

Chapter 1

Semisimple Lie algebras

1.1 Semisimple Lie algebras and Killing form

Definition 1.1.1 A Lie algebra $\mathfrak{g}$ is a vector space over a field k together with an alternate bilinear map $[\cdot, \cdot] : \mathfrak{g} \times \mathfrak{g} \rightarrow \mathfrak{g}$ satisfying the Jacobi identity $[x, [y, z]] + [[x, z], y] + [z, [x, y]] = 0$.

Example 1.1.2 The basic examples of Lie algebras are $\mathfrak{gl}(V) = \text{End}(V)$ the set of endomorphisms of a fixed vector space V with Lie bracket $[f, g] = f \circ g - g \circ f$. The Lie algebra $\mathfrak{sl}(V)$ is defined for V of finite dimension by $\mathfrak{sl}(V) = \{f \in \mathfrak{gl}(V) \mid \text{Tr}(f) = 0\}$.

To a Lie algebra one defines its **adjoint representation** $\text{ad} : \mathfrak{g} \rightarrow \mathfrak{gl}(\mathfrak{g}) = \text{End}(\mathfrak{g})$ defined by $\text{ad}(x)(y) = [x, y]$. This is a Lie algebra morphism thanks to Jacobi identity.

Definition 1.1.3 More generally, a Lie algebra representation of $\mathfrak{g}$ is a vector space V together with a Lie algebra map $\mathfrak{g} \rightarrow \mathfrak{gl}(V)$.

When V is a finite dimensional representation of $\mathfrak{g}$, one define an invariant quadratic form on $\mathfrak{g}$ by $(x, y) = \text{Tr}_V(\varphi(x)\varphi(y))$ where $\varphi : \mathfrak{g} \rightarrow \mathfrak{gl}(V)$ defines the representation. Here invariant means that we have $(x, [y, z]) = ([x, y], z)$. In particular, if $\mathfrak{g}$ is finite dimensional, the adjoint representation leads to the **Killing form** $\kappa(x, y)$ on $\mathfrak{g}$.

Definition 1.1.4 (i) An ideal $\mathfrak{a}$ of a Lie algebra $\mathfrak{g}$ is a subvectorspace such that $[\mathfrak{g}, \mathfrak{a}] \subset \mathfrak{a}$.

Remark that if $\mathfrak{a}$ is an ideal of $\mathfrak{g}$, then the quotient $\mathfrak{g}/\mathfrak{a}$ is again a Lie algebra.

(ii) A Lie algebra $\mathfrak{g}$ is **abelian** if $[\mathfrak{g}, \mathfrak{g}] = 0$.

(iii) A Lie algebra $\mathfrak{g}$ is **simple** if $2 \leq \dim \mathfrak{g} < +\infty$ and $\mathfrak{g}$ as no non trivial ideal.

(iv) A Lie algebra $\mathfrak{g}$ is **semisimple** if $\mathfrak{g}$ is a direct sum of finitely many simple Lie algebras.

Example 1.1.5 The Lie algebra $\mathfrak{sl}(V)$ is simple for any finite dimensional vector space V .

Proposition 1.1.6 Let $\mathfrak{g}$ be a finite dimensional Lie algebra. The following are equivalent:

(i) The Lie algebra $\mathfrak{g}$ is semisimple.

(ii) The Killing form is non degenerate.

(iii) There is no non trivial abelian ideal.

For Kac-Moody Lie algebras one can not define the Killing form because the Lie algebra will be of infinite dimension so that the trace is not defined. However, we will look for equivariant non degenerate quadratic forms. This will not always exist but in a large class of Kac-Moody Lie algebras called **symmetrisable** it will be the case.

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