x A)\tilde{s}(x) \\ &= -A\tilde{s}(x) + A\tilde{s}(x) \\ &= 0, \end{aligned}$$

which proves the proposition. \square

Notation. By Lemma 8.1, $\nabla(s)$ gives us for each $p \in M$ a linear map $\nabla(s)_p: T_p M \rightarrow V_p$. For $X \in T_p M$ we shall write

$$\nabla_X(s) = \nabla(s)(X) \in V_p \quad (8.11)$$

and this is called the covariant derivative of s in the direction X .

Proposition 8.3. *The covariant derivative satisfies*

- (1) $\nabla_{X+Y}(s) = \nabla_X(s) + \nabla_Y(s)$
- (2) $\nabla_X(s + s') = \nabla_X(s) + \nabla_X(s')$
- (3) $\nabla_{\lambda X}(s) = \nabla_X(\lambda s) = \lambda \nabla_X(s)$
- (4) $\nabla_X(fs) = X(f)s + f(p)\nabla_X(s)$

for all $X, Y \in T_p M$, $s \in \Gamma(M, V)$, $\lambda \in \mathbb{R}$ and $f \in C^\infty(M)$.

Exercise 8.4. Prove proposition 8.3.

Next let us express the curvature form of the connection ω on the frame bundle E in terms of the covariant derivative ∇ . First let us introduce the notation

$$\text{End}(V) = E_{M(n)} \quad (8.12)$$

for the vector bundle associated with the adjoint representation (8.2) of $\text{GL}(n, \mathbb{R})$ on $M(n)$. This is justified by the following lemma.

Lemma 8.5. *There is a 1 – 1 correspondence between horizontal Ad-equivariant k -forms $\tilde{\Theta} \in \Omega^k(E, M(n))$ and families of k -linear maps*

$$\Theta_p: T_p M \times \cdots \times T_p M \longrightarrow \text{End}(V_p)$$

which varies differentiably in the sense that k vector fields X_1, \dots, X_k and a section $s \in \Gamma(M, V)$ give rise to another differentiable section $\Theta(X_1, \dots, X_k)(s)$ given by

$$\Theta(X_1, \dots, X_k)(s)(p) = \Theta_p(X_1(p), \dots, X_k(p))(s(p)) \quad (8.13)$$

Proof. This is analogous to the proof of Lemma 8.1 and the proof is left to the reader. We only note that for $x \in \pi^{-1}(p)$ and $\tilde{X}_1, \dots, \tilde{X}_k \in T_x E$ with $\pi_* \tilde{X}_i = X_i$, $i = 1, \dots, k$, $\tilde{\Theta}$ and Θ is related by

$$\Theta_p(X_1, \dots, X_k) = x \circ \tilde{\Theta}_x(\tilde{X}_1, \dots, \tilde{X}_k) \circ x^{-1}, \quad (8.14)$$

where $x \in E_p = \text{Iso}(\mathbb{R}^n, V_p)$. \square

Proposition 8.6. *Let $\tilde{F}_\omega \in \Omega^2(E, M(n))$ be the curvature form for the connection ω and let $F_\omega \in \Omega^2(M, \text{End}(V))$ be the corresponding 2-form as in Lemma 8.1. Let ∇ denote the covariant derivation associated to ω . Then for X, Y differentiable vector fields on M and s a section of V we have*

$$F_\omega(X, Y)(s) = (\nabla_X \nabla_Y - \nabla_Y \nabla_X - \nabla_{[X, Y]})(s). \quad (8.15)$$

Proof. Since it is enough to prove (8.15) locally we can assume V and hence E to be trivial; hence we can choose \tilde{X} and \tilde{Y} on $E = M \times \text{GL}(n, \mathbb{R})$ such that \tilde{X} respectively \tilde{Y} are π -related to X respectively Y (that is $\pi_* \tilde{X}_x = X_{\pi(x)}$ and $\pi_* \tilde{Y}_x = Y_{\pi(x)}$, $\forall x \in E$). Also, as in the proof of Theorem 7.2 we can assume \tilde{X} and \tilde{Y} to be horizontal. Furthermore for $s \in \Gamma(M, V)$ let $\tilde{s}: E \rightarrow \mathbb{R}^n$ be the corresponding ι -equivariant function. Then by (8.14) and (7.16) we have for $\pi(x) = p$:

$$\begin{aligned} F_\omega(X_p, Y_p)(s(p)) &= x \circ \tilde{F}_\omega(\tilde{X}_p, \tilde{Y}_p) \circ x^{-1}(s(p)) \\ &= -x \circ \omega_x([\tilde{X}, \tilde{Y}]_x)(\tilde{s}(x)). \end{aligned} \quad (8.16)$$

On the other hand by (8.7) $\nabla_{X_p}(s) = x \circ \tilde{\nabla}(\tilde{s})(\tilde{X}_x)$, and hence

$$\nabla_{Y_p}(\nabla_{X_p}) = x \circ \tilde{\nabla}(\tilde{\nabla}(\tilde{s})(\tilde{X}))(\tilde{Y}_x).$$

Therefore (8.15) is equivalent to

$$\begin{aligned} -\omega([\tilde{X}, \tilde{Y}](\tilde{s})) &= \tilde{\nabla}(\tilde{\nabla}(\tilde{s}(\tilde{X}))) (\tilde{Y}) - \tilde{\nabla}(\tilde{\nabla}(\tilde{s}(\tilde{Y}))) (\tilde{X}) \\ &\quad - \tilde{\nabla}(\tilde{s})([\tilde{X}, \tilde{Y}]), \end{aligned} \quad (8.17)$$

where we have used that $[\tilde{X}, \tilde{Y}]$ is π -related to $[X, Y]$. But since \tilde{X} and \tilde{Y} are horizontal we have

$$\tilde{\nabla}(\tilde{\nabla}(\tilde{s}(\tilde{X}))) (\tilde{Y}) = d(d(\tilde{s})(\tilde{X})) (\tilde{Y}) = \tilde{Y}(\tilde{X}(\tilde{Y})),$$

and similarly for \tilde{X} and \tilde{Y} interchanged. Hence the right hand side of (8.17) becomes

$$\tilde{Y}(\tilde{X}(\tilde{s})) - \tilde{X}(\tilde{Y}(\tilde{s})) - [\tilde{X}, \tilde{Y}](\tilde{s}) - \omega([\tilde{X}, \tilde{Y}]) = -\omega([\tilde{X}, \tilde{Y}]),$$

which was to be proved. \square

Next let us express ∇ in terms of local trivializations. Suppose $\{U_\alpha\}_{\alpha \in \Sigma}$ is a covering of M with local trivializations $f_\alpha: V|_{U_\alpha} \rightarrow \mathbb{R}^n$, and associated transition functions $g_{\alpha\beta}: U_\alpha \cap U_\beta \rightarrow \text{GL}(n, \mathbb{R})$. Then there is a 1-1 correspondence between sections s of V and families $\{s_\alpha\}_{\alpha \in \Sigma}$ of differentiable functions $s_\alpha: U_\alpha \rightarrow \mathbb{R}^n$, satisfying for $\alpha, \beta \in \Sigma$:

$$s_\beta(p) = g_{\beta\alpha}(p)s_\alpha(p), \quad p \in U_\alpha \cap U_\beta. \quad (8.18)$$

In fact s and $\{s_\alpha\}$ are related by

$$f_\alpha \circ s(p) = (p, s_\alpha(p)), \quad p \in U_\alpha. \quad (8.19)$$

Now $\{g_{\alpha\beta}\}_{\alpha, \beta \in \Sigma}$ are also transition functions for the frame bundle $E = F(V)$ corresponding to the local trivializations $\{\varphi_\alpha = \tilde{f}_\alpha\}_{\alpha \in \Sigma}$ corresponding to $\{f_\alpha\}_{\alpha \in \Sigma}$, as in (2.1). In the notation of Proposition 6.11 we have the following proposition.

Proposition 8.7. *Let $s \in \Gamma(M, V)$ correspond to the family $\{s_\alpha\}_{\alpha \in \Sigma}$ as above, then $\nabla(s) \in \Omega^1(\cdot, M), V$ corresponds to the family of 1-forms $\{\nabla(s_\alpha)\}_{\alpha \in \Sigma}$ given by*

$$\nabla(s_\alpha) = ds_\alpha + A_\alpha s_\alpha \quad (8.20)$$

where $\{A_\alpha\}_{\alpha \in \Sigma}$ are the local connection forms for ω defining ∇ .

Proof. Notice that for $\alpha \in \Sigma$ the trivializations $\varphi_\alpha: E|_{U_\alpha} \rightarrow U_\alpha \times \text{GL}(n, \mathbb{R})$ corresponding to f_α has the inverse defined by $\varphi_\alpha^{-1}(p, g) = (f_\alpha)_p^{-1} \circ g$. and hence the section $\sigma_\alpha: U_\alpha \rightarrow E|_{U_\alpha}$ used in proposition 6.11 is given by

$$\sigma_\alpha(p) = \varphi_\alpha^{-1}(p, \text{id}) = (f_\alpha)_p^{-1} \in \text{Iso}(\mathbb{R}^n, V_p) = E_p.$$

For $s \in \Gamma(U)$ the corresponding ι -equivariant function $\tilde{s}: R \rightarrow \mathbb{R}^n$ is related to $\{s_\alpha\}_{\alpha \in \Sigma}$ by

$$s_\alpha = \tilde{s} \circ \sigma_\alpha$$

and hence the local 1-form $\nabla(s_\alpha)$ corresponding to the horizontal ι -equivariant 1-form is given by

$$\begin{aligned} \nabla(s_\alpha) &= (\sigma_\alpha)^*(\tilde{\nabla}(\tilde{s})) \\ &= \sigma_\alpha^*(d\tilde{s} + \omega\tilde{s}) \\ &= d(\tilde{s} \circ \sigma_\alpha) + (\sigma_\alpha^*\omega)(\tilde{s} \circ \sigma_\alpha) \\ &= d(s_\alpha) + A_\alpha s_\alpha, \end{aligned}$$

where $A_\alpha = \sigma_\alpha^*\omega$ by the proof of Corollary 6.9. □

Exercise 8.8. Let G be an arbitrary Lie group and $\rho: G \rightarrow \text{GL}(n, \mathbb{R})$ a representation. Let (E, π, M) be a principal G -bundle. and let V be the associated vector bundle. Let ω be a connection in E .

(1) Show that the frame bundle of V is the extension of E to $\text{GL}(n, \mathbb{R})$ via ρ , and conclude that ω has a unique extension ω_ρ to $F(V)$, cf. exercise 6.18.

(2) Now choose a covering $\{U_\alpha\}_{\alpha \in \Sigma}$ of M and local trivializations of E and hence also V and $F(V)$. Show that the the covariant derivative ∇ corresponding to ω_ρ is given in terms of the local trivializations by

$$\nabla(s_\alpha) = ds_\alpha + \rho_*(A_\alpha)s_\alpha \tag{8.21}$$

where ω corresponds to $\{A_\alpha \in \Omega^1(U_\alpha, \mathfrak{g})\}$, $\rho_*: \mathfrak{g} \rightarrow M(n)$ is the differential of ρ , and $\{s_\alpha\}_{\alpha \in \Sigma}$ defines a section in V .

Again return to the case of a vector bundle V on M , $E = F(V)$ the frame bundle and let ∇ be the covariant derivative.

Definition 8.9. A section $s \in \Gamma(M, V)$ is called *parallel* if $\nabla_X(s) = 0$ for all tangent vectors $X \in T_p M$ and for all $p \in M$.

In the notation of Proposition 8.7 we have the following corollary.

Corollary 8.10. *Let $s \in \Gamma(M, V)$ correspond to $\{s_\alpha: U_\alpha \rightarrow \mathbb{R}^n\}_{\alpha \in \Sigma}$. Then s is parallel if and only if*

$$ds_\alpha = -A_\alpha s_\alpha, \quad \alpha \in \Sigma. \quad (8.22)$$

That is, locally a parallel section satisfies a differential system as in (1.4).

Proposition 8.11. *The following are equivalent:*

- (1) *Every point of M has a neighborhood U and parallel sections $\sigma_1, \dots, \sigma_n \in \Gamma(U, V)$ such that $\{\sigma_1(p), \dots, \sigma_n(p)\}$ is a basis for V_p for all $p \in U$.*
- (2) *The connection is flat, ie., $F_\omega = 0$*

Proof. As in the proof of corollary 2.15 a set of sections $\sigma_1, \dots, \sigma_n \in \Gamma(U, V)$ defining a local frame for $V|_U$ gives a trivialization of $V|_U$, $f: V|_U \rightarrow U \times \mathbb{R}^n$, such that

$$f \circ \sigma_i = (p, e_i), \quad i = 1, \dots, n,$$

where $\{e_1, \dots, e_n\}$ is the canonical basis for \mathbb{R}^n . Hence by (8.20) $\nabla(\sigma_i)$ is given in terms of this trivialization by $\nabla(\sigma_i) = Ae_i$, where A is the local connection form for ω . It follows that $\sigma_1, \dots, \sigma_n$ are parallel if and only if $A = 0$, that is, $\omega|_{E|_U}$ is induced by the Maurer-Cartan connection via the trivialization (2.1) of $E|_U$ corresponding to f . The proposition now follows from Theorem 7.2 (1). \square

Exercise 8.12. We consider the $\text{GL}(k, \mathbb{R})$ -bundle $(W_{n,k}, \gamma_{n,k}, G_k(\mathbb{R}^n))$, for $k \leq n$, and we consider $W(n, k) \subseteq M(n, k) = \mathbb{R}^{nk}$ as the open set of $n \times k$ matrices X of rank k (cf. exercise 4.8).

- (1) Show that the 1-form

$$\omega = (X^t X)^{-1} X^t dX \in \Omega^1(W_{n,k}, M(k)), \quad (8.23)$$

gives a connection in the above bundle.

(2) Show that the curvature form is given by

$$F_\omega = (X^t X)^{-1} dX^t \wedge dX - (X^t X)^{-1} dX^t \wedge X(X^t X)^{-1} X^t dX. \quad (8.24)$$

(3) Show that the restriction of ω to the Stiefel manifold $V_{n,k} \subseteq W_{n,k}$ is given by

$$\omega = X^t dX \quad (8.25)$$

and that this defines a reduction to the $O(k)$ -bundle $(V_{n,k}, \gamma_{n,k}, G_k(\mathbb{R}^n))$ with curvature form

$$\begin{aligned} F_\omega &= dX^t \wedge dX - dX^t \wedge X X^t dX \\ &= dX^t \wedge dX + X^t dX \wedge X^t dX. \end{aligned} \quad (8.26)$$

(4) For $k = 1$ the connection ω in the \mathbb{R}^* -bundle $(\mathbb{R}^n \setminus \{0\}, \eta, \mathbb{R}P^{n-1})$ is given by

$$\omega = \frac{x^t}{|x|^2} dx, \quad x \in \mathbb{R}^n \setminus \{0\}.$$

Show that this connection is flat, ie. $F_\omega = 0$, and conclude that the real Hopf-bundle has locally a non-vanishing parallel section. Notice that this does not exist globally.

9. The Chern-Weil Homomorphism

We can now associate to a principal G -bundle (E, π, M) with a connection ω some closed differential forms on M , and as we shall see, the corresponding classes in de Rham cohomology does not depend on ω but only the isomorphism class of the G -bundle.

First some linear algebra: Let V be a finite dimensional real vector space. For $k \geq 1$ let $S^k(V^*)$ denote the vector space of *symmetric* k -linear functions

$$P: V \times V \times \dots \times V \longrightarrow \mathbb{R}.$$

We shall identify P with with the corresponding linear map

$$P: V \otimes V \otimes \dots \otimes V \longrightarrow \mathbb{R}$$

which is invariant under the action of the symmetric group acting on $V \otimes V \otimes \dots \otimes V$. That is

$$P(v_{\sigma_1} \otimes \dots \otimes v_{\sigma_k}) = P(v_1 \otimes \dots \otimes v_k)$$

for every permutation σ of $1, \dots, k$. We also have a product

$$\circ: S^k(V^*) \otimes S^l(V^*) \longrightarrow S^{k+l}(V^*)$$

defined by

$$\begin{aligned} P \circ Q(v_1, \dots, v_{k+l}) \\ = \frac{1}{(k+l)!} \sum_{\sigma} P(v_{\sigma_1}, \dots, v_{\sigma_k}) Q(v_{\sigma_{k+1}}, \dots, v_{\sigma_{k+l}}) \end{aligned} \tag{9.1}$$

where σ runs over all permutations of $1, \dots, k+l$. We also put $S^0(V^*) = \mathbb{R}$ and then

$$S^*(V^*) = \bigoplus_{k=0}^{\infty} S^k(V^*)$$

becomes a commutative ring with unit $1 \in \mathbb{R} = S^0(V^*)$. The associativity can be shown directly from 9.1, but it follows from the proposition below. Choose a basis $\{e_1, \dots, e_n\}$ for V and let $\mathbb{R}[x_1, \dots, x_n]$ denote the polynomial ring in the variables x_1, \dots, x_n . Let $\mathbb{R}[x_1, \dots, x_n]^k$ denote the subset of homogeneous polynomials of degree k , and define a mapping

$$S^k(V^*) \xrightarrow{\sim} \mathbb{R}[x_1, \dots, x_n]^k$$

by

$$\tilde{P}(x_1, \dots, x_n) = P(v, \dots, v), \quad v = \sum_{i=1}^n x_i e_i \quad (9.2)$$

for $P \in S^k(V^*)$. We then have

Proposition 9.1. (1) *The mapping $P \mapsto \tilde{P}$ is an isomorphism of vector spaces*

$$S^k(V^*) \cong \mathbb{R}[x_1, \dots, x_n]^k. \quad (9.3)$$

(2) $(P \circ Q)^\sim = \tilde{P} \cdot \tilde{Q}$, hence (9.3) gives an isomorphism of rings

$$S^*(V^*) \xrightarrow{\cong} \mathbb{R}[x_1, \dots, x_n]$$

Proof. (2) Clearly follows from (9.1).

(1) We first show injectivity. For this notice that the coefficient to $x_{i_1} \cdots x_{i_n}$ is a positive multiple of

$$P(e_1, \dots, e_1, e_2, \dots, e_2, \dots, e_n, \dots, e_n) = a_{i_1 \dots i_n},$$

where e_j is repeated i_j times, $j = 1, \dots, n$. Hence if $\tilde{P} = 0$ then $a_{i_1 \dots i_n} = 0$ for all $\{i_1, \dots, i_n\}$ satisfying $i_1 + \dots + i_n = k$. By the symmetry of P we conclude that

$$P(e_{j_1}, \dots, e_{j_k}) = 0, \quad \text{for all } j_1, \dots, j_k \in \{1, \dots, n\}.$$

Hence by the multi-linearity of P ,

$$P(v_1, \dots, v_k) = 0, \quad \text{for all } v_1, \dots, v_k \in V,$$

that is, $P = 0$. It follows that $S^*(V^*)$ is isomorphic to a subring of $\mathbb{R}[x_1, \dots, x_n]$. But since

$$S^1(V^*) = \text{Hom}(V, \mathbb{R}) \xrightarrow{\sim} \mathbb{R}[x_1, \dots, x_n]^1$$

is clearly an isomorphism, the subring has to contain x_1, \dots, x_n and hence is the full polynomial ring. \square

Remark. We have thus shown that $P \in S^k(V^*)$ is determined by the function $\tilde{P}: v \mapsto P(v, \dots, v)$. This is called a polynomial function for V . A choice of basis $\{e_i, \dots, e_n\}$ for V gives an identification of the ring of polynomial functions with the usual polynomial ring in n variables. The inverse operation which to a polynomial function \tilde{P} associates a symmetric multi-linear map P is often called *polarization*.

We now let $V = \mathfrak{g}$ be the Lie algebra of a Lie group G . Then the adjoint representation of G on the Lie algebra \mathfrak{g} induces an action of G on $S^k(\mathfrak{g}^*)$ for every k :

$$(gP)(X_1, \dots, X_k) = P(\text{Ad}(g^{-1})X_1, \dots, \text{Ad}(g^{-1})X_k),$$

where $X_1, \dots, X_k \in \mathfrak{g}$ and $g \in G$.

Definition 9.2. (1) $P \in S^k(\mathfrak{g}^*)$ is called *invariant* if $gP = P, \forall g \in G$.

(2) The set of invariant elements in $S^*(\mathfrak{g}^*)$ is denoted $I^*(G)$ and $P \in I^k(G)$ is called an *invariant polynomial* (although it is a k -linear function).

Remark. $I^*(G) = \bigoplus_{k=0}^{\infty} I^k(G)$ is a subring of $S^*(\mathfrak{g}^*)$.

We now return to the situation of a principal G -bundle (E, π, M) with connection ω . Let $F_\omega \in \Omega^2(E, \mathfrak{g})$ be the associated curvature form. For $k \geq 1$ we have

$$F_\omega^k = F_\omega \wedge \dots \wedge F_\omega \in \Omega^{2k}(E, \mathfrak{g} \otimes \dots \otimes \mathfrak{g}) \quad (9.4)$$

and since $P \in I^k(G)$ defines a linear map

$$P: \mathfrak{g} \otimes \dots \otimes \mathfrak{g} \longrightarrow \mathbb{R}$$

we obtain a $2k$ -form $P(F_\omega) \in \Omega^{2k}(E)$. Since F_ω is Ad-equivariant and horizontal (by Theorem 7.2) and since P is invariant, it follows that $P(F_\omega^k)$ is invariant and horizontal i.e. a basic $2k$ -form. Hence by Collolary 6.13 there is a unique $2k$ -form on M which pulls back to $P(F_\omega^k)$ by $\pi^*: \Omega^{2k}(M) \rightarrow \Omega^{2k}(E)$.

Notation. The form on M corresponding to $P(F_\omega^k) \in \Omega^{2k}(E)$ is also denoted by $P(F_\omega^k)$, and is called the *characteristic form* corresponding to P .

Remark. In the notation of Theorem 7.2 the characteristic form is given in U_α by $P(F_{A_\alpha}^k) \in \Omega^{2k}(U_\alpha)$ where $A = \{A_\alpha\}_{\alpha \in \Sigma}$ are the local connection forms. In these terms we shall write $P(F_A^k) \in \Omega^{2k}(M)$ for the globally defined characteristic form.

Proposition 9.3. (1) $P(F_\omega^k) \in \Omega^{2k}(M)$ is a closed form, that is, $d(P(F_\omega^k)) = 0$.

(2) For $P \in I^k(G)$ and $Q \in I^l(G)$ we have

$$P \circ Q(F_\omega^{k+l}) = P(F_\omega^k) \wedge Q(F_\omega^l).$$

(3) Consider a bundle map (f, \bar{f}') :

$$\begin{array}{ccc} E' & \xrightarrow{\bar{f}} & E \\ \pi' \downarrow & & \downarrow \pi \\ M' & \xrightarrow{f} & M \end{array}$$

Then for ω a connection in E and $\omega' = \bar{f}^* \omega$ the induced connection in E' we have

$$P(F_{\omega'}^k) = f^*(P(F_\omega^k)).$$

Proof. (1) Since $\pi^*: \Omega^k(M) \rightarrow \Omega^k(E)$ is injective it suffices to prove that $d(P(F_\omega^k)) = 0$ in $\Omega^k(E)$. By Bianchi's identity we get

$$d(P(F_\omega^k)) = kP(dF_\omega \wedge F_\omega^{k-1}) = kP([F_\omega, \omega] \wedge F_\omega^{k-1}) \quad (9.5)$$

using the symmetry of P . But since the form in 9.5 is horizontal it is enough to show that it vanishes on sets of horizontal vectors. But this is obvious since $[F_\omega, \omega]$ vanishes on sets of horizontal vectors.

(2) For σ a permutation of $1, \dots, k+l$ let T_σ denote the endomorphism of $\mathfrak{g}^{\otimes k}$ given by

$$T_\sigma(X_1 \otimes \dots \otimes X_{k+l}) = X_{\sigma(1)} \otimes \dots \otimes X_{\sigma(k+l)}, \quad X_1, \dots, X_{k+l} \in \mathfrak{g}.$$

Then by (5.2)

$$F_\omega^{k+l} = T_\sigma \circ F_\omega^{k+l} = T_\sigma \circ (F_\omega^k \wedge F_\omega^l)$$

since F_ω has degree two. Hence by (9.1)

$$\begin{aligned} (P \circ Q)(F_\omega^{k+l}) &= \frac{1}{(k+l)!} \sum_\sigma (P \otimes Q) \circ T_\sigma \circ (F_\omega^{k+l}) \\ &= \frac{1}{(k+l)!} \sum_\sigma (P(F_\omega^k) \wedge Q(F_\omega^l)) \\ &= P(F_\omega^k) \wedge Q(F_\omega^l). \end{aligned}$$

(3) Since $F_{\omega'} = \bar{f}^*(P(F_\omega))$ we clearly have in $\Omega(E')$:

$$P(F_{\omega'}^k) = \bar{f}^* P(F_\omega^k).$$

Hence the statement follows from the injectivity of $\pi'^*: \Omega^{2k}(M') \rightarrow \Omega^{2k}(E')$. \square

Remark. In particular if $\varphi: E' \rightarrow E$ is a bundle isomorphism and ω is a connection in E then for $\omega^\varphi = \varphi^*(\omega)$ we have

$$P(F_{\omega^\varphi}^k) = P(F_\omega^k)$$

It follows that gauge equivalent connections have the same characteristic forms.

Definition 9.4. Let (E, π, M) be a principal G -bundle with connection ω . For $P \in I^k(G)$ let

$$\omega(E; P) = [P(F_\omega^k)] \in H^{2k}(\Omega^*(M)) = H_{\text{dR}}^{2k}(M)$$

denote the cohomology class of $P(F_\omega^k)$.

Notation. The mapping $w(E; -): I^k(G) \rightarrow H^{2k}(M)$ is called the *Chern-Weil homomorphism*. It is often just denoted by $w(-)$ if the bundle E is clear from the context. For $P \in I^k(G)$, $w(E; P) \in H_{\text{dR}}^{2k}(M)$ is called the *characteristic class* for E corresponding to P .

Theorem 9.5. (1) *The cohomology class $w(E, P) \in H_{\text{dR}}^{2k}(M)$ does not depend on the connection ω , and depends only on the isomorphism class of E .*

(2) $w(E; -): (I^*(G), \circ) \rightarrow (H_{\text{dR}}^*, \wedge)$ *is a ring homomorphism.*

(3) *For a bundle map*

$$\begin{array}{ccc} E' & \xrightarrow{\bar{f}} & E \\ \pi' \downarrow & & \downarrow \pi \\ M' & \xrightarrow{f} & M \end{array}$$

*we have $w(E', P) = f^*w(E, P)$.*

For the proof we need the following version of the Poincaré lemma which we will state without proof.

Let $h: \Omega^k(M \times \mathbb{R}) \rightarrow \Omega^{k-1}(M)$ be the operator defined as follows: For $\omega \in \Omega^k(M \times \mathbb{R})$, $k \geq 1$ write $\omega = ds \wedge \alpha + \beta$, where s is the variable in \mathbb{R} , and put

$$h(\omega) = \int_{s=0}^1 \alpha, \quad \text{and} \quad h(\omega) = 0, \quad \text{for} \quad \omega \in \Omega^0(M \times \mathbb{R}).$$

Lemma 9.6. *Let $i_0, i_1: M \rightarrow M \times \mathbb{R}$ be the inclusions $i_0(p) = (p, 0)$, $i_1(p) = (p, 1)$, $p \in M$. Then*

$$dh(\omega) + h(d\omega) = i_1^*\omega - i_0^*\omega, \quad \text{for} \quad \omega \in \Omega^*(M \times \mathbb{R}).$$

Proof of Theorem 9.5. We only have to show that $[P(F_\omega^k)]$ is independent of the choice of connection. Then the remaining statements follow from Proposition 9.3.

Let ω_0 and ω_1 be the two connections in E and consider the principal bundle $(E \times \mathbb{R}, \pi \times \text{id}, M \times \mathbb{R})$. This has connection $\tilde{\omega} \in \Omega^1(E \times \mathbb{R}, \mathfrak{g})$ defined by

$$\tilde{\omega} = (1 - s)\omega_{0x} + s\omega_{1x}, \quad (x, s) \in E \times \mathbb{R}.$$

This is a connection by Proposition 6.5, and clearly $i_\nu^*(\tilde{\omega}) = \omega_\nu$, $\nu = 0, 1$. Hence

$$i_\nu^*(F_{\tilde{\omega}}) = F_{\omega_\nu}, \quad \nu = 0, 1$$

and we obtain from Lemma 9.6:

$$\begin{aligned} dh(P(F_{\tilde{\omega}}^k)) &= i_1^*P(F_{\tilde{\omega}}) - i_0^*P(F_{\tilde{\omega}}) \\ &= P(F_{\tilde{\omega}_1}) - P(F_{\tilde{\omega}_0}), \end{aligned} \tag{9.6}$$

since $d(P(F_{\tilde{\omega}}^k)) = 0$ by Proposition 9.3. Hence by (9.6) $P(F_{\tilde{\omega}_1})$ and $P(F_{\tilde{\omega}_0})$ represent the same cohomology class in the de Rham complex. \square

Motivated by Theorem 9.5 let us introduce the following:

Definition 9.7. A *characteristic class* c (with \mathbb{R} coefficients) for a principal G -bundle associates to every principal G -bundle (E, π, M) a cohomology class $c(E) \in H_{\text{dR}}^*(M)$ such that for any bundle map $(\tilde{f}, f): (E', \pi', M') \rightarrow (E, \pi, M)$ we have

$$c(E') = f^*(c(E)).$$

If $c(E) \in H_{\text{dR}}^l(M)$ then c is said to have degree l .

Remark. The set of characteristic classes (with \mathbb{R} coefficients) is a ring denoted H_G^* (or $H_G^*(\mathbb{R})$).

Corollary 9.8. Let $P \in I^k(G)$. Then $E \mapsto w(E; P)$ defines a characteristic class $w(-, P) = w(P)$.

One can prove the following theorem:

Theorem 9.9 (H. Cartan). Let G be a compact Lie group. Then $w: I^*(G) \rightarrow H_G^*$ is an isomorphism.

Remark. (1) Theorem 9.9 also determines the ring of characteristic classes in the case G is an arbitrary Lie group with finitely many connected components. In that case there is a maximal compact subgroup $K \subseteq G$ and one shows that the inclusion gives an isomorphism $H_G^* \cong H_K^*$.

(2) We can also define the ring of complex valued G -invariant polynomials on the Lie algebra \mathfrak{g} , using multi-linear functions (over \mathbb{R}) $P: \mathfrak{g} \times \cdots \times \mathfrak{g} \rightarrow \mathbb{C}$. The ring of these is denoted $I_{\mathbb{C}}^*(G)$. The constructions in this chapter goes through and we can thus define a Chern-Weil homomorphism for (E, π, M) a G -bundle with connection

$$w_{\mathbb{C}}(E, -): I_{\mathbb{C}}^*(G) \rightarrow H(\Omega^*(M, \mathbb{C})) = H_{\text{dR}}^*(M, \mathbb{C}).$$

Finally let us consider the behaviour of the Chern-Weil homomorphism in connection with extensions and reductions. For simplicity we restrict to the case of $H \subseteq G$ is a Lie subgroup and $\mathfrak{h} \subseteq \mathfrak{g}$ the corresponding Lie algebras. Let (E, π, M) be a principal G -bundle, and suppose $F \subseteq E$ is a submanifold, so that $(F, \pi|_F, M)$ is a principal H -bundle. Then F is a reduction of E to H (cf. chapter 4). The following lemma is a special case of exercise 6.18.

Lemma 9.10. *If $\omega_F \in \Omega^1(F, \mathfrak{h})$ is a connection in F then there is a unique connection $\omega_E \in \Omega^1(E, \mathfrak{g})$, such that $\omega_E|_F = \omega_F$.*

Proof. Let $\{U_{\alpha}\}_{\alpha \in \Sigma}$ be a covering of M with trivialisations of $F|_{U_{\alpha}} \rightarrow U_{\alpha} \times H$ with transition functions $\{h_{\alpha\beta}\}$, $h_{\alpha\beta}: U_{\alpha} \cap U_{\beta} \rightarrow H$. Then $\{h_{\alpha\beta}\}$ is also a set of transition functions for E . The form ω_F is determined by $\{A_{\alpha}\}_{\alpha \in \Sigma}$, $A_{\alpha} \in \Omega^1(U_{\alpha}, \mathfrak{g})$ such that $A_{\beta} = \text{Ad}(h_{\alpha\beta}^{-1}) \circ A_{\alpha} + h_{\alpha\beta}^* \circ \omega_0^H$. Since $h_{\alpha\beta}$ maps to $H \subseteq G$ and $\omega_0^G|_H = \omega_0^H$ we have $h_{\alpha\beta}^* \omega_0^H = h_{\alpha\beta}^* \omega_0^G$. Hence $\{A_{\alpha} \in \Omega^1(U_{\alpha}, \mathfrak{g})\}$ determines a unique connection on E by Corollary 6.9 □

The proof of the following proposition is straight-forward and is left as an exercise.

Proposition 9.11. *Let (E, π, M) be a G -bundle with a reduction $(F, \pi|_F, M)$ and suppose $\omega \in \Omega^1(E, \mathfrak{g})$ is induced from a connection $\omega_F \in \Omega^1(F, \mathfrak{h})$ as above. Then for $P \in I^k(G)$ we have*

$$P(F_{\omega_F}^k) = P(F_{\omega_E}^k) \quad \text{in} \quad \Omega^{2k}(M).$$

In particular we have the following commutative diagram

$$\begin{array}{ccc} I^*(G) & \xrightarrow{\text{res}} & I^*(H) \\ & \searrow w(E,-) & \swarrow w(F,-) \\ & & H^*(M) \end{array}$$

where res denotes the restriction map of polynomials on the Lie algebra \mathfrak{g} to the Lie algebra \mathfrak{h} .

10. Examples of Invariant Polynomials and Characteristic Classes

We now give some examples of invariant polynomials for some classical groups. In all cases we shall exhibit the polynomial function $v \mapsto P(v, \dots, v)$, $v \in \mathfrak{g}$ for each $P \in I^k(G)$.

Example 10.1. $G = \mathrm{GL}(n, \mathbb{R})$. The Lie algebra is $\mathfrak{g} = M(n, \mathbb{R})$, the set of $n \times n$ real matrices with Lie bracket

$$[A, B] = AB - BA, \quad A, B \in M(n, \mathbb{R}),$$

and the adjoint representation

$$\mathrm{Ad}(g)(A) = gAg^{-1}, \quad A \in M(n, \mathbb{R}), g \in \mathrm{GL}(n, \mathbb{R}).$$

For k a positive integer we let $P_{k/2}$ denote the homogeneous polynomial of degree k which is the coefficient of λ^{n-k} for the polynomial in λ given by

$$\det\left(\lambda I - \frac{1}{2\pi}A\right) = \sum_{k=0}^n P_{k/2}(A, \dots, A)\lambda^{n-k}, \quad A \in M(n, \mathbb{R}).$$

The polynomial $P_{k/2}$, called the $k/2$ -th *Pontrjagin polynomial*, is clearly Ad-invariant. For (E, π, M) a principal $\mathrm{GL}(n, \mathbb{R})$ -bundle

$$p_{k/2}(E) = w(E, P_{k/2}) \in H_{\mathrm{dR}}^{2k}(M)$$

is called the *Pontrjagin class* for E . For V an n -dimensional real vector bundle on M we write

$$p_{k/2}(V) = p_{k/2}(F(V))$$

where $F(V)$ is the frame bundle.

Example 10.2. $G = O(n) \subseteq GL(n, \mathbb{R})$ the orthogonal group of matrices g satisfying $g^t g = I$. The Lie algebra is $\mathfrak{o}(n) \subseteq M(n, \mathbb{R})$ of skew-symmetric matrices, i.e.

$$\mathfrak{o}(n) = \{A \in M(n, \mathbb{R}) \mid A + A^t = I\}. \tag{10.1}$$

hence, by transposing

$$\det\left(\lambda I + \frac{1}{2\pi}A\right) = \det\left(\lambda I - \frac{1}{2\pi}A\right), \quad A \in \mathfrak{o}(n).$$

and it follows that the restriction of $P_{k/2}$ to $\mathfrak{o}(n)$ vanishes for k odd. We shall therefore only consider $P_l \in I^{2l}(O(n))$ for $l = 0, \dots, [n/2]$. Notice that since every vector bundle can be given a Riemannian metric it follows that the frame bundle has a reduction to $O(n)$. Therefore also for any $GL(n, \mathbb{R})$ -bundle E we have $p_{k/2}(E) = 0$ for k odd, although the representing characteristic form is not necessarily equal to zero.

Example 10.3. $G = SO(2m) \subseteq O(2m)$, the subgroup of orthogonal matrices satisfying $\det(g) = 1$. The Lie algebra is $\mathfrak{so}(2m) = \mathfrak{o}(2m)$ given by (10.1). Hence the Pontrjagin polynomials $P_l \in I^{2l}(SO(2m))$, $l = 0, 1, \dots, m$ are also invariant polynomials in this case. But there is another homogeneous polynomial Pf called the ‘‘Pfaffian polynomial’’ of degree m given by

$$\begin{aligned} \text{Pf}(A, \dots, A) &= \frac{1}{2^{2m} \pi^m m!} \sum_{\sigma} (\text{sgn } \sigma) a_{\sigma_1 \sigma_2} a_{\sigma_3 \sigma_4} \cdots a_{\sigma_{2m-1} \sigma_{2m}}, \end{aligned} \tag{10.2}$$

where σ runs through the set of permutations of $1, \dots, 2m$, and where $A = (a_{ij})$ satisfies $a_{ij} = -a_{ji}$.

Let us show that Pf is Ad-invariant: Let $g = (g_{ij}) \in O(2m)$ and put

$$gAg^{-1} = gAg^t = A' = (a'_{ij})$$

that is

$$a'_{ij} = \sum_{k_1 k_2} g_{ik_1} a_{k_1 k_2} g_{jk_2}.$$

Then

$$\begin{aligned} \text{Pf}(A', \dots, A') &= \sum_{k_1, \dots, k_{2m}} a_{k_1 k_2} \cdots a_{k_{2m-1} k_{2m}} \sum_{\sigma} \text{sgn}(\sigma) g_{\sigma 1 k_1} \cdots g_{\sigma(2m) k_{2m}}. \end{aligned}$$

In this sum the coefficient to $a_{k_1 k_2} \cdots a_{k_{2m-1} k_{2m}}$ is just the determinant of $(g_{i k_j})$. This determinant is clearly zero unless (k_1, \dots, k_{2m}) is a permutation of $(1, \dots, 2m)$. Hence

$$\begin{aligned} \text{Pf}(A', \dots, A') &= \sum_{\sigma} \det(g_{i \sigma j}) a_{\sigma 1 \sigma 2} \cdots a_{\sigma(2m-1) \sigma(2m)} \\ &= \det(g_{ij}) \sum_{\sigma} \text{sgn}(\sigma) a_{\sigma 1 \sigma 2} \cdots a_{\sigma(2m-1) \sigma(2m)} \\ &= \det(g) \text{Pf}(A, \dots, A). \end{aligned}$$

That is

$$\text{Pf}(A', \dots, A') = \det(g) \text{Pf}(A, \dots, A) \quad (10.3)$$

for all $A \in \mathfrak{o}(2m)$, $g \in \text{O}(2m)$. In particular Pf is an invariant polynomial for $\text{SO}(2m)$, but it is not an invariant polynomial for $\text{O}(2m)$ since

$$\text{Pf}(A', \dots, A') = -\text{Pf}(A, \dots, A)$$

if $\det(g) = -1$.

For an $\text{SO}(2m)$ -bundle (E, π, M) the characteristic class

$$e(E) = w(E, \text{Pf}) \in H_{\text{dR}}^{2m}(M) \quad (10.4)$$

is called the Euler class for E . If E is the reduction to $\text{SO}(2m)$ of the frame bundle of an oriented vector bundle V on M then $e(V) = e(E)$ is called the Euler class of V . One can show that for a compact oriented Riemannian manifold of dimension $2m$ the Euler-Poincaré characteristic $\chi(M)$ satisfies

$$\chi(M) = \langle e(TM), [M] \rangle = \int_M \text{Pf}(F_{\omega}^m), \quad (10.5)$$

where TM is the tangent bundle of M and ω is the connection for the reduction to $\text{SO}(2m)$ of the orthogonal frame bundle of TM determined

by the orientation. (Usually the connection is chosen to be the Levi-Civita connection). The formula (10.5) is the higher-dimensional Gauss-Bonnet Theorem.

Example 10.4. $G = \text{GL}(n, \mathbb{C})$. The Lie algebra is $M(n, \mathbb{C})$, the set of $n \times n$ complex matrices. As in the remark at the end of chapter 9 we shall consider the polynomials with complex values C_k , $k = 0, 1, \dots, n$, given as the coefficients to λ^{n-k} in the polynomial in λ :

$$\det\left(\lambda I - \frac{1}{2\pi i} A\right) = \sum_k C_k(A, \dots, A) \lambda^{n-k}, \quad A \in M(n, \mathbb{C}), \tag{10.6}$$

with $i = \sqrt{-1}$. For (E, π, M) a principal $\text{GL}(n, \mathbb{C})$ -bundle we thus obtain characteristic classes in deRham cohomology

$$c_k(E) = w(E, C_k) \in H_{\text{dR}}^{2k}(M, \mathbb{C}) \tag{10.7}$$

where the differential forms have complex values. The polynomials C_k are called the *Chern polynomials* and the classes in (10.7) are called the *Chern classes* of E . Again for V a complex vector bundle over M we have an associated frame bundle of complex frames $F(V)$ which is a principal $\text{GL}(n, \mathbb{C})$ -bundle and we define

$$c_k(V) = c_k(F(V))$$

the Chern classes of a complex vector bundle V . Notice that the restriction of C_k to $M(n, \mathbb{R})$ satisfies

$$i^k C_k(A, \dots, A) = P_{k/2}(A, \dots, A), \quad A \in M(n, \mathbb{R}).$$

Hence if we extend a principal $\text{GL}(n, \mathbb{R})$ -bundle E to a principal $\text{GL}(n, \mathbb{C})$ -bundle $E_{\mathbb{C}}$ then for $k = 2l$ we have in $H_{\text{dR}}^{4l}(M, \mathbb{C})$:

$$(-1)^l c_{2l}(E_{\mathbb{C}}) = P_l(E). \tag{10.8}$$

Example 10.5. $G = \text{U}(n) \subseteq \text{GL}(n, \mathbb{C})$ the subgroup of unitary matrices, ie. the complex matrices g satisfying $g\bar{g}^t = I$ where \bar{g} denotes the complex conjugate of g . The Lie algebra is $\mathfrak{u}(n) \subseteq M(n, \mathbb{C})$ of skew-Hermitian matrices, ie.

$$\mathfrak{u}(n) = \{A \in M(n, \mathbb{C}) \mid A + \bar{A}^t = 0\}$$

In particular we have for $A \in \mathfrak{u}(n)$

$$\det\left(\lambda I - \frac{1}{2\pi i} A\right) = \det\left(\lambda I - \frac{1}{2\pi i} \bar{A}^t\right) = \overline{\det\left(\lambda I - \frac{1}{2\pi i} A\right)}.$$

That is, $C_k(A, \dots, A) \in \mathbb{R}$ for $A \in \mathfrak{u}(n)$, hence C_k is a real-valued polynomial on $\mathfrak{u}(n)$. For (E, π, M) a $U(n)$ -bundle the Chern classes are therefore real cohomology classes.

Since every complex vector bundle can be given a Hermitian metric it follows that any principal $GL(n, \mathbb{C})$ -bundle has a reduction to $U(n)$ and hence all Chern classes for a $GL(n, \mathbb{C})$ -bundle are real cohomology classes.

Finally let us calculate the first Chern class in a non-trivial case.

Example 10.6. Consider the complex Hopf-bundle over $\mathbb{C}P^n$: This is the $GL(1, \mathbb{C}) = \mathbb{C}^*$ -bundle $(H_{\mathbb{C}}, \gamma, \mathbb{C}P^n)$ with total space $H_{\mathbb{C}} = \mathbb{C}^{n+1} \setminus \{0\}$ and where γ is the natural projection map

$$\gamma(z_0, \dots, z_n) = [z_0, \dots, z_n], \quad (z_0, \dots, z_n) \in \mathbb{C}^{n+1} \setminus \{0\}.$$

Notice that the Lie algebra of \mathbb{C}^* is just the abelian Lie algebra \mathbb{C} so that a connection in $H_{\mathbb{C}}$ is a complex valued 1-form on $\mathbb{C}^{n+1} \setminus \{0\}$. We claim that

$$\omega = \frac{\bar{z}^t dz}{|z|^2}$$

is a connection. That is, we must check (1) and (2) in the definition of a connection.

(1) For fixed $z \in \mathbb{C}^{n+1} \setminus \{0\}$ the map $v_z: \mathbb{C}^* \rightarrow \mathbb{C}^{n+1} \setminus \{0\}$ given by $v_z(\lambda) = z\lambda$ satisfies

$$v_z^* \omega = \frac{\bar{z}^t z \bar{\lambda} d\lambda}{|z\lambda|^2} = \frac{d\lambda}{\lambda}$$

so that for $\lambda = 1$ $(v_z^* \omega)_1 = d\lambda$ as required.

(2) For fixed $\lambda \in \mathbb{C}^*$ we have

$$R_{\lambda}^* \omega = \frac{\bar{z}^t dz \bar{\lambda} \lambda}{|z\lambda|^2} = \omega$$

as required since \mathbb{C}^* is abelian.

Hence ω is a connection. Again since \mathbb{C}^* is abelian the curvature is given by

$$F_\omega = d\omega = \frac{1}{|z|^2} dz^t \wedge dz + d\left(\frac{1}{|z|^2}\right) \wedge \bar{z}^t dz$$

which is also a basic form, i.e. the pullback of a form on $\mathbb{C}P^n$. Now the inclusion $S^{2n+1} \subset \mathbb{C}^{n+1} \setminus \{0\}$ induces a diffeomorphism $S^{2n+1}/U(1) \cong \mathbb{C}P^n$ and since $|z|^2 = 1$ on S^{2n+1} we conclude that as a form on $S^{2n+1}/U(1)$ the curvature is given by

$$F_\omega = d\bar{z}^t \wedge dz.$$

Notice also that

$$\bar{F}_\omega = dz^t \wedge d\bar{z} = -F_\omega$$

so F_ω takes on purely imaginary values. Finally F_ω is invariant under the action of $U(n+1)$ on $\mathbb{C}P^n$ since

$$g^*F_\omega = (dz^t)g^t \wedge gdz = d\bar{z}^t \wedge dz, \quad g \in U(n+1).$$

In the notation of Example A15 $F_\omega = i \operatorname{Im} F_\omega$ now corresponds to the $U(n)$ invariant real alternating 2-form $2i\kappa$ defined on $\mathbb{C}^n = \operatorname{span}\{e_1, \dots, e_n\}$ since

$$d\bar{z}^t \wedge dz(e_1, ie_1) = i - (-i) = 2i.$$

Now the first Chern polynomial on $\mathfrak{gl}(1, \mathbb{C}) = \mathbb{C}$ is given by

$$C_1(A) = -\frac{1}{2\pi i} A, \quad A \in \mathbb{C}.$$

It follows that

$$\begin{aligned} c_1(H_{\mathbb{C}}) &= \left[-\frac{1}{2\pi i} dz^t \wedge dz \right] \in H_{\text{dR}}^2(\mathbb{C}P^n) \\ &= -\frac{1}{\pi} \kappa \in \operatorname{Alt}_{\mathbb{R}}^2(\mathbb{C}^n)^{U(n)} \end{aligned}$$

so in particular $c_1(H_{\mathbb{C}}) \neq 0$. The constant in $C_1(A)$ is chosen such that for $n = 1$

$$\int_{\mathbb{C}P^1} c_1(F_\omega) = -1.$$

A. Cohomology of Homogeneous Spaces

In this section we show how to calculate de Rham cohomology of compact homogeneous spaces. For notation see [DG].

In the following G is a Lie group and $H \subseteq G$ is a closed Lie subgroup, with Lie algebras \mathfrak{g} and $\mathfrak{h} \subseteq \mathfrak{g}$ respectively. We shall study the homogeneous manifold $M = G/H$ with projection $\pi: G \rightarrow M$.

Proposition A1. (1) *The following sequence of vector spaces*

$$0 \longrightarrow \mathfrak{h} \hookrightarrow \mathfrak{g} \xrightarrow{\pi_*} T_{eH}(G/H) \longrightarrow 0$$

is exact.

(2) *Given $h \in H$ we have the following commutative diagram.*

$$\begin{array}{ccccccc} 0 & \longrightarrow & \mathfrak{h} & \longrightarrow & \mathfrak{g} & \xrightarrow{\pi_*} & T_{eH}(G/H) \longrightarrow 0 \\ & & \downarrow \text{Ad}(h) & & \downarrow \text{Ad}(h) & & \downarrow L_{h*} \\ 0 & \longrightarrow & \mathfrak{h} & \longrightarrow & \mathfrak{g} & \xrightarrow{\pi_*} & T_{eH}(G/H) \longrightarrow 0 \end{array}$$

Proof. (1) The differentiable structure on G/H is defined as follows: For $\mathfrak{g} = \mathfrak{m} \oplus \mathfrak{h}$ and $U_{\mathfrak{m}} \subseteq \mathfrak{m}$ a suitable neighborhood of 0, the composite mapping

$$U_{\mathfrak{m}} \xrightarrow{\exp} G \xrightarrow{\pi} G/H$$

is a diffeomorphism onto a open neighborhood of eH (see e.g. [DG, Theorem. 9.43]. Consequently $\pi_*: \mathfrak{m} \rightarrow T_{eH}(G/H)$ is an isomorphism, this shows the claim.

(2) It is clear that $\text{Ad}(h)$ on \mathfrak{h} is the restriction of $\text{Ad}(h)$ on \mathfrak{g} . The commutativity of the square to the right follows from the following commutative diagram

$$\begin{array}{ccc} G & \xrightarrow{\pi} & G/H \\ \sigma_h \downarrow & & \downarrow L_h \\ G & \xrightarrow{\pi} & G/H \end{array}$$

where $\sigma_h(x) = h x h^{-1}$ and $L_h(xH) = h x H$. □

Remark. We see from the above proposition that π_* induces an isomorphism

$$\pi_*: \mathfrak{g}/\mathfrak{h} \xrightarrow{\cong} T_{eH}(G/H)$$

and that the isotropy representation of H on $T_{eH}(G/H)$, that is, $h \mapsto L_{h*}$, is identified with the adjoint representation on $\mathfrak{g}/\mathfrak{h}$.

Notation. For V a finite dimensional vector space let $\text{Alt}^k(V)$, $k \in \mathbb{N}$, denote the vector space of alternating k -linear forms on V . For $H \subseteq G$ as above with Lie algebras $\mathfrak{h} \subseteq \mathfrak{g}$ let

$$\text{Alt}^k(\mathfrak{g}/\mathfrak{h})^H \subseteq \text{Alt}^k(\mathfrak{g})$$

be the subspace consisting of $\alpha \in \text{Alt}^k(\mathfrak{g})$ satisfying

- (1) $\alpha(v_1, \dots, v_k) = 0$ if at least one $v_i \in \mathfrak{h}$
- (2) $\alpha(\text{Ad}(h)v_1, \dots, \text{Ad}(h)v_k) = \alpha(v_1, \dots, v_k)$ for all $h \in H$.

Finally for a manifold M let $\Omega^k(M)$, $k \in \mathbb{N}$ denote the vector space of differential forms of degree k on M . If $M = G/H$ as above then

$$\Omega^k(M)^G \subseteq \Omega^k(M),$$

denotes the subspace of G -invariant forms, that is, forms ω satisfying

$$L_g^* \omega = \omega \quad \text{for all } g \in G,$$

where $L_g: M \rightarrow M$ is given by $L_g(xH) = gxH$, for all $x \in G$.

Proposition A2. *Let $H \subseteq G$ and $M = G/H$ as above.*

(1) *There is a natural isomorphism of vector spaces*

$$\iota: \Omega^k(M)^G \xrightarrow{\cong} \text{Alt}^k(\mathfrak{g}/\mathfrak{h})^H.$$

(2) *Furthermore ι is a chain map, where the differential on the right hand side is defined by*

$$(d\alpha)(v_1, \dots, v_{k+1}) = \sum_{i < j} (-1)^{i+j} \alpha([v_i, v_j], v_1, \dots, \hat{v}_i, \dots, \hat{v}_j, \dots, v_{k+1}),$$

$$\alpha \in \text{Alt}^k(\mathfrak{g}/\mathfrak{h})^H, \quad v_1, \dots, v_{k+1} \in \mathfrak{g}.$$

Proof. (1) As before we let $\pi: G \rightarrow G/H$ be the canonical projection map and let $\omega \in \Omega^k(M)^G$ be a G -invariant form. We define $\iota(\omega)$ by

$$\iota(\omega) = (\pi^*\omega)_e \in \text{Alt}^k(\mathfrak{g})$$

and we clearly have that $\iota(\omega) \in \text{Alt}^k(\mathfrak{g}/\mathfrak{h})^H$. Furthermore it is clear that ι is injective because $\omega \in \Omega^k(M)^G$ satisfies

$$\omega_{gH}(v_1, \dots, v_k) = \omega_{eH}((L_{g^{-1}})_*v_1, \dots, (L_{g^{-1}})_*v_k),$$

for all $g \in G$ and $v_1, \dots, v_k \in T_{gH}M$. For the surjectivity of ι let $\alpha \in \text{Alt}^k(\mathfrak{g}/\mathfrak{h})^H$ be given and we define $\omega_{gH} \in \text{Alt}^k(T_{gH}M)$ by

$$\omega_{gH}(v_1, \dots, v_k) = \alpha((L_{g^{-1}})_*v_1, \dots, (L_{g^{-1}})_*v_k),$$

$$g \in G \quad v_1, \dots, v_k \in T_{gH}M.$$

Since $\alpha \in \text{Alt}^k(\mathfrak{g}/\mathfrak{h})^H$ it follows easily that ω_{gH} is independent of choice of $g \in G$ and of the choice of representatives for $(L_{g^{-1}})_*v_i$ in \mathfrak{g} . To see that ω is differentiable, we notice that, because ω by definition is G -invariant, it is enough to show that ω is differentiable in a neighborhood of eH . But in this neighborhood we can find a local cross section, that is, a submanifold $U \subseteq G$ with $e \in U$ such that $\pi: U \rightarrow \pi(U)$ is a diffeomorphism. Thus it is enough to see that $\pi^*(\omega)$ is differentiable. For this we choose a basis $\{X_1, \dots, X_n\}$ for \mathfrak{g} and let $\{\tilde{X}_1, \dots, \tilde{X}_n\}$ be the corresponding left invariant vector fields on G . Because these are smooth, the 1-forms $\{\gamma_1, \dots, \gamma_n\}$ on G defined by

$$\gamma_i(\tilde{X}_j) = \delta_{ij}$$

are also smooth. But $\pi^*(\omega)$ is G -invariant so it can be written as a linear combination of the forms

$$\{\gamma_{i_1} \wedge \dots \wedge \gamma_{i_k} \mid 1 \leq i_1 \leq \dots \leq i_k \leq n\}$$

with constant coefficients. It follows that $\pi^*(\omega)$ is smooth.

(2) Because $d\pi^* = \pi^*d$ and $\pi^*: \Omega^*(M)^G \rightarrow \Omega^*(G)^G$ is injective it is enough to show the formula on G . As before let $\{\tilde{X}_1, \dots, \tilde{X}_n\}$ be a basis for the left invariant vector fields on G , so that $\{\tilde{X}_{1g}, \dots, \tilde{X}_{ng}\}$ is a basis for T_gG for every $g \in G$. It suffices to show the formula

$$\begin{aligned} (d\omega)(\tilde{X}_{l_1}, \dots, \tilde{X}_{l_{k+1}}) \\ = \sum_{i < j} (-1)^{i+j} \omega([\tilde{X}_{l_i}, \tilde{X}_{l_j}], \dots, \hat{\tilde{X}}_{l_i}, \dots, \hat{\tilde{X}}_{l_j}, \dots) \end{aligned}$$

for all tuples (l_1, \dots, l_{k+1}) satisfying $1 \leq l_{i_1} \leq \dots \leq l_{i_{k+1}} \leq n$. This follows from the formula for $d\omega$ because the remaining terms in the formula are directional derivatives of functions on the form

$$\omega(\tilde{X}_{l_1}, \dots, \hat{\tilde{X}}_{l_j}, \dots, \tilde{X}_{l_{k+1}})$$

which are clearly constant when ω and \tilde{X}_j are G -invariant. \square

Remark. It follows that the formula in (2) defines a form in $\text{Alt}^{k+1}(\mathfrak{g}/\mathfrak{h})^H$

Exercise A3. Show the claim in the remark above directly. (Hint: First show that for $\alpha \in \text{Alt}^k(\mathfrak{g}/\mathfrak{h})^H$ and $X \in \mathfrak{h}$ we have

$$\sum_{i=1}^k \alpha(v_1, \dots, v_{i-1}, [X, v_i], v_{i+1}, \dots, v_k) = 0, \quad \text{for all } v_1, \dots, v_k \in \mathfrak{g}.$$

Corollary A4. *If H is compact and connected then $M = G/H$ has a G -invariant volume form, that is, a nonzero element $v_M \in \Omega^n(M)^G$, $n = \dim(M)$, and v_M is unique up to a scalar multiple.*

Proof. Since $\text{Alt}^n(\mathfrak{g}/\mathfrak{h})$ is 1-dimensional we have $\dim(\text{Alt}^n(\mathfrak{g}/\mathfrak{h}))^H \leq 1$ with equality if and only if $\det(\text{Ad}(h)) = 1$ for all $h \in H$, where $\text{Ad}(h): \mathfrak{g}/\mathfrak{h} \rightarrow \mathfrak{g}/\mathfrak{h}$ is induced by the diagram in Proposition A1 (2). But $\lambda(h) = \det(\text{Ad}(h))$

defines a continuous homomorphism $\lambda: H \rightarrow \mathbb{R} \setminus \{0\}$, and since H is compact $\lambda(h) = \pm 1$, for all $h \in H$. Hence λ is locally constant and since H is connected $\lambda \equiv 1$. \square

Example A5. If we identify $\mathrm{SO}(n-1)$ with the subgroup of matrices in $\mathrm{SO}(n)$ of the form

$$\begin{bmatrix} 1 & 0 \\ 0 & h \end{bmatrix}, \quad h \in \mathrm{SO}(n-1),$$

there is a natural diffeomorphism

$$\pi: \mathrm{SO}(n)/\mathrm{SO}(n-1) \xrightarrow{\cong} S^{n-1} \subseteq \mathbb{R}^n$$

given by $\pi(g \mathrm{SO}(n-1)) = ge_1$, $g \in \mathrm{SO}(n)$, where $e_1 = (1, 0, \dots, 0)$ (cf. [DG, Exercise 9.45]). Notice that π commutes with the $\mathrm{SO}(n)$ action, and the $\mathrm{SO}(n)$ action on \mathbb{R}^n is given by matrix multiplication. It follows from corollary A4 that S^{n-1} has a $\mathrm{SO}(n)$ -invariant volume form $v_{S^{n-1}} \in \Omega^n(S^{n-1})$.

Exercise A6. Given the coordinates (x_1, \dots, x_n) on \mathbb{R}^n show that

$$v_{S^{n-1}} = c \sum_{i=1}^n (-1)^i x_i dx_1 \wedge \dots \wedge \widehat{dx}_i \wedge \dots \wedge dx_n, \quad c \in \mathbb{R} \setminus \{0\}.$$

Proposition A7. Let G be a compact Lie group and $\rho: G \rightarrow \mathrm{GL}(V)$ a representation on a finite dimensional vector space (that is, ρ is a Lie group homomorphism). Then there exists an inner product on V such that $\rho(g)$ is orthogonal for all $g \in G$, that is,

$$\langle \rho(g)v, \rho(g)w \rangle = \langle v, w \rangle \quad \text{for all } v, w \in V, g \in G.$$

Proof. Pick an arbitrary inner product $\langle \cdot, \cdot \rangle$ on V and choose an orientation on G . It follows from Corollary A4 with $H = \{e\}$ that there is a unique volume form v_G on G that satisfies

$$\int_G v_G = 1.$$

In fact, for $v'_G \in \Omega^n(G)^G$ a volume form we have (as G is compact) that $\mathrm{Vol} = \int_G v'_G > 0$ and it follows that $v_G = v'_G/\mathrm{Vol}$. We now define the inner product on V by

$$\langle v, w \rangle = \int_G \langle \rho(g^{-1})v, \rho(g^{-1})w \rangle v_G.$$

Then, for an arbitrary $g' \in G$ we have for $v, w \in V$:

$$\begin{aligned} \langle \rho(g'^{-1})v, \rho(g'^{-1})w \rangle &= \int_G \langle \rho((g'g)^{-1})v, \rho((g'g)^{-1})w \rangle v_G \\ &= \int_G \langle \rho(g^{-1})v, \rho(g^{-1})w \rangle (L_{g'^{-1}})^* v_G \\ &= \int_G \langle \rho(g^{-1})v, \rho(g^{-1})w \rangle v_G \\ &= \langle v, w \rangle. \end{aligned}$$

□

Remark. Let $O(V) \subseteq GL(V)$ denote the group of orthogonal transformations with respect to the inner product $\langle \cdot, \cdot \rangle$. Then $O(V)$ is compact and therefore a closed Lie subgroup in $GL(V)$. It follows that $\rho: G \rightarrow O(V)$ is a Lie group homomorphism. If G is connected $\rho(g) \in SO(V)$ for all $g \in G$, where $SO(V) \subseteq O(V)$ is the subgroup of orthogonal transformations with determinant 1.

Theorem A8. *Let $M = G/H$, with G and $H \subseteq G$ as above and G compact and connected. We then have the following.*

- (1) *The inclusion $i: \Omega^*(M)^G \rightarrow \Omega^*(M)$ induces an isomorphism in cohomology.*
- (2) *There is a natural isomorphism*

$$H_{\text{dR}}^*(M) \cong H^*(\text{Alt}^*(\mathfrak{g}/\mathfrak{h})^H)$$

Proof. Clearly (2) follows from (1) and proposition A2.

To show (1) we pick, according to proposition A7, an inner product on the Lie algebra \mathfrak{g} of G which is invariant under the adjoint representation $\text{Ad}: G \rightarrow GL(\mathfrak{g})$, and since G is assumed to be connected we have $\text{Ad}(g) \in SO(\mathfrak{g})$ for all $g \in G$. By multiplying the inner product by a positive scalar we can assume that the open unit disc

$$B = \{X \in \mathfrak{g} \mid \langle X, X \rangle < 1\}$$

is mapped diffeomorphically under the exponential map onto an open neighborhood U of $e \in G$. As in the proof of proposition A7 we let v_G

be the unique left invariant volume form on G that satisfies

$$\int_G v_G = 1.$$

Finally for $g \in G$ we let $L_g: M \rightarrow M$ denote the diffeomorphism given by left multiplication with $g \in G$.

For $\omega \in \Omega^k(M)$ we will define a G -invariant k -form $\bar{\omega} \in \Omega^k(M)^G$, in the following way: Let $p \in M$ and $v_1, \dots, v_k \in T_p M$ and notice that

$$g \mapsto (L_g^* \omega)_p(v_1, \dots, v_k) = \omega_{gp}(L_{g*} v_1, \dots, L_{g*} v_k)$$

defines a differentiable function on G . We now put

$$\bar{\omega}_p(v_1, \dots, v_k) = \int_{g \in G} \omega_{gp}(L_{g*} v_1, \dots, L_{g*} v_k) v_G$$

or for short

$$\bar{\omega} = \int_{g \in G} (L_g^* \omega) v_G.$$

We shall show the following three claims:

- (i) $\bar{\omega}$ is a G -invariant differential k -form.
- (ii) If $\omega \in \Omega^k(M)^G$ then $\bar{\omega} = \omega$.
- (iii) There are linear operators

$$S^0 = 0, S^k: \Omega^k(M) \rightarrow \Omega^{k-1}(M), \quad k = 1, 2, \dots$$

satisfying

$$dS^k \omega + S^{k+1} d\omega = \bar{\omega} - \omega \quad \text{for all } \omega \in \Omega^k(M), k = 0, 1, 2, \dots$$

The theorem then follows from (i)–(iii).

- (i) That $\bar{\omega}$ is differentiable is seen the same way as in the proof of proposition A2. To see that $\bar{\omega}$ is G -invariant we first notice that v_G is a right G -invariant form on G , that is $R_g^*(v_G) = v_G$ for all $g \in G$. This follows from the fact that $R_{g'}^* v_G$ again is left invariant so that

$$(R_{g'})^* v_G = \lambda(g') v_G, \quad \lambda(g') \in \mathbb{R} \setminus \{0\},$$

where $\lambda: G \rightarrow \mathbb{R} \setminus \{0\}$ is a differentiable homomorphism hence is constantly equal to 1 since G is compact and connected. We now get

$$\begin{aligned} (L_{g'})^* \bar{\omega} &= \int_{g \in G} (L_{g'}^* L_g^* \omega) v_G \\ &= \int_{g \in G} ((L_{gg'})^* \omega) v_G \\ &= \int_{x \in G} (L_x^* \omega) ((R_{g'^{-1}})^* v_G) \\ &= \int_{x \in G} (L_x^* \omega) v_G = \bar{\omega}, \end{aligned}$$

where $x = gg'$ that is $g = x(g')^{-1} = R_{g'^{-1}}(x)$, it follows that $L_{g'^{-1}}^*(\bar{\omega}) = \bar{\omega}$, which was to be proven.

(ii) For $\omega \in \Omega(M)^G$ we have

$$\bar{\omega} = \int_{g \in G} L_g^*(\omega) v_G = \int_{g \in G} \omega v_G = \omega \int_G v_G = \omega$$

(iii) For this we use the neighborhood $U = \exp B$. We first notice that

$$\langle U \rangle = \bigcup_i U^i = \bigcup_{i=1}^{\infty} \underbrace{U \cdots U}_i$$

is an open subgroup in G and since G is connected we have $\langle U \rangle = G$ (because the complement consists of cosets which are also open).

As $U^i \subseteq U^{i+1}$ and G is compact, there is a $j \in \mathbb{N}$ such that $G = U^j$. We get that $\{L_g U \mid g \in U^j\}$ is an open covering of G hence by compactness we obtain $G = \bigcup_{i=1}^l g_i U$. Now define inductively W_1, \dots, W_l by

$$W_1 = g_1 U, \dots, W_{i+1} = g_{i+1} U - \left(\bigcup_{\nu=1}^i W_\nu \right).$$

Then $G = W_1 \cup \dots \cup W_l$ is a disjoint union and

$$V = \text{int}(W_1) \cup \dots \cup \text{int}(W_l)$$

is a open subset such that $\partial V \subseteq \bigcup_{i=1}^l g_i \partial U$, is a union of $(m - 1)$ -dimensional submanifolds in G , where $m = \dim G$. For f an arbitrary continuous function on G we thus have

$$\int_G f v_G = \int_V f v_G = \sum_{i=1}^l \int_{\text{int}(W_i)} f v_G.$$

For $g \in W_i \subseteq g_i U$, $g_i \in U^j$, we write g in the form

$$g = \exp(X_1) \cdots \exp(X_j) \exp(X)$$

and define a curve $\gamma(t, g) \in G$, $t \in [0, 1]$ by

$$\gamma(t, g) = \exp(tX_1) \cdots \exp(tX_j) \exp(tX).$$

Then $\gamma(0, g) = e$ and $\gamma(1, g) = g$. From γ we get a homotopy $L_{\gamma(t, g)}: M \rightarrow M$, $t \in [0, 1]$, where $L_{\gamma(0, g)} = \text{id}$ and $L_{\gamma(1, g)} = L_g$. As in the proof of the Poincaré Lemma we get an operator

$$S_g^k: \Omega^k(M) \rightarrow \Omega^{k-1}(M)$$

such that

$$dS_g^k \omega + S_g^{k+1} d\omega = L_g^* \omega - \omega.$$

Here $S_g^k \omega$ is explicitly given by the formula

$$S_g^k(\omega)_p(v_1, \dots, v_{k-1}) = \int_0^1 ((L_{\gamma(-, g)})^* \omega)_p \left(\frac{d}{dt}, v_1, \dots, v_{k-1} \right) dt,$$

$$v_1, \dots, v_k \in T_p M$$

This is differentiable in g for $g \in \text{int}(W_i)$ and we may define

$$S^k(\omega) = \int_{g \in V} (S_g^k \omega) v_G.$$

By integration of the formula above we get

$$\begin{aligned} dS^k \omega + S^{k+1} d\omega &= \int_{g \in V} (L_g^* \omega) v_G - \int_{g \in V} (\omega) v_G \\ &= \int_{g \in G} (L_g^* \omega) v_G - \int_{g \in G} (\omega) v_G \\ &= \bar{\omega} - \omega. \end{aligned}$$

□

Exercise A9. Let $M = G/H$, where G is a compact Lie group with identity component $G_0 \subseteq G$.

(1) Show that the number of components of M is $[G:G_0H]$, and that each component is diffeomorphic to $M_0 = G_0/G_0 \cap H$.

(2) Conclude that

$$H_{\text{dR}}^*(M) \cong H^*(\text{Alt}^*(\mathfrak{g}/\mathfrak{h})^{G_0 \cap H})^{[G:G_0H]}.$$

Exercise A10. Let $M^n = G/H$, where G is a compact connected Lie group. Show that the following statements are equivalent:

(1) M is orientable.

(2) $H_{\text{dR}}^n(M) \neq 0$.

(3) For all $h \in H$, $\det(\text{Ad}(h)) = 1$ where $\text{Ad}(h): \mathfrak{g}/\mathfrak{h} \rightarrow \mathfrak{g}/\mathfrak{h}$.

(4) There is a volume form $v_G \in \Omega^n(M)^G$ with $\int_G v_G = 1$.

Exercise A11. Let G be a compact Lie group and $\rho: G \rightarrow \text{GL}(V)$ a representation on a finite dimensional vector space V . We write $gv = \rho(g)v$ for $g \in G, v \in V$. Now define the dual representation on $V^* = \text{Hom}_{\mathbb{R}}(V, \mathbb{R})$ by

$$(gv^*)(v) = v^*(g^{-1}v), \quad v^* \in V^*, v \in V, g \in G$$

Let $V^G = \{v \in V \mid gv = v\}$ and $(V^*)^G = \{v^* \in V^* \mid gv^* = v^*\}$.

(1) Show that the natural mapping given by restriction

$$(V^*)^G \rightarrow (V^G)^*$$

is an isomorphism.

(2) Now let V and V' be two finite dimensional vector spaces with G -representations as above and let $B: V \times V' \rightarrow \mathbb{R}$ be a non-degenerate G -invariant bilinear function. (B is non-degenerate if the mapping $B^\sharp: V' \rightarrow V^*$ given by $B^\sharp(v')(v) = B(v, v')$, $v \in V, v' \in V'$, is an isomorphism. B is G -invariant if $B(gv, gv') = B(v, v')$ for all $v \in V, v' \in V', g \in G$.)

Show that B by restriction gives a non-degenerate bilinear function

$$B: V^G \times V'^G \rightarrow \mathbb{R}.$$

Exercise A12 (Poincaré duality). Let G be a compact connected Lie group, $H \subseteq G$ a closed Lie subgroup and put $M = G/H$. Assume that M is oriented and for $k = 0, \dots, n$ define the bilinear function

$$\Omega^k(M)^G \times \Omega^{n-k}(M)^G \longrightarrow \mathbb{R}$$

by

$$B(\alpha, \beta) = \int_M \alpha \wedge \beta, \quad \alpha \in \Omega^k(M)^G, \quad \beta \in \Omega^{n-k}(M)^G.$$

- (1) Show that B is non-degenerate (cf. exercise A11).
- (2) Show the formula

$$B(d\alpha, \beta) = (-1)^k B(\alpha, d\beta), \quad \text{for all } \alpha \in \Omega^{k-1}(M)^G, \beta \in \Omega^{n-k}(M)^G.$$

- (3) Show that B induces a non-degenerate bilinear function

$$\bar{B}: H_{\text{dR}}^k(M) \times H_{\text{dR}}^{n-k}(M) \longrightarrow \mathbb{R} \quad k = 0, \dots, n.$$

That is $\bar{B}^\sharp: H_{\text{dR}}^{n-k} \longrightarrow H_{\text{dR}}^k(M)^*$ is an isomorphism.

Hints to (1): First show the following lemma: For V an n -dimensional vector space and $v \in \text{Alt}^n(V)$ a generator, the bilinear function $B: \text{Alt}^k(V) \times \text{Alt}^{n-k}(V) \longrightarrow \mathbb{R}$ given by

$$\alpha \wedge \beta = B(\alpha, \beta)v, \quad \alpha \in \text{Alt}^k(V), \beta \in \text{Alt}^{n-k}(V)$$

is non-degenerate.

We conclude the appendix with a few examples.

Example A13. $M = S^n$ (cf. example A5). Let \mathbb{R}^{n+1} have the coordinates (x_0, \dots, x_n) and consider the diffeomorphism

$$\pi: \text{SO}(n+1)/\text{SO}(n) \xrightarrow{\cong} S^n \subseteq \mathbb{R}^{n+1}$$

given by $\pi(g\text{SO}(n)) = ge_0$, $g \in \text{SO}(n+1)$, where $e_0 = (1, 0, \dots, 0)$. The differential

$$\pi_*: \mathfrak{so}(n+1)/\mathfrak{so}(n) \longrightarrow \mathbb{R}^n = \text{span}(e_0)^\perp$$

satisfies

$$\pi_*(\text{Ad}(h)X) = h\pi_*(X) \quad X \in \mathfrak{so}(n+1), \quad h \in \text{SO}(n)$$

and thereby induces an isomorphism

$$\text{Alt}^k(\mathbb{R}^n)^{\text{SO}(n)} \xrightarrow{\pi_*} \text{Alt}^k(\mathfrak{so}(n+1)/\mathfrak{so}(n))^{\text{SO}(n)} \quad k = 0, \dots, n,$$

where

$$\text{Alt}^k(\mathbb{R}^n)^{\text{SO}(n)} = \{\alpha \in \text{Alt}^k(\mathbb{R}^n) \mid \alpha(hv_1, \dots, hv_k) = \alpha(v_1, \dots, v_k)\},$$

for all $v_1, \dots, v_k \in \mathbb{R}^n$ and $h \in \text{SO}(n)$. We now have

$$\text{Alt}^k(\mathbb{R}^n)^{\text{SO}(n)} = \begin{cases} \mathbb{R} \det & k = n \\ 0 & k = 1, \dots, n-1 \end{cases}$$

where “det” is defined by the determinant. It is clear that “det” is $\text{SO}(n)$ -invariant (by definition). So let us show that every $\alpha \in \text{Alt}^k(\mathbb{R}^n)$, $k < n$, is 0:

Let $\{e_1, \dots, e_n\}$ be the canonical basis for \mathbb{R}^n , and notice that α is determined by $\{\alpha(e_{i_1}, \dots, e_{i_k}) \mid 1 \leq i_1 < \dots < i_k \leq n\}$. But for $k < n$ there are $h, h' \in \text{SO}(n)$ such that

$$h(e_1) = e_{i_1}, \dots, h(e_k) = e_{i_k}$$

and

$$h'(e_1) = -e_{i_1}, h'(e_2) = e_{i_2}, \dots, h'(e_k) = e_{i_k}$$

hence

$$\alpha(e_{i_1}, \dots, e_{i_k}) = \alpha(e_1, \dots, e_k) = -\alpha(e_{i_1}, \dots, e_{i_k}),$$

that is $\alpha(e_{i_1}, \dots, e_{i_k}) = 0$. We have thus shown that

$$H_{\text{dR}}^k(S^n) = \begin{cases} \mathbb{R}[v_{S^n}] & k = n \\ 0 & k = 1, \dots, n-1 \\ \mathbb{R} & k = 0 \end{cases}$$

where $v_{S^n} \in \Omega^n(S^n)$ is the volume form from example A5.

Exercise A14. For $M = \mathbb{R}P^n$ the n -dimensional projective space, show that

$$H_{\text{dR}}^k(\mathbb{R}P^n) = \begin{cases} \mathbb{R} & k = 0 \text{ and } k = n \text{ odd} \\ 0 & \text{otherwise.} \end{cases}$$

Example A15. $M = \mathbb{C}P^n = \text{U}(n+1)/(\text{U}(1) \times \text{U}(n))$. \mathbb{C}^{n+1} has the coordinates (z_0, \dots, z_n) and $H = \text{U}(1) \times \text{U}(n) \subseteq \text{U}(n+1)$ is the subgroup of matrices on the form

$$g = \begin{pmatrix} \lambda & 0 \\ 0 & h \end{pmatrix} \quad \lambda \in \text{U}(1), h \in \text{U}(n).$$

It is easy to show that the mapping

$$\pi_*: \mathfrak{u}(n+1)/\mathfrak{u}(n) \longrightarrow \mathbb{C}^n$$

given by

$$\pi_*(X) = \begin{bmatrix} x_{n,1} \\ \vdots \\ x_{n,n} \end{bmatrix}$$

is an isomorphism, and that

$$\pi_*(\text{Ad}(g)X) = \bar{\lambda}h\pi_*(X), \quad \text{for } X \in \mathfrak{u}(n+1) \subseteq M(n+1)$$

and $g \in H$ as above. That is we get an isomorphism

$$\text{Alt}_{\mathbb{R}}^k(\mathbb{C}^n)^{\text{U}(n)} \xrightarrow{\pi_*} \text{Alt}_{\mathbb{R}}^k(\mathfrak{u}(n+1)/(\mathfrak{u}(1) \times \mathfrak{u}(n)))$$

where

$$\text{Alt}_{\mathbb{R}}^k(\mathbb{C}^n)^{\text{U}(n)} = \{\alpha \in \text{Alt}_{\mathbb{R}}^k(\mathbb{C}^n) \mid \alpha(hv_1, \dots, hv_k) = \alpha(v_1, \dots, v_k)\},$$

for all $v_1, \dots, v_k \in \mathbb{C}^n$ and $h \in \text{U}(n)$. Notice that $\kappa \in \text{Alt}_{\mathbb{R}}^2(\mathbb{C}^n)$ given by

$$\kappa(v, w) = -\text{Im}(\bar{w}^t v)$$

is $\text{U}(n)$ invariant and that $\kappa(e_1, ie_1) = 1$ so that

$$\text{Alt}_{\mathbb{R}}^2(\mathbb{C}^n)^{\text{U}(n)} \neq 0.$$

We show that

$$\text{Alt}_{\mathbb{R}}^k(\mathbb{C}^n)^{\text{U}(n)} = \begin{cases} \mathbb{R}\kappa^{k/2} & 0 \leq k \leq 2n, k \text{ even} \\ 0 & \text{otherwise.} \end{cases} \quad (\text{A.1})$$

Since $\mathbb{C}^n = \text{span}_{\mathbb{R}}\{e_1, \dots, e_n, ie_1, \dots, ie_n\}$, $\alpha \in \text{Alt}^k(\mathbb{C}^n)^{\text{U}(n)}$ is determined by the values

$$\alpha(e_{i_1}, \dots, e_{i_p}, ie_{j_1}, \dots, ie_{j_q}),$$

where $1 \leq i_1 < \dots < i_p \leq n$, $1 \leq j_1 < \dots < j_q \leq n$ and $p + q = k$. But if there is a $j_s \notin \{i_1, \dots, i_p\}$ then the mapping

$$e_l \mapsto \begin{cases} -e_l & l = j_s \\ e_l & l \neq j_s \end{cases}$$

is unitary so that

$$\alpha(e_{i_1}, \dots, e_{i_p}, ie_{j_1}, \dots, ie_{j_q}) = -\alpha(e_{i_1}, \dots, e_{i_p}, ie_{j_1}, \dots, ie_{j_q}),$$

that is $\alpha(e_{i_1}, \dots, e_{i_p}, ie_{j_1}, \dots, ie_{j_q}) = 0$. In the same way we show that if $i_t \notin \{j_1, \dots, j_q\}$ then $\alpha(e_{i_1}, \dots, e_{i_p}, ie_{j_1}, \dots, ie_{j_q}) = 0$. That is, $\alpha = 0$ if $p \neq q$ and for $k = 2p$, α is determined by the values

$$\alpha(e_{i_1}, \dots, e_{i_p}, ie_{i_1}, \dots, ie_{i_p}).$$

There is an $h \in \text{U}(n)$ such that $h(e_l) = e_{i_l}$, $l = 1, \dots, p$, hence α is determined by $\alpha(e_1, \dots, e_p, ie_1, \dots, ie_p)$.

We get that $\text{Alt}_{\mathbb{R}}^{2p}(\mathbb{C}^n)^{\text{U}(n)}$ is at most 1-dimensional, so it is enough to show that $\kappa^p \neq 0$. An easy calculation shows that

$$\kappa^p(e_1, \dots, e_p, ie_1, \dots, ie_p) = p!, \quad p \leq n,$$

which shows (A.1). This also shows that

$$H_{\text{dR}}^k(\mathbb{C}P^n) = \begin{cases} \mathbb{R}\kappa^{k/2} & 0 \leq k \leq 2n, k \text{ even} \\ 0 & \text{otherwise.} \end{cases} \quad (\text{A.2})$$

Exercise A16 (Symmetric spaces). Let $M = G/H$, where G is a compact connected Lie group and $H \subseteq G$ is a closed Lie subgroup. Let $\mathfrak{h} \subseteq \mathfrak{g}$

be the Lie algebras for H and G respectively, and assume that there is a complement $\mathfrak{m} \subseteq \mathfrak{g}$ such that $\mathfrak{g} = \mathfrak{m} \oplus \mathfrak{h}$ and such that the following is satisfied:

- (1) $\text{Ad}(h)(X) \in \mathfrak{m}$ for all $h \in H, X \in \mathfrak{m}$.
- (2) $[X, Y] \in \mathfrak{h}$ for all $X, Y \in \mathfrak{m}$.

Show that there is a natural isomorphism

$$H_{\text{dR}}^k(M) \cong \text{Alt}^k(\mathfrak{m})^H, \quad k = 0, 1, 2, \dots$$

where the action of H on $\text{Alt}^k(\mathfrak{m})$ is induced by the adjoint action of H on \mathfrak{m} given by (1).

Exercise A17. Let G be a compact connected Lie group. As G acts on the Lie algebra \mathfrak{g} by the adjoint representation, show that there is a natural isomorphism

$$H_{\text{dR}}^k(G) \cong \text{Alt}^k(\mathfrak{g})^G.$$

Hint: Use exercise A16 for the case $H \subseteq G \times G, H = \{(g, g) \mid g \in G\}$.