Chapter 1: Curves

Author: Meng-Gen Tsai
Email: plover@gmail.com

Section 1-1: Introduction

Classical differential geometry: the study of local properties of curves and surfaces.

Global differential geometry: the study of the influence of the local properties on the behavior of the entire curve and surface.

No exercises.

Section 1-2: Parametrized Curves

Exercise 1-2.1. *Find a parametrized curve $\alpha(t)$ whose trace is the circle $x^2 + y^2 = 1$ such that $\alpha(t)$ runs clockwise around the circle with $\alpha(0) = (0, 1)$.*

Proof. $\alpha(t) = (\sin t, \cos t)$, $t \in \mathbb{R}$. □

Exercise 1-2.2. *Let $\alpha(t)$ be a parametrized curve which does not pass through the origin. If $\alpha(t_0)$ is the point of the trace of α closest to the origin and $\alpha'(t_0) \neq 0$, show that the position vector $\alpha(t_0)$ is orthogonal to $\alpha'(t_0)$.*

Proof. Let $f(t) = |\alpha(t)|^2 = \alpha(t) \cdot \alpha(t)$. $f(t)$ is differentiable and $f(t)$ has a local minimum at a point $t = t_0 \in I$. So $f'(t_0) = 0$. [Theorem 5.8 in W. Rudin, Principles of Mathematical Analysis, 3rd edition.] Since

$$f'(t) = 2\alpha(t) \cdot \alpha'(t),$$

$f'(t_0) = 2\alpha(t_0) \cdot \alpha'(t_0) = 0$, or $\alpha(t_0) \cdot \alpha'(t_0) = 0$. Since $\alpha(t_0) \neq 0$ and $\alpha'(t_0) \neq 0$, $\alpha(t_0)$ is orthogonal to $\alpha'(t_0)$. □

Exercise 1-2.3. *A parametrized curve $\alpha(t)$ has a property that its second derivative $\alpha''(t)$ is identically zero. What can be said about α?*

$\alpha(t)$ is a straight line.

Proof. Since $\alpha''(t)$ is identically zero, $\alpha'(t) = a$ is a constant. [Theorem 5.11 in W. Rudin, Principles of Mathematical Analysis, 3rd edition.] Define

$f(t) = \alpha(t) - at$ (on I). Since $f'(t) = \alpha'(t) - a = 0$, $f(t) = \alpha(t) - at = b$ is a constant again. Therefore, $\alpha(t) = at + b$, which is a straight line (on I). $\square$

Exercise 1-2.4. *Let $\alpha : I \to \mathbb{R}^3$ be a parametrized curve and let $v \in \mathbb{R}^3$ be a fixed vector. Assume that $\alpha'(t)$ is orthogonal to v for all $t \in I$ and that $\alpha(0)$ is orthogonal to v. Prove that $\alpha(t)$ is orthogonal to v for all $t \in I$.*

Need to assume that $\alpha(t) \neq 0$ for all $t \in I$.

Proof. Given any $t \neq 0 \in I$. (Nothing to do at $t = 0$.) Define $f : I \to \mathbb{R}$ by $f(t) = \alpha(t) \cdot v$. By the mean value theorem, there exists a point ξ between 0 and t such that

$$f(t) - f(0) = f'(\xi)(t - 0),$$

where $f'(t) = \alpha'(t) \cdot v + \alpha(t) \cdot v' = \alpha'(t) \cdot v$. Note that $f(0) = 0$ since $\alpha(0)$ is orthogonal to v, and $f'(\xi) = 0$ since $\alpha'(t)$ is orthogonal to v. So the identity is reduced to

$$f(t) = 0,$$

or $\alpha(t) \cdot v = 0$, or $\alpha(t)$ is orthogonal to v. $\square$

Exercise 1-2.5. *Let $\alpha : I \to \mathbb{R}^3$ be a parametrized curve, with $\alpha'(t) \neq 0$ for all $t \in I$. Show that $|\alpha(t)|$ is a nonzero constant if and only if $\alpha(t)$ is orthogonal to $\alpha'(t)$ for all $t \in I$.*

The same trick in Exercise 1-2.2.

Proof. It is equivalent to *show that $|\alpha(t)|^2$ is a nonzero constant if and only if $\alpha(t)$ is orthogonal to $\alpha'(t)$ for all $t \in I$.* Let

$$f(t) = |\alpha(t)|^2 = \alpha(t) \cdot \alpha(t).$$

Notice that $\alpha'(t) \neq 0$, and thus

$$\begin{aligned}
&|\alpha(t)| \text{ is a nonzero constant} \\
\Longleftrightarrow\, &f(t) = |\alpha(t)|^2 \text{ is a nonzero constant} \\
\Longleftrightarrow\, &f'(t) = 0 \text{ and } f(t) \text{ is a nonzero constant} \\
\Longleftrightarrow\, &\alpha(t) \cdot \alpha'(t) = 0 \text{ and } \alpha(t) \text{ is a nonzero constant} \\
\Longleftrightarrow\, &\alpha(t) \text{ is orthogonal to } \alpha'(t) \text{ for all } t \in I.
\end{aligned}$$

$\square$

Section 1-3: Regular Curves; Arc Length

Exercise 1-3.1. *Show that the tangent lines to the regular parametrized curve $\alpha(t) = (3t, 3t^2, 2t^3)$ make a constant angle with the line $y = 0$, $z = x$.*

Proof. $\alpha'(t) = (3, 6t, 6t^2)$. The line $y = 0$, $z = x$ is $\beta(t) = (1, 0, 1)$. The cosine of the angle θ between these to curves is

$$\begin{aligned}
\cos\theta &= \frac{(3, 6t, 6t^2) \cdot (1, 0, 1)}{|(3, 6t, 6t^2)||(1, 0, 1)|} \\
&= \frac{3 + 6t^2}{\sqrt{3^2 + (6t)^2 + (6t^2)^2}\sqrt{2}} \\
&= \frac{3 + 6t^2}{\sqrt{9 + 36t^2 + 36t^4}\sqrt{2}} \\
&= \frac{3 + 6t^2}{\sqrt{(3 + 6t^2)^2}\sqrt{2}} \\
&= \frac{1}{\sqrt{2}}.
\end{aligned}$$

(Notice $3 + 6t^2 > 0$ for all $t \in \mathbb{R}$.) That is, the angle between α' and β is a constant $(= \pi/4)$. □

Exercise 1-3.2. *A circular disk of radius* 1 *in the plane xy rolls without slipping along the x axis. The figure described by a point of the circumference of of the disk is called a* ***cycloid*** *(Figure 1-7 in Mantredo P. do Carmo, Differential Geometry of Curves and Surfaces).*

(a) *Obtain a parametrized curve $\alpha : \mathbb{R} \to \mathbb{R}^2$ the trace of which is the cycloid and determine its singular points.*

(b) *Compute the arc length of the cycloid corresponding to a complete rotation of the disk.*

Proof of (a).

(1) Since

$$\begin{cases} x = t - \sin t \\ y = 1 - \cos t, \end{cases}$$

we define $\alpha(t) = (t - \sin t, 1 - \cos t)$.

(2) $\alpha'(t) = (1 - \cos t, \sin t)$. $\alpha'(t) = 0$ if and only if $t = 2n\pi$ where $n \in \mathbb{Z}$. That is, all singular points are $\alpha(2n\pi) = (2n\pi, 0)$ where $n \in \mathbb{Z}$.

□

Proof of (b). The arc length of the cycloid corresponding to a complete rotation of the disk is

$$\begin{aligned}
\int_0^{2\pi} |\alpha'(t)|dt &= \int_0^{2\pi} \sqrt{(1-\cos t)^2 + (\sin t)^2}dt \\
&= \int_0^{2\pi} \sqrt{2}\sqrt{1-\cos t}dt \\
&= \int_0^{2\pi} 2\sin\frac{t}{2}dt \\
&= \left[-4\cos\frac{t}{2}\right]_{t=0}^{t=2\pi} \\
&= 8.
\end{aligned}$$

□

Supplement. The cycloid is not an algebraic curve.

Exercise 1-3.4. *Let $\alpha : (0, \pi) \to \mathbb{R}^2$ be given by*

$$\alpha(t) = \left(\sin t, \cos t + \log\tan\frac{t}{2}\right),$$

where t is the angle that the y axis makes with the vector $\alpha(t)$. The trace of α is called the ***tractrix****. (Figure 1-9 in Mantredo P. do Carmo, Differential Geometry of Curves and Surfaces). Show that*

(a) *α is a differentiable parametrized curve, regular except at $t = \frac{\pi}{2}$.*

(b) *The length of the segment of the tangent of the tractrix between the point of tangency and the y axis is constantly equal to 1.*

Proof of (a).

$$\begin{aligned}
\alpha'(t) &= \left(\cos t, -\sin t + \frac{1}{\tan\frac{t}{2}}\frac{1}{\cos^2\frac{t}{2}}\frac{1}{2}\right) \\
&= \left(\cos t, -\sin t + \frac{1}{2\sin\frac{t}{2}\cos\frac{t}{2}}\right) \\
&= \left(\cos t, \frac{\cos^2 t}{\sin t}\right)
\end{aligned}$$

exists. And $\alpha'(t) = 0$ if and only if $t = \frac{\pi}{2}$. That is, there is an unique singular point at $t = \frac{\pi}{2}$. □

Proof of (b). The the tangent line of the tractrix through the regular point t is parametrized by $\beta : \mathbb{R} \to \mathbb{R}^2$ which is defined by

$$\begin{aligned}\beta(u) &= u\alpha'(t) + \alpha(t) \\ &= \left(u \cos t + \sin t, u\frac{\cos^2 t}{\sin t} + \cos t + \log \tan \frac{t}{2}\right).\end{aligned}$$

By construction, this tangent line $\beta(u)$ meets the tractrix at $u = 0$, and meets the y-axis when $u \cos t + \sin t = 0$ or $u = -\tan t$. So the length of the segment is

$$\begin{aligned}|\beta(0) - \beta(-\tan t)| &= \sqrt{(-\tan t \cos t)^2 + \left(-\tan t\frac{\cos^2 t}{\sin t}\right)^2} \\ &= \sqrt{(\sin t)^2 + (\cos t)^2} \\ &= 1.\end{aligned}$$

□

Exercise 1-3.10. *(Straight Lines as Shortest.) Let $\alpha : I \to \mathbb{R}^3$ be a parametrized curve. Let $[a, b] \subseteq I$ and set $\alpha(a) = p$, $\alpha(b) = q$.*

(a) *Show that, for any constant vector v, $|v| = 1$,*

$$(q - p) \cdot v = \int_a^b \alpha'(t) \cdot v dt \leq \int_a^b |\alpha'(t)|dt.$$

(b) *Set*

$$v = \frac{q - p}{|q - p|}$$

and show that

$$|\alpha(b) - \alpha(a)| \leq \int_a^b |\alpha'(t)|dt;$$

that is, the curve of shortest length from $\alpha(a)$ to $\alpha(b)$ is the straight line joining these points.

Assume $p \neq q$ (otherwise $v = \frac{q-p}{|q-p|}$ is meaningless).

Proof of (a). Let $f(t) = \alpha(t) \cdot v$ defined on I. By the fundamental theorem of calculus,

$$\int_a^b f'(t)dt = f(b) - f(a).$$

Since $f'(t) = \alpha'(t) \cdot v$,

$$(\alpha(b) - \alpha(a)) \cdot v = \int_a^b \alpha'(t) \cdot v dt.$$

Therefore,

$$\begin{aligned}(q-p)\cdot v &= \int_a^b \alpha'(t)\cdot v dt\\ &\leq \int_a^b |\alpha'(t)\cdot v| dt\\ &\leq \int_a^b |\alpha'(t)||v| dt\\ &= \int_a^b |\alpha'(t)| dt.\end{aligned}$$

□

Proof of (b). $|v| = \frac{|q-p|}{|q-p|} = 1$. So,

$$\begin{aligned}(q-p)\cdot \frac{q-p}{|q-p|} &\leq \int_a^b |\alpha'(t)| dt,\\ |q-p| &\leq \int_a^b |\alpha'(t)| dt.\end{aligned}$$

□

Section 1-4: The Vector Product in $\mathbb{R}^3$

Exercise 1-4.13. *Let $u(t) = (u_1(t), u_2(t), u_3(t))$ and $v(t) = (v_1(t), v_2(t), v_3(t))$ be differentiable maps from the interval (a, b) into $\mathbb{R}^3$. If the derivatives $u'(t)$ and $v'(t)$ satisfy the conditions*

$$u'(t) = au(t) + bv(t), v'(t) = cu(t) - av(t),$$

where a, b, and c are constants, show that $u(t) \wedge v(t)$ is a constant vector.

Proof. Since

$$\begin{aligned}\frac{d}{dt}(u(t)\wedge v(t)) &= u'(t)\wedge v(t) + u(t)\wedge v'(t)\\ &= (au(t) + bv(t))\wedge v(t) + u(t)\wedge(cu(t) - av(t))\\ &= au(t)\wedge v(t) + u(t)\wedge(-av(t))\\ &= a(u(t)\wedge v(t)) + (-a)(u(t)\wedge v(t))\\ &= (0, 0, 0),\end{aligned}$$

$u(t)\wedge v(t)$ is a constant vector. □

Section 1-5: The Local Theory of Curves Parametrized by Arc Length

Exercise 1-5.2. *Show that the torsion τ of α is given by*

$$\tau(s) = -\frac{\alpha'(s) \wedge \alpha''(s) \cdot \alpha'''(s)}{|\kappa(s)|^2}.$$

Proof.

(1) Take inner product $n(s)$ to the definition of torsion $\tau(s)n(s) = b'(s)$, we have

$$\tau(s) = b'(s) \cdot n(s).$$

Since $b'(s) = t(s) \wedge n'(s)$, we have to compute $n'(s)$ first.

(2) Compute $n'(s)$.

$$n'(s) = \frac{d}{ds}\left(\frac{\alpha''(s)}{\kappa(s)}\right) = \frac{\alpha'''(s)}{\kappa(s)} - \frac{\alpha''(s)\kappa'(s)}{\kappa(s)^2}.$$

(3) By (1)(2),

$$\begin{aligned}
\tau(s) &= b'(s) \cdot n(s) \\
&= (t(s) \wedge n'(s)) \cdot n(s) \\
&= \left(\alpha'(s) \wedge \left(\frac{\alpha'''(s)}{\kappa(s)} - \frac{\alpha''(s)\kappa'(s)}{\kappa(s)^2}\right)\right) \cdot \frac{\alpha''(s)}{\kappa(s)} \\
&= \left(\alpha'(s) \wedge \frac{\alpha'''(s)}{\kappa(s)}\right) \cdot \frac{\alpha''(s)}{\kappa(s)} \\
&= \frac{\alpha'(s) \wedge \alpha'''(s) \cdot \alpha''(s)}{|\kappa(s)|^2},
\end{aligned}$$

or

$$\tau(s) = \frac{\alpha'(s) \wedge \alpha'''(s) \cdot \alpha''(s)}{\alpha''(s)^2}.$$

□

Section 1-6: The Local Canonical Form

Section 1-7: Global Properties of Plane Curves