## MAT 552

Introduction to

Lie Groups and Lie Algebras

Claude LeBrun Stony Brook University

March 16, 2021

which defines a positive-definite inner product on each tangent space  $T_pM$ :

which defines a positive-definite inner product on each tangent space  $T_pM$ :

 $v \neq 0 \implies \mathbf{g}(v,v) > 0.$ 

which defines a positive-definite inner product on each tangent space  $T_pM$ :

$$v \neq 0 \implies g(v,v) > 0.$$

**Proposition.** Every smooth manifold M admits a Riemannian metric g.

which defines a positive-definite inner product on each tangent space  $T_pM$ :

$$v \neq 0 \implies \mathbf{g}(v, v) > 0.$$

**Proposition.** Every smooth manifold M admits Riemannian metrics g.

which defines a positive-definite inner product on each tangent space  $T_pM$ :

 $v \neq 0 \implies g(v,v) > 0.$ 

**Proposition.** Every smooth manifold M admits Riemannian metrics g.

**Proof.** Partition of unity argument...

If M is a smooth manifold, let  $\mathfrak{X} = \mathfrak{X}(M) := C^{\infty}(TM)$ 

$$\mathfrak{X} = \mathfrak{X}(M) := C^{\infty}(TM)$$

denote the smooth tangent vector fields on M.

 $\mathfrak{X} = \mathfrak{X}(M) := C^{\infty}(TM)$ 

denote the smooth tangent vector fields on M.

**Definition.** An affine connection  $\nabla$  on a smooth manifold M is an operation

 $\mathfrak{X} = \mathfrak{X}(M) := C^{\infty}(TM)$ 

denote the smooth tangent vector fields on M.

**Definition.** An affine connection  $\nabla$  on a smooth manifold M is an operation

$$\nabla: \mathfrak{X} \times \mathfrak{X} \longrightarrow \mathfrak{X}$$
$$(u, v) \longmapsto \nabla_u v$$

 $\mathfrak{X} = \mathfrak{X}(M) := C^{\infty}(TM)$ 

denote the smooth tangent vector fields on M.

**Definition.** An affine connection  $\nabla$  on a smooth manifold M is an operation

 $\nabla: \mathfrak{X} \times \mathfrak{X} \longrightarrow \mathfrak{X}$  $(u, v) \longmapsto \nabla_u v$ 

such that, for  $u, v, w \in \mathfrak{X}$ , and  $f \in C^{\infty}$  one has

 $\mathfrak{X} = \mathfrak{X}(M) := C^{\infty}(TM)$ 

denote the smooth tangent vector fields on M.

**Definition.** An affine connection  $\nabla$  on a smooth manifold M is an operation

 $\nabla: \mathfrak{X} \times \mathfrak{X} \longrightarrow \mathfrak{X}$  $(u, v) \longmapsto \nabla_{u} v$ 

such that, for  $u, v, w \in \mathfrak{X}$ , and  $f \in C^{\infty}$  one has

 $\nabla_{u+v}w = \nabla_u w + \nabla_v w$ 

 $\mathfrak{X} = \mathfrak{X}(M) := C^{\infty}(TM)$ 

denote the smooth tangent vector fields on M.

**Definition.** An affine connection  $\nabla$  on a smooth manifold M is an operation

$$\nabla : \mathfrak{X} \times \mathfrak{X} \longrightarrow \mathfrak{X}$$
$$(u, v) \longmapsto \nabla_u v$$

such that, for  $u, v, w \in \mathfrak{X}$ , and  $f \in C^{\infty}$  one has

 $\nabla_{u+v}w = \nabla_u w + \nabla_v w$  $\nabla_{fu}w = f\nabla_u w$ 

 $\mathfrak{X} = \mathfrak{X}(M) := C^{\infty}(TM)$ 

denote the smooth tangent vector fields on M.

**Definition.** An affine connection  $\nabla$  on a smooth manifold M is an operation

$$\nabla: \mathfrak{X} \times \mathfrak{X} \longrightarrow \mathfrak{X}$$
$$(u, v) \longmapsto \nabla_u v$$

such that, for  $u, v, w \in \mathfrak{X}$ , and  $f \in C^{\infty}$  one has

$$\nabla_{u+v}w = \nabla_{u}w + \nabla_{v}w$$
$$\nabla_{fu}w = f\nabla_{u}w$$
$$\nabla_{u}(v+w) = \nabla_{u}v + \nabla_{u}w$$

 $\mathfrak{X} = \mathfrak{X}(M) := C^{\infty}(TM)$ 

denote the smooth tangent vector fields on M.

**Definition.** An affine connection  $\nabla$  on a smooth manifold M is an operation

$$\nabla : \mathfrak{X} \times \mathfrak{X} \longrightarrow \mathfrak{X}$$
$$(u, v) \longmapsto \nabla_u v$$

such that, for  $u, v, w \in \mathfrak{X}$ , and  $f \in C^{\infty}$  one has

$$\nabla_{u+v}w = \nabla_{u}w + \nabla_{v}w$$
$$\nabla_{fu}w = f\nabla_{u}w$$
$$\nabla_{u}(v+w) = \nabla_{u}v + \nabla_{u}w$$
$$\nabla_{u}(fw) = (uf)w + f\nabla_{u}w$$

**Theorem.** Let g be a Riemannian metric on M.

• 
$$\nabla_v w - \nabla_w v = [v, w]$$

• 
$$\nabla_v w - \nabla_w v = [v, w];$$
 and

•  $ug(v,w) = g(\nabla_u v,w) + g(v,\nabla_u w).$ 

• torsion-free:

• torsion-free:  $\mathcal{T}_{\nabla} = 0$ 

• torsion-free:  $\mathcal{T}_{\nabla} = 0$ 

$$\mathcal{T}_{\nabla}(v,w) := \nabla_v w - \nabla_w v - [v,w]$$

- torsion-free; and
- metric compatible:

- torsion-free; and
- metric compatible:  $\nabla g = 0$ .

- torsion-free; and
- metric compatible:  $\nabla g = 0$ .

$$(\nabla g)(u, v, w) := ug(v, w) - g(\nabla_u v, w) - g(v, \nabla_u w)$$

• 
$$\nabla_v w - \nabla_w v = [v, w];$$
 and

•  $ug(v,w) = g(\nabla_u v,w) + g(v,\nabla_u w).$ 

• left-invariant:

$${L_{\mathsf{a}}}^*g=g \quad \forall \mathsf{a} \in \mathsf{G}$$

• left-invariant:

$$L_{a}^{*}g = g \quad \forall a \in G$$
$$L_{a} : G \rightarrow G$$
$$b \mapsto ab$$

• left-invariant:

$${L_{\mathsf{a}}}^*g=g \quad \forall \mathsf{a} \in \mathsf{G}$$

• left-invariant:

$${L_{\mathsf{a}}}^*g=g \quad \forall \mathsf{a} \in \mathsf{G}$$

• right-invariant:

$$R_{\mathsf{a}}{}^*g = g \quad \forall \mathsf{a} \in \mathsf{G}$$

• left-invariant:

$$L_{\mathsf{a}}{}^*g = g \quad \forall \mathsf{a} \in \mathsf{G}$$

• right-invariant:

$$R_{a}^{*}g = g \quad \forall a \in G$$
  
 $R_{a}: G \rightarrow G$   
 $b \mapsto ba$ 

• left-invariant:

$${L_{\mathsf{a}}}^*g=g \quad \forall \mathsf{a} \in \mathsf{G}$$

• right-invariant:

$$R_{\mathsf{a}}{}^*g = g \quad \forall \mathsf{a} \in \mathsf{G}$$

• left-invariant:

$$L_{\mathsf{a}}^*g = g \quad \forall \mathsf{a} \in \mathsf{G}$$

• right-invariant:

$$R_{\mathsf{a}}{}^*g = g \quad \forall \mathsf{a} \in \mathsf{G}$$

• bi-invariant: both left- and right-invariant.

**Proof.** Construct positive-definite inner product  $\langle , \rangle$  on  $T_{e}G = \mathfrak{g}$  which is invariant under adjoint actions  $Ad_* : G \to \mathbf{GL}(T_{e}G)$ .

**Proof.** Construct positive-definite inner product  $\langle , \rangle$  on  $T_{\mathbf{e}}\mathsf{G} = \mathfrak{g}$  which is invariant under adjoint actions  $Ad_* : \mathsf{G} \to \mathbf{GL}(T_{\mathbf{e}}\mathsf{G})$ .

$$Ad_* = \left(L_{\mathsf{a}}R_{\mathsf{a}^{-1}}\right)_*\big|_{\mathsf{e}}$$

**Proof.** Construct positive-definite inner product  $\langle , \rangle$  on  $T_{e}G = \mathfrak{g}$  which is invariant under adjoint actions  $Ad_* : G \to \mathbf{GL}(T_{e}G)$ .

**Proof.** Construct positive-definite inner product  $\langle , \rangle$  on  $T_{e}G = \mathfrak{g}$  which is invariant under adjoint actions  $Ad_* : G \to \mathbf{GL}(T_{e}G)$ .

Let g be left-invariant extension of  $\langle , \rangle$ :

**Proof.** Construct positive-definite inner product  $\langle , \rangle$  on  $T_{e}G = \mathfrak{g}$  which is invariant under adjoint actions  $Ad_{*} : G \to \mathbf{GL}(T_{e}G)$ .

Let g be left-invariant extension of  $\langle , \rangle$ :

 $g|_{\mathsf{a}} = L_{\mathsf{a}*}\langle \;,\; 
angle$ 

**Proof.** Construct positive-definite inner product  $\langle , \rangle$  on  $T_{e}G = \mathfrak{g}$  which is invariant under adjoint actions  $Ad_* : G \to \mathbf{GL}(T_{e}G)$ .

Let g be left-invariant extension of  $\langle , \rangle$ .

Then g is also right-invariant, because  $\langle \ , \ \rangle$  is invariant under

$$Ad_* = \left( L_{\mathsf{a}} R_{\mathsf{a}^{-1}} \right)_* \big|_{\mathsf{e}}$$

**Proof.** Construct positive-definite inner product  $\langle , \rangle$  on  $T_{e}G = \mathfrak{g}$  which is invariant under adjoint actions  $Ad_* : G \to \mathbf{GL}(T_{e}G)$ .

Let g be left-invariant extension of  $\langle , \rangle$ .

Then g is also right-invariant, because  $\langle \ , \ \rangle$  is invariant under

$$Ad_* = \left(L_{\mathsf{a}^{-1}}R_{\mathsf{a}}\right)^*\big|_{\mathsf{e}}$$

**Proof.** Construct positive-definite inner product  $\langle , \rangle$  on  $T_{e}G = \mathfrak{g}$  which is invariant under adjoint actions  $Ad_* : G \to \mathbf{GL}(T_{e}G)$ .

Let g be left-invariant extension of  $\langle , \rangle$ .

Then g is also right-invariant, because  $\langle \ , \ \rangle$  is invariant under

$$Ad_* = R_a^* L_{a^{-1}}^*$$

$$\nabla_X Y = \frac{1}{2} [X, Y]$$

$$\nabla_X Y = \frac{1}{2}[X, Y]$$

for any left-invariant vector fields  $X, Y \in \mathfrak{g}$ .

$$\nabla_X Y = \frac{1}{2}[X, Y]$$

for any left-invariant vector fields  $X, Y \in \mathfrak{g}$ .

**Proof.** Any  $Z \in \mathfrak{g}$  is a Killing field:

$$\nabla_X Y = \frac{1}{2} [X, Y]$$

for any left-invariant vector fields  $X, Y \in \mathfrak{g}$ .

**Proof.** Any  $Z \in \mathfrak{g}$  is a Killing field:

 $0 = (\mathcal{L}_Z g)(X, Y) = g(\nabla_X Z, Y) + g(X, \nabla_Y Z)$ 

$$\nabla_X Y = \frac{1}{2} [X, Y]$$

for any left-invariant vector fields  $X, Y \in \mathfrak{g}$ .

**Proof.** Any  $Z \in \mathfrak{g}$  is a Killing field:

 $0 = (\mathcal{L}_Z g)(X, Y) = g(\nabla_X Z, Y) + g(X, \nabla_Y Z)$ 

$$\nabla_X Y = \frac{1}{2} [X, Y]$$

for any left-invariant vector fields  $X, Y \in \mathfrak{g}$ .

**Proof.** Any  $Z \in \mathfrak{g}$  is a Killing field:

 $0 = (\mathcal{L}_Z g)(X, Y) = g(\nabla_X Z, Y) + g(X, \nabla_Y Z)$ 

Inner products of left-invariant fields are constant:  $0 = Yq(X, Z) = q(\nabla_V X, Z) + q(X, \nabla_V Z)$ 

$$\nabla_X Y = \frac{1}{2} [X, Y]$$

for any left-invariant vector fields  $X, Y \in \mathfrak{g}$ .

**Proof.** Any  $Z \in \mathfrak{g}$  is a Killing field:

$$0 = (\mathcal{L}_Z g)(X, Y) = g(\nabla_X Z, Y) + g(X, \nabla_Y Z)$$

$$0 = Yg(X, Z) = g(\nabla_Y X, Z) + g(X, \nabla_Y Z)$$
$$0 = Xg(Y, Z) = g(\nabla_X Y, Z) + g(Y, \nabla_X Z)$$

$$\nabla_X Y = \frac{1}{2} [X, Y]$$

for any left-invariant vector fields  $X, Y \in \mathfrak{g}$ .

**Proof.** Any  $Z \in \mathfrak{g}$  is a Killing field:

$$g(Y, \nabla_X Z) = -g(X, \nabla_Y Z)$$

$$g(\nabla_Y X, Z) = -g(X, \nabla_Y Z)$$
$$g(\nabla_X Y, Z) = -g(Y, \nabla_X Z)$$

$$\nabla_X Y = \frac{1}{2} [X, Y]$$

for any left-invariant vector fields  $X, Y \in \mathfrak{g}$ .

**Proof.** Any  $Z \in \mathfrak{g}$  is a Killing field:

$$g(Y, \nabla_X Z) = -g(X, \nabla_Y Z)$$

$$g(\nabla_Y X, Z) = -g(X, \nabla_Y Z)$$
$$g(\nabla_X Y, Z) = -g(Y, \nabla_X Z)$$

$$. \quad g(\nabla_X Y, Z) = -g(\nabla_Y X, Z) \quad \forall \ Z \in \mathfrak{g}$$

$$\nabla_X Y = \frac{1}{2} [X, Y]$$

for any left-invariant vector fields  $X, Y \in \mathfrak{g}$ .

**Proof.** Any  $Z \in \mathfrak{g}$  is a Killing field:

$$g(Y, \nabla_X Z) = -g(X, \nabla_Y Z)$$

$$g(\nabla_Y X, Z) = -g(X, \nabla_Y Z)$$
$$g(\nabla_X Y, Z) = -g(Y, \nabla_X Z)$$

$$\nabla_X Y = -\nabla_Y X$$

$$\nabla_X Y = \frac{1}{2} [X, Y]$$

for any left-invariant vector fields  $X, Y \in \mathfrak{g}$ .

**Proof.** So  $\forall X, Y \in \mathfrak{g}$ ,  $\nabla_X Y = -\nabla_Y X$ 

$$\nabla_X Y = \frac{1}{2}[X, Y]$$

for any left-invariant vector fields  $X, Y \in \mathfrak{g}$ .

**Proof.** So  $\forall X, Y \in \mathfrak{g}$ ,  $\nabla_X Y = -\nabla_Y X$ 

Torsion-free condition:

$$\nabla_X Y - \nabla_Y X = [X, Y]$$

$$\nabla_X Y = \frac{1}{2} [X, Y]$$

for any left-invariant vector fields  $X, Y \in \mathfrak{g}$ .

**Proof.** So  $\forall X, Y \in \mathfrak{g}$ ,  $\nabla_X Y = -\nabla_Y X$ 

Torsion-free condition:

$$\nabla_X Y - \nabla_Y X = [X, Y]$$

$$2\nabla_X Y = [X, Y]$$

$$\nabla_X Y = \frac{1}{2} [X, Y]$$

for any left-invariant vector fields  $X, Y \in \mathfrak{g}$ .

**Proof.** So  $\forall X, Y \in \mathfrak{g}$ ,  $\nabla_X Y = -\nabla_Y X$ 

Torsion-free condition:

$$\nabla_X Y - \nabla_Y X = [X, Y]$$

$$\therefore \quad \nabla_X Y = \frac{1}{2} [X, Y]$$

$$\nabla_X Y = \frac{1}{2}[X, Y]$$

for any left-invariant vector fields  $X, Y \in \mathfrak{g}$ .

**Proof.** So  $\forall X, Y \in \mathfrak{g}$ ,  $\nabla_X Y = -\nabla_Y X$ 

Torsion-free condition:

$$\nabla_X Y - \nabla_Y X = [X, Y]$$

$$\therefore \quad \nabla_X Y = \frac{1}{2} [X, Y]$$

QED