

Elementary Differential Geometry

Hassium

1	Calculus on Euclidean Space	6	Geometry of Surfaces in \mathbb{R}^3
2	Frame Fields	7	Riemannian Geometry
3	Euclidean Geometry	8	Global Structure of Surfaces
4	Calculus on a Surface		Exercises and Proofs
5	Shape Operators		Alphabetical Index

1 Calculus on Euclidean Space

Definition 1.1. The *Euclidean 3-space*, denoted \mathbb{R}^3 , is the set of ordered triples of the form $p = (p_1, p_2, p_3)$, where $p_i \in \mathbb{R}$. An element of \mathbb{R}^3 is called a *point*.

Let $p = (p_1, p_2, p_3), q = (q_1, q_2, q_3) \in \mathbb{R}^3$ and let $a \in \mathbb{R}$. Define the addition to be $p + q = (p_i + q_i)$ and define the scalar multiplication to be $ap = (ap_i)$. The additive identity $0 = (0, 0, 0)$ is called the *origin* of \mathbb{R}^3 . It is trivial that \mathbb{R}^3 is a vector space over \mathbb{R} .

Definition 1.2. Let x, y , and z be real-valued functions on \mathbb{R}^3 such that for all $p = (p_1, p_2, p_3) \in \mathbb{R}^3$, $x(p) = p_1$, $y(p) = p_2$, and $z(p) = p_3$. We call x, y , and z the *natural coordinate functions* of \mathbb{R}^3 .

Let x, y , and z be the natural coordinate functions, rewrite $x = x_1, y = x_2$, and $z = x_3$. Then we have $p = (p_i) = (x_i(p))$.

Definition 1.3. A real-valued function f on \mathbb{R}^3 is *differentiable* if all partial derivatives exist and continuous.

Let $x = (x_1, x_2, x_3) \in \mathbb{R}^3$, we define the norm to be $\|x\| = \sqrt{\sum x_i^2}$.

Definition 1.4. A subset $O \subset \mathbb{R}^3$ is *open* if for all $p \in O$, there exists $\varepsilon > 0$ such that $\{x \in \mathbb{R}^3 \mid \|x - p\| < \varepsilon\} \subset O$.

Let $f : O \rightarrow \mathbb{R}$ be a function defined on an open set. The differentiability of f at p can be determined entirely from values of f on O . This means that differentiation is a local operation. We will discuss this later.

Definition 1.5. A *tangent vector* v_p is an ordered pair $v_p = (v, p)$, where $v, p \in \mathbb{R}^3$. Here v is called the *vector part* and p is called its *point of application*. Two tangent vectors are said to be *parallel* if they have the same vector part and different points of application.

Definition 1.6. Let $p \in \mathbb{R}^3$. The *tangent space* at p , denoted $T_p(\mathbb{R}^3)$, is the set of all tangent vectors that have p as point of application.

Fix a tangent space $T_p(\mathbb{R}^3)$ and let $T_p(\mathbb{R}^3)$ adapt the operations from $\mathbb{R}^3 \times \mathbb{R}^3$. We have a natural linear map $f : T_p(\mathbb{R}^3) \rightarrow \mathbb{R}^3$ defined by $v_p \rightarrow v$ and it is trivially an isomorphism.

Definition 1.7. A *vector field* V on \mathbb{R}^3 is a function $V : \mathbb{R}^3 \rightarrow \mathbb{R}^3$ such that for all $p \in \mathbb{R}^3$, $V(p) \in T_p(\mathbb{R}^3)$.

Let V and W be vector field. Let f be a real-valued function. For all $p \in \mathbb{R}^3$, define $V + W$ by $(V + W)(p) = V(p) + W(p)$ and $(fV)(p) = f(p)V(p)$.

Definition 1.8. Let U_1, U_2 , and U_3 be vector fields on \mathbb{R}^3 such that $U_1(p) = (1, 0, 0)_p$, $U_2(p) = (0, 1, 0)_p$, and $U_3(p) = (0, 0, 1)_p$ for all $p \in \mathbb{R}^3$. We call (U_1, U_2, U_3) the *natural frame field* on \mathbb{R}^3 .

Proposition. Let V be a vector field on \mathbb{R}^3 . There are three uniquely determined real-valued functions v_1 , v_2 , and v_3 on \mathbb{R}^3 such that $V = v_1U_1 + v_2U_2 + v_3U_3$.

Proof. For all $p \in \mathbb{R}^3$, $V(p) = (v_1(p), v_2(p), v_3(p))_p = v_1(p)(1, 0, 0)_p + v_2(p)(0, 1, 0)_p + v_3(p)(0, 0, 1)_p = v_1(p)U_1(p) + v_2(p)U_2(p) + v_3(p)U_3(p)$, hence $V = \sum v_iU_i$. \square

The functions v_1 , v_2 , and v_3 are called the *Euclidean coordinate functions* on V .

Definition 1.9. A vector field V is *differentiable* if its Euclidean coordinate functions are differentiable.

Definition 1.10. Let f be a differentiable real-valued function on \mathbb{R}^3 and let v_p be a tangent vector on \mathbb{R}^3 . The *directional derivative* of f with respect to v_p , denoted $v_p[f]$, is defined to be $(d/dt)f(p + tv)$ at $t = 0$.

Remark. We will not write the restriction every time for convenience.

Proposition. Let $v_p = (v_1, v_2, v_3)_p$ be a tangent vector, then $v_p[f] = \sum v_i(\partial f / \partial x_i)(p)$.

Proof. Let $p = (p_1, p_2, p_3)$. Then $v_p[f] = (d/dt)f(p + tv)|_{t=0} = \sum (\partial f / \partial z)(p) \cdot (d/dt)(p_i + tv_i) = \sum (\partial f / \partial x_i)(p)v_i$. \square

Example. Consider $f = x^2yz$ with $p = (1, 1, 0)$ and $v = (1, 0, -3)$. By the definition, $p + tv = (1 + t, 1, -3t)$, so $v_p[f] = (d/dt)(-3t^3 - 6t^2 - 3t) = -3$. Since $(\partial f / \partial x) = 2xyz$, $(\partial f / \partial y) = x^2z$, and $(\partial f / \partial z) = x^2y$, we have $(\partial f / \partial x)(p) = (\partial f / \partial y)(p) = 0$ and $(\partial f / \partial z)(p) = 1$, so $v_p[f] = -3$.

Proposition. Let f and g be functions on \mathbb{R}^3 . Let v_p and w_p be tangent vectors. For all $a, b \in \mathbb{R}$, the following properties hold.

1. $(av_p + bw_p)[f] = av_p[f] + bw_p[f]$.
2. $v_p[af + bg] = av_p[f] + bv_p[g]$.
3. $v_p[fg] = v_p[f]g(p) + f(p)v_p[g]$.

Proof. (i) We have $(av_p + bw_p)[f] = \sum (av_i + bw_i)(\partial f / \partial x_i)(p) = \sum av_i(\partial f / \partial x_i)(p) + \sum bw_i(\partial f / \partial x_i)(p) = av_p[f] + bw_p[f]$. (ii) We have $v_p[af + bg] = \sum v_i(\partial(af + bg) / \partial x_i)(p) = \sum v_i(\partial(af) / \partial x_i)(p) + \sum v_i(\partial(bg) / \partial x_i)(p) = av_p[f] + bv_p[g]$. (iii) We have $v_p[fg] = \sum v_i(\partial(fg) / \partial x_i)(p) = \sum v_i(\partial f / \partial x_i)(p)g(p) + f(p) \sum v_i(\partial g / \partial x_i)(p) = v_p[f]g(p) + f(p)v_p[g]$. \square

Let V be a vector field, we define $V[f]$ at $p \in \mathbb{R}^3$ to be $V(p)[f]$. By the convention, $U_i(p)[f] = (\partial f / \partial x_i)(p)$.

Proposition. Let V and W be vector fields. Let f , g , and h be real-valued functions. For all $a, b \in \mathbb{R}$, the following properties hold.

1. $(fV + gW)[h] = fV[h] + gW[h]$.
2. $V[af + bg] = aV[f] + bV[g]$.
3. $V[f]g = V[f]g + fV[g]$.

Proof. (i) For all $p \in \mathbb{R}^3$, $(fV + gW)(p)[h] = (f(p)V(p) + g(p)W(p))[h] = fV[h] + gW[h]$. (ii) For all $p \in \mathbb{R}^3$, $V(p)[af + bg] = aV(p)[f] + bV(p)[g]$. (iii) For all $p \in \mathbb{R}^3$, $V(p)[f]g(p) + f(p)V(p)[g] = V[f](p)g(p) + f(p)V[g](p) = (V[f]g + fV[g])(p)$. \square

Example. Let $V = xU_1 - y^2U_3$ and let $f = x^2y + z^3$. Then $V[f] = xU_1[x^2y] + xU_1[z^3] - y^2U_3[x^2y] - y^2U_3[z^3] = 2x^2y - 3y^2z^2$.

Let $I \subset \mathbb{R}$ be an open interval. Let $\alpha : I \rightarrow \mathbb{R}^3$ be a function. We can rewrite $\alpha(t)$ as $(\alpha_1(t), \alpha_2(t), \alpha_3(t))$, where $\alpha_i : I \rightarrow \mathbb{R}$. We say α is *differentiable* if α_i are differentiable.

Definition 1.11. A *curve* in \mathbb{R}^3 is a differentiable function $\alpha : I \rightarrow \mathbb{R}^3$, where $I \subset \mathbb{R}$ is an open interval.

Example. Here are some examples of curves.

1. A curve $\alpha : \mathbb{R} \rightarrow \mathbb{R}^3$ defined by $\alpha(t) = p + tq$, where $\alpha(0) = p$ and $q \neq 0$, is called a *straight line*.

2. The curve $\alpha : \mathbb{R} \rightarrow \mathbb{R}^3$ defined by $\alpha(t) = (a \cos t, a \sin t, bt)$.
3. The curve $\alpha : \mathbb{R} \rightarrow \mathbb{R}^3$ defined by $\alpha(t) = (1 + \cos t, \sin t, 2 \sin(t/2))$.
4. The curve $\alpha : \mathbb{R} \rightarrow \mathbb{R}^3$ defined by $\alpha(t) = (e^t, e^{-t}, \sqrt{2}t)$.
5. The curve $\alpha : \mathbb{R} \rightarrow \mathbb{R}^3$ defined by $\alpha(t) = (3t - t^3, 3t^2, 3t + t^3)$.

Definition 1.12. Let $\alpha : I \rightarrow \mathbb{R}^3$ be a curve with $\alpha = (\alpha_1, \alpha_2, \alpha_3)$. For all $t \in I$, the *velocity vector* of α at t is the tangent vector $\alpha'(t) = ((d\alpha_1/dt)(t), (d\alpha_2/dt)(t), (d\alpha_3/dt)(t))_{\alpha(t)}$ at the point $\alpha(t) \in \mathbb{R}^3$. The curve α is said to be *regular* if $\alpha_i \neq 0$ for all i .

Consider the velocity vector $\alpha'(t)$, we can rewrite it by the natural frame fields, so $\alpha'(t) = \sum (d\alpha_i/dt)(t) U_i(\alpha(t))$.

Definition 1.13. Let $\alpha : I \rightarrow \mathbb{R}^3$ be a curve and let $h : J \rightarrow I$ be differentiable, where J is an open interval of \mathbb{R} . The *reparametrization* of α by h is the composition $\alpha \circ h : J \rightarrow \mathbb{R}^3$.

The composition of differentiable functions is differentiable, so any reparametrization is differentiable, which means it is a curve.

Proposition. Let β be the reparametrization of α by h , then $\beta'(s) = (dh/ds)(s) \alpha'(h(s))$.

Proof. Rewrite $\beta(s) = \alpha(h(s))$, then we have $\beta'(s) = (d(\alpha_i h_i)/ds)(s)_{\alpha(h(s))} = (d\alpha_i/ds)(h(s)) \cdot (dh/ds)(s)_{\alpha(h(s))} = (dh/ds)(s) \alpha'(h(s))$. \square

Proposition. Let α be a curve and let f be a differentiable function on \mathbb{R}^3 , then $\alpha'(t)[f] = (d(f\alpha)/dt)(t)$.

Proof. We have $\alpha'(t)[f] = \sum (d\alpha_i/dt)(t) \cdot (\partial f/\partial x_i)(\alpha(t)) = (d(f\alpha)/dt)(t)$ by the chain rule. \square

Now we show a general idea of parametrizations. The proofs will be included in other sections when we have enough tools. Assume every result is correct for now.

Definition 1.14. A *1-form* φ on \mathbb{R}^3 is a function $\varphi : \coprod_{p \in \mathbb{R}^3} T_p(\mathbb{R}^3) \rightarrow \mathbb{R}$ such that for all $a, b \in \mathbb{R}$ and $v, w \in T_p(\mathbb{R}^3)$ for some $p \in \mathbb{R}^3$, $\varphi(av + bw) = a\varphi(v) + b\varphi(w)$.

Given a 1-form φ , for any point p , denote the restriction $\varphi|_{T_p(\mathbb{R}^3)} : T_p(\mathbb{R}^3) \rightarrow \mathbb{R}$ by φ_p , then φ_p is linear. Let φ and ψ be 1-forms. Define the addition and scalar multiplication by $(\varphi + \psi)(v) = \varphi(v) + \psi(v)$ and $(f\varphi)(v_p) = f(p)\varphi(v_p)$. Given any 1-form φ and point p , φ_p is a linear functional in $T_p^*(\mathbb{R}^3)$, the dual space of $T_p(\mathbb{R}^3)$.

Definition 1.15. Let φ be a 1-form and let V be a vector field. For all $p \in \mathbb{R}^3$, define $\varphi(V)(p) = \varphi_p(V(p))$. We say φ is *differentiable* if for every differentiable vector field V , the function $\varphi(V)$ is differentiable.

Now let V and W be vector fields, we have $\varphi(fV + gW)(p) = \varphi((fV + gW)(p)) = \varphi(fV(p) + gW(p)) = (f\varphi(V) + g\varphi(W))(p)$. Similarly, $(f\varphi + g\psi)(V) = f\varphi(V) + g\psi(V)$.

Definition 1.16. If $f : \mathbb{R}^3 \rightarrow \mathbb{R}$ is differentiable. The *differential* of f , denoted df , is the function $df(v_p) = v_p[f]$ for all tangent vectors v_p .

Let $v_p, w_p \in T_p(\mathbb{R}^3)$ and let $a, b \in \mathbb{R}$, then $df(av_p + bw_p) = (av_p + bw_p)[f] = av_p[f] + bw_p[f] = a df(v_p) + b df(w_p)$. Hence df is a 1-form.

Example. Consider the natural coordinate functions x_i . We have $dx_i(v_p) = v_p[x_i] = \sum v_i(\partial x_i/\partial x_j)(p) = v_i$.

Proposition. If φ is a 1-form on \mathbb{R}^3 , then $\varphi = \sum f_i dx_i$, where $f_i = \varphi(U_i)$.

Proof. Let $v_p \in T_p(\mathbb{R}^3)$, then $\varphi(v_p) = \varphi(\sum v_i U_i(p)) = \sum v_i \varphi(U_i(p)) = \sum v_i f_i(p) = \sum f_i(p) dx_i(v_p) = (\sum f_i dx_i)(v_p)$, hence $\varphi = \sum f_i dx_i$. \square

The functions f_1, f_2 , and f_3 are called the *Euclidean coordinate functions* of the 1-form φ .

Proposition. Let f be a differentiable function on \mathbb{R}^3 , then $df = \sum(\partial f/\partial x_i)dx_i$.

Proof. Let $v_p \in T_p(\mathbb{R}^3)$, then $df(v_p) = v_p[f] = \sum v_i(\partial f/\partial x_i)(p) = \sum(\partial f/\partial x_i)(p)dx_i(v_p) = (\sum(\partial f/\partial x_i)dx_i)(v_p)$, hence $df = \sum(\partial f/\partial x_i)dx_i$. \square

Let f and g be differentiable functions on \mathbb{R}^3 , then $d(f+g) = \sum(\partial(f+g)/\partial x_i)dx_i = \sum(\partial f/\partial x_i)dx_i + \sum(\partial g/\partial x_i)dx_i = df + dg$. Now we denote the multiplication to be fg .

Proposition. Let f and g be differentiable functions on \mathbb{R}^3 , then $d(fg) = gdf + f dg$.

Proof. We have $d(fg) = \sum(\partial(fg)/\partial x_i)dx_i = \sum((\partial f/\partial x_i)g + (\partial g/\partial x_i)f)dx_i = gdf + f dg$. \square

Proposition. Let $f : \mathbb{R}^3 \rightarrow \mathbb{R}$ and $h : \mathbb{R} \rightarrow \mathbb{R}$ be differentiable, then $d(h(f)) = (dh(f)/dx)df$.

Proof. We have $d(h(f)) = \sum(\partial h(f)/\partial x_i)dx_i$, by the chain rule, $(\partial h(f)/\partial x_i)dx_i = (dh(f)/df)(\partial x/\partial x_i)$, so $d(h(f)) = (dh(f)/df)df$. \square

Example. Consider the function $f = (x^2 - 1)y + (y^2 + 2)z$. We have $df = d((x^2 - 1)y) + d((y^2 + 2)z) = yd(x^2 - 1) + (x^2 + 1)dy + zd(y^2 + 2) + (y^2 + 2)dz = 2xydx + (x^2 + 2yz - 1)dy + (y^2 + 2)dz$. Since $v_p[f] = df(v_p)$, $v_p[f] = 2p_1p_2v_1 + (p_1^2 + 2p_2p_3 - 1)v_2 + (p_2^2 + 2)v_3$.

Let V be the vector space \mathbb{R}^3 and denote the space of all k -linear forms on V by $\Lambda^k(V^*)$.

More generally, $\Lambda^k(V^*)$

- 2 Frame Fields
- 3 Euclidean Geometry
- 4 Calculus on a Surface
- 5 Shape Operators
- 6 Geometry of Surfaces in \mathbb{R}^3
- 7 Riemannian Geometry
- 8 Global Structure of Surfaces

Exercises and Proofs

Exercise 1.1.1. Let $f = x^2y$ and $g = y \sin z$ be functions on \mathbb{R}^3 . Express the following functions in terms of x , y , and z : fg^2 , $\frac{\partial f}{\partial x}g + \frac{\partial g}{\partial y}f$, $\frac{\partial^2(fg)}{\partial y \partial z}$, and $\frac{\partial}{\partial y}(\sin f)$.

Proof. (i) We have $fg^2 = x^2yy^2\sin^2z = x^2y^3\sin^2z$. (ii) We have $\partial f/\partial x = 2xy$ and $\partial g/\partial y = \sin z$, then $\frac{\partial f}{\partial x}g + \frac{\partial g}{\partial y}f = 2xy^2\sin z + x^2y\sin z$. (iii) We have $fg = x^2y^2\sin z$, then $\frac{\partial^2(fg)}{\partial y \partial z} = 2x^2y\cos z$. (iv) We have $\sin f = \sin(x^2y)$, then $\frac{\partial}{\partial y}(\sin f) = x^2\cos(x^2y)$. \square

Exercise 1.1.3. Express $\partial f/\partial x$ in terms of x , y , and z for the following functions.

1. $f = x \sin(xy) + y \cos(xz)$;
2. $f = \sin g$, $g = e^h$, and $h = x^2 + y^2 + z^2$.

Proof. (i) We have $\frac{\partial f}{\partial x} = \frac{\partial(x \sin(xy))}{\partial x} + \frac{\partial(y \cos(xz))}{\partial x} = \sin(xy) + xy \cos(xy) - yz \sin(xz)$. (ii) We have $f = \sin(e^{x^2+y^2+z^2})$, then $\frac{\partial f}{\partial x} = 2x \cos(e^{x^2+y^2+z^2})e^{x^2+y^2+z^2}$. \square

Exercise 1.2.1. Let $v = (-2, 1, -1)$ and $w = (0, 1, 3)$. At an arbitrary point p , express the tangent vector $3v_p - 2w_p$ as a linear combination of $U_1(p)$, $U_2(p)$, and $U_3(p)$.

Proof. We have $3v_p - 2w_p = (-6, 1, -9)_p = -6U_1(p) + U_2(p) - 9U_3(p)$. \square

Exercise 1.2.3. Let $p = (p_1, p_2, p_3)$. In each case, express the given vector field V in the standard form $\sum v_i U_i$.

1. $2z^2U_1 = 7V + xyU_3$.
2. $V(p) = (p_1, p_3 - p_1, 0)_p$ for all p .
3. $V = 2(xU_1 + yU_2) - x(U_1 - y^2U_3)$.
4. For all $p \in \mathbb{R}^3$, $V(p)$ is the vector from (p_1, p_2, p_3) to $(1 + p_1, p_2p_3, p_2)$.
5. For all $p \in \mathbb{R}^3$, $V(p)$ is the vector from p to 0.

Proof. (i) We have $V = (2z^2U_1 - xyU_3)/7$. For all $p \in \mathbb{R}^3$, $V(p) = ((2z^2, 0, 0) - (0, 0, xy))/7 = (2z^2/7, 0, -xy/7)$, so $(v_i) = (2z^2/7, 0, -xy/7)$. (ii) Here $V(p) = xU_1 + (z - x)U_2 + 0U_3$. \square

Exercise 1.2.5. Let $V_1 = U_1 - xU_3$, $V_2 = U_2$, and $V_3 = xU_1 + U_3$. Prove that the vectors $V_1(p)$, $V_2(p)$, $V_3(p)$ are linearly independent at each $p \in \mathbb{R}^3$. Express the vector field $xU_1 + yU_2 + zU_3$ as a linear combination of V_i .

Proof. For all $p \in \mathbb{R}^3$, we have $V_1(p) = U_1(p) - xU_3(p) = (1, 0, -x)$. Similarly, $V_2(p) = (0, 1, 0)$ and $V_3 = (x, 0, 1)$. Consider $aV_1(p) + bV_2(p) + cV_3(p) = 0$, where $a, b, c \in \mathbb{R}$. Solve for (a, b, c) , then $c(x^2 + 1) = 0$, so $c = 0$. Now $(a, b, c) = (0, 0, 0)$, hence $V_i(p)$ are linearly independent. For all $p \in \mathbb{R}^3$, $aV_1(p) + bV_2(p) + cV_3(p) = (a + cx, b, c - a)$ and $xU_1(p) + yU_2(p) + zU_3(p) = (x, y, z)$. Solve $(a + cx, b, c - a) = (x, y, z)$, then $(a, b, c) = ((x - zx)/(1 + x^2), y, (x^2 + z)/(1 + x^2))$. \square

Exercise 1.3.1. Let v_p be the tangent vector with $v = (2, -1, 3)$ and $p = (2, 0, -1)$. Use the definition to compute the directional derivative for the following functions.

1. $f = y^2z$.
2. $f = x^7$.
3. $f = e^x \cos y$.

Proof. We have $p + tv = (2 + 2t, -t, 3t - 1)$. (i) Now $f(p + tv) = 3t^3 - t^2$, then $v_p[f] = 9t^2 - 2t = 0$. (ii) Now $f(p + tv) = (2 + 2t)^7$, then $v_p[f] = 7(2 + 2t)^6 \cdot 2 = 14(2 + 2t)^6 = 7 \cdot 2^7$. (iii) Now $f(p + tv) = e^{2+2t} \cos(-t)$, then $v_p[f] = e^{2+2t} \sin(-t) + 2e^{2+2t} \cos(-t) = 2e^2$. \square

Exercise 1.3.3. Let $V = y^2U_1 - xU_3$. Let $f = xy$ and let $g = z^3$. Compute the following functions.

1. $V[f]$.

2. $V[g]$.
3. $V[fg]$.
4. $fV[g] - gV[f]$.
5. $V[f^2 + g^2]$.
6. $V[V[f]]$.

Proof. (i) We have $V[f] = y^2U_1[xy] - xU_3[xy] = y^3$. (ii) We have $V[g] = y^2U_1[z^3] - xU_3[z^3] = -3xz^2$. (iii) We have $V[fg] = V[f]g + fV[g] = y^3z^3 - 3x^2yz^2$. (iv) We have $fV[g] - gV[f] = -3x^2yz^2 - y^3z^3$. (v) We have $V[f^2 + g^2] = V[f^2] + V[g^2] = V[f]f + fV[f] + V[g]g + gV[g] = 2xy^4 - 6xz^5$. (vi) We have $V[V[f]] = V[y^3] = y^2U_1[y^3] - xU_3[y^3] = 0$. \square

Exercise 1.3.5. If $V[f] = W[f]$ for all f on \mathbb{R}^3 , prove that $V = W$.

Proof. Let $V = \sum a_i U_i$ and let $W = \sum b_i U_i$. Since $V[f] = W[f]$, $(V - W)[f] = \sum (a_i - b_i) \frac{\partial f}{\partial x_i} = 0$. Pick $f = x$, then $a_1 = b_1$. Similarly, if we pick $f = y$ and $f = z$, we have $a_2 = b_2$ and $a_3 = b_3$. Hence $V = W$. \square

Alphabetical Index

1-form, 3

curve, 2

differentiable, 1–3

differential, 3

directional derivative, 2

Euclidean 3-space, 1

Euclidean coordinate functions,
2, 3

natural coordinate functions, 1

natural frame field, 1

open, 1

origin, 1

parallel, 1

point, 1

point of application, 1

regular, 3

reparametrization, 3

straight line, 2

tangent space, 1

tangent vector, 1

vector field, 1

vector part, 1

velocity vector, 3