

ESC 195 Lecture Notes

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ESC 195

The up-to-date version of this document can be found at <https://github.com/HaysonC/skulenotes>

1 More on Integrals

1.1 Riemann Sum - Non-Uniform Partition

Example 1.1.1. Given the following definite integral:

$$\int_0^2 \sqrt{x} dx$$

, we cannot evaluate its Riemann sum with uniform partition, since the series of root cannot be easily evaluated.

The definite integral of \sqrt{x} from 0 to 2 using a Riemann sum with a non-uniform partition is given by:

$$\int_0^2 \sqrt{x} dx = \lim_{n \rightarrow \infty} \sum_{i=1}^n \sqrt{x_i} \Delta x_i$$

where:

- $x_0 = 0, x_n = 2$,
- $x_i = i^2 \cdot \frac{2}{n^2}$ for $i = 0, 1, 2, \dots, n$,
- $\Delta x_i = x_i - x_{i-1} = \frac{2}{n^2} \cdot (2i - 1)$.

The Riemann sum becomes:

$$S_n = \sum_{i=1}^n \sqrt{i^2 \cdot \frac{2}{n^2}} \cdot \frac{2}{n^2} \cdot (2i - 1).$$

Simplifying further:

$$S_n = \sum_{i=1}^n \sqrt{\frac{2i^2}{n^2}} \cdot \frac{2}{n^2} \cdot (2i - 1).$$

Taking the limit as $n \rightarrow \infty$, the sum converges to the exact value of the integral using the series of squares.

$$\int_0^2 \sqrt{x} dx = \frac{4\sqrt{2}}{3}.$$

Condition $n \rightarrow \infty$ Ensures $\Delta x_i \rightarrow 0$

As $n \rightarrow \infty$, the partition points x_i become increasingly dense. This ensures that the partition becomes infinitely fine.

1.2 Integration By Parts

Using the product rule:

$$\frac{d}{dx}[u(x)v(x)] = u'(x)v(x) + u(x)v'(x),$$

integrating both sides with respect to x gives:

$$u(x)v(x) = \int u'(x)v(x) dx + \int u(x)v'(x) dx.$$

Rearranging this:

$$\int u'(x)v(x) dx = u(x)v(x) - \int u(x)v'(x) dx.$$

Integration by parts formula

$$\int u dv = uv - \int v du. \tag{1}$$

Example 1.2.1. We want to solve the integral

$$\int x e^{2x} dx$$

using integration by parts.

Let:

$$u = x, \quad dv = e^{2x} dx.$$

Then, we compute the derivatives and integrals:

$$du = dx, \quad v = \frac{e^{2x}}{2}.$$

Now, apply the integration by parts formula:

$$\int u dv = uv - \int v du.$$

Substituting in the values:

$$\int x e^{2x} dx = x \cdot \frac{e^{2x}}{2} - \int \frac{e^{2x}}{2} dx.$$

1.2 Integration By Parts

Next, compute the remaining integral:

$$\int \frac{e^{2x}}{2} dx = \frac{e^{2x}}{4}.$$

Thus, the result is:

$$\int x e^{2x} dx = \frac{x e^{2x}}{2} - \frac{e^{2x}}{4} + C.$$

Example 1.2.2. We want to solve

$$\int x^2 \sin(2x) dx$$

using double integration by parts.

First, let:

$$u = x^2, \quad dv = \sin(2x) dx.$$

Then:

$$du = 2x dx, \quad v = -\frac{1}{2} \cos(2x).$$

Using the IBP formula:

$$\int u dv = uv - \int v du,$$

we get:

$$\int x^2 \sin(2x) dx = -\frac{x^2}{2} \cos(2x) + \int x \cos(2x) dx.$$

Now, apply IBP again to $\int x \cos(2x) dx$, let:

$$u = x, \quad dv = \cos(2x) dx.$$

Then:

$$du = dx, \quad v = \frac{1}{2} \sin(2x).$$

Using the IBP formula again:

$$\int x \cos(2x) dx = \frac{x}{2} \sin(2x) - \int \frac{1}{2} \sin(2x) dx,$$

and solving the remaining integral:

$$\int \frac{1}{2} \sin(2x) dx = -\frac{1}{4} \cos(2x).$$

Thus, the final result is:

$$\int x^2 \sin(2x) dx = -\frac{x^2}{2} \cos(2x) + \frac{x}{2} \sin(2x) + \frac{1}{4} \cos(2x) + C.$$

1.3 Trigonometric Integrals

Case I This is the case I trigonometric integrals, the strategy is using the pythagorean identity.

We want to solve the class of integrals:

$$\int \sin^n(x) \cos^m(x) dx \quad (2)$$

, where m or n is odd.

Example 1.3.1. We want to solve the integral:

$$I = \int \sin^3(x) \cos^2(x) dx$$

We use the identity: $\sin^2(x) = 1 - \cos^2(x)$. Thus, the integral becomes:

$$\begin{aligned} I &= \int \sin(x)(1 - \cos^2(x)) \cos^2(x) dx \\ &= \int (\cos^2(x) \sin(x) - \cos^4(x) \sin(x)) dx \end{aligned}$$

which is now easily solvable with substitution $u = \cos(x)$.

Case II The follwoing is generally solvable via case I and case III below. In general, we solve the integral by reducing the power of the trigonometric functions to arrive at a solvable integral Case I or III.

We want to solve the class of integrals:

$$\int \sin^n(x) \cos^m(x) dx \quad (3)$$

, where m and n is even.

Example 1.3.2. We want to solve the integral:

$$I = \int \sin^2(x) \cos^4(x) dx$$

We can apply the double angle formulas:

$$\sin(x) \cos(x) = \frac{1}{2} \sin(2x) \quad (4)$$

$$\sin^2(x) = \frac{1 - \cos(2x)}{2} \quad (5)$$

$$\cos^2(x) = \frac{1 + \cos(2x)}{2} \quad (6)$$

Thus, the integral becomes:

$$I = \frac{1}{8} \int \sin^2(2x) dx + \frac{1}{8} \int \cos(2x) \sin^2(2x) dx$$

1.3 Trigonometric Integrals

Case III This is the case III trigonometric integrals, the strategy is using the reduction formula via IBP.

Reduction Formula We can solve integrals by reducing the power of the trigonometric functions. These are done using IBP and trigonometric identities.

We want to solve the classes of integrals:

$$\int \sin^n(x) dx, \quad \int \cos^n(x) dx \quad (7)$$

, where n is a positive integer. For demonstration, We can obtain the reduction formula of $\sin^n(x)$ via IBP.

$$\begin{aligned} I_n &= \int \sin^n(x) dx \\ &= \int \sin^{n-1}(x) \sin(x) dx \\ &= \frac{-\cos(x) \sin^{n-1}(x)}{n} + \frac{(n-1)}{n} \int \cos^2(x) \sin^{n-2}(x) dx \\ &= \frac{-\cos(x) \sin^{n-1}(x)}{n} + \frac{(n-1)}{n} I_{n-2} \end{aligned} \quad (8)$$

Reduction for $\cos^n(x)$ We can obtain the reduction formula of $\cos^n(x)$ via IBP.

$$\begin{aligned} I_n &= \int \cos^n(x) dx \\ &= \int \cos^{n-1}(x) \cos(x) dx \\ &= \frac{\sin(x) \cos^{n-1}(x)}{n} + \frac{(n-1)}{n} \int \sin^2(x) \cos^{n-2}(x) dx \\ &= \frac{\sin(x) \cos^{n-1}(x)}{n} + \frac{(n-1)}{n} I_{n-2} \end{aligned} \quad (9)$$

Case IV The following is generally solvable via simple trigonometric integrals. In general, we solve the integral by applying the angle sum formulas.

We want to solve the classes of integrals:

$$\int \sin(mx) \cos(nx) dx, \quad \int \sin(mx) \sin(nx) dx, \quad \int \cos(mx) \cos(nx) dx \quad (10)$$

1.3 Trigonometric Integrals

We could apply the angle sum formulas:

$$\sin(mx) \cos(nx) = \frac{1}{2} [\sin((m+n)x) + \sin((m-n)x)] \quad (11)$$

$$\sin(mx) \sin(nx) = \frac{1}{2} [\cos((m-n)x) - \cos((m+n)x)] \quad (12)$$

$$\cos(mx) \cos(nx) = \frac{1}{2} [\cos((m-n)x) + \cos((m+n)x)] \quad (13)$$

Case V The following is generally solvable via the following trigonometric identities listed below, which convert it into a reduction formula.

$$\tan^2(x) = \sec^2(x) - 1 \quad (14)$$

$$\cot^2(x) = \csc^2(x) - 1 \quad (15)$$

$$\frac{d}{dx} \tan(x) = \sec^2(x) \quad (16)$$

We want to solve the classes of integral:

$$\int \tan^n(x) dx, \quad \int \cot^n(x) dx \quad (17)$$

We know that $\tan^2(x) = \sec^2(x) - 1$. Thus, we can solve the integral by reducing the power of the tangent function.

Reduction for $\tan^n(x)$ We can obtain the reduction formula of $\tan^n(x)$ via the trigonometric identities.

$$\begin{aligned} I_n &= \int \tan^n(x) dx \\ &= \int \tan^{n-1}(x) \tan(x) dx \\ &= \frac{\tan^{n-1}(x)}{n-1} - \int \tan^{n-2}(x) dx \\ &= \frac{\tan^{n-1}(x)}{n-1} - I_{n-2} \end{aligned} \quad (18)$$

Reduction for $\cot^n(x)$ We can obtain the reduction formula of $\cot^n(x)$ via the trigonometric identities.

$$\begin{aligned} I_n &= \int \cot^n(x) dx \\ &= \int \cot^{n-1}(x) \cot(x) dx \\ &= \frac{\cot^{n-1}(x)}{n-1} - \int \cot^{n-2}(x) dx \\ &= \frac{\cot^{n-1}(x)}{n-1} - I_{n-2} \end{aligned} \quad (19)$$

1.3 Trigonometric Integrals

Case VI The following is generally solvable via the trigonometric identities (14) and (15).

We want to solve the classes of integral:

$$\int \tan^m(x) \sec^n(x) dx, \quad \int \cot^m(x) \csc^n(x) dx \quad (20)$$

We can solve the integral by reducing the power of the converted trigonometric functions using (14) and (15).

Case VII The following is generally solvable via the trigonometric identities (14) and (15).

We want to solve the classes of integral:

$$\int \tan^m(x) \sec^n(x) dx, \quad \int \cot^m(x) \csc^n(x) dx \quad (21)$$

We can solve the integral by converting between the tangent and secant functions using the trigonometric identities.

Case VIII This is the case VIII integrals, the strategy is using the trigonometric substitution.

Trigonometric Substitution We can solve integrals by substituting the trigonometric functions with other trigonometric functions.

Example 1.3.3. We want to solve the integral:

$$\int \frac{dx}{\sqrt{1-x^2}}$$

We can substitute $x = \sin(\theta)$, then $dx = \cos(\theta) d\theta$. The integral becomes:

$$\int \frac{\cos(\theta) d\theta}{\sqrt{1-\sin^2(\theta)}} = \int \frac{\cos(\theta) d\theta}{\cos(\theta)} = \int d\theta = \theta + C.$$

In general, we can use the following substitutions:

- $x = a \sin(\theta)$ for $\sqrt{a^2 - x^2}$,
- $x = a \tan(\theta)$ for $\sqrt{a^2 + x^2}$,
- $x = a \sec(\theta)$ for $\sqrt{x^2 - a^2}$.

1.4 Partial Fractions

Weierstrass Substitution We can solve integrals by using the Weierstrass substitution:

$$\tan\left(\frac{x}{2}\right) = t \Leftrightarrow \cos(x) = \frac{1-t^2}{1+t^2} \quad \sin(x) = \frac{2t}{1+t^2} \quad dx = \frac{2dt}{1+t^2} \quad (22)$$

This substitution is useful for solving integrals with trigonometric functions, by converting them into rational functions.

Summary We can solve trigonometric integrals by using the following strategies:

Case	Strategy and General Form
I	Use $\sin^2(x) + \cos^2(x) = 1$; simplify using substitution. General Form: $\int \sin^n(x) \cos^m(x) dx$, where m or n is odd.
II	Convert to Case I and Case III using double angle formulas. General Form: $\int \sin^n(x) \cos^m(x) dx$, where both m and n are even.
III	Apply reduction formulas derived via integration by parts. General Form: $\int \sin^n(x) dx$ or $\int \cos^n(x) dx$.
IV	Use angle sum formulas to simplify. General Form: $\int \sin(mx) \cos(nx) dx$.
V	Reduce tangent/cotangent powers using $\tan^2(x) = \sec^2(x) - 1$ and substitution. General Form: $\int \tan^n(x) dx$ or $\int \cot^n(x) dx$.
VI	Convert to Case V via Pythagorean identities. General Form: $\int \tan^m(x) \sec^n(x) dx$ or $\int \cot^m(x) \csc^n(x) dx$.
VII	Convert between tangent and secant functions for simplification. General Form: $\int \tan^m(x) \sec^n(x) dx$.
VIII	Use trigonometric substitution: $x = a \sin(\theta), a \tan(\theta), a \sec(\theta)$. General Form: $\int \frac{dx}{\sqrt{a^2-x^2}}, \int \frac{dx}{\sqrt{a^2+x^2}}, \int \frac{dx}{\sqrt{x^2-a^2}}$.

Table 1: Strategies and General Forms for Case I-VIII Integrals

1.4 Partial Fractions

Partial Fraction Decomposition We can decompose a rational function into partial fractions to simplify integration.

We want to solve the integral:

$$\int \frac{P(x)}{Q(x)} dx \quad (23)$$

, where $P(x)$ and $Q(x)$ are polynomials.

Example 1.4.1. We want to solve the integral:

$$\int \frac{2x^2 + 3x + 1}{x^3 + 2x^2 + x} dx$$

1.5 Improper Integrals

We can decompose the rational function into partial fractions:

$$\frac{2x^2 + 3x + 1}{x^3 + 2x^2 + x} = \frac{A}{x} + \frac{B}{x+1} + \frac{C}{(x+1)^2}$$

We can solve for the constants A , B , and C by equating the coefficients of the partial fractions to the original function. We have:

$$2x^2 + 3x + 1 = A(x+1)^2 + Bx(x+1) + Cx$$

Thus, we can solve it by setting $x = 0$, $x = -1$

Summary We can solve integrals using partial fraction decomposition by following these steps:

Step	Description
1	Factorize the denominator of the rational function.
2	Write the partial fraction decomposition.
3	Solve for the constants by equating the coefficients.
4	Integrate the partial fractions.

Table 2: Steps for Partial Fraction Decomposition

1.5 Improper Integrals

Improper Integral An improper integral is an integral with an infinite limit or a discontinuity in the interval of integration.

We want to solve the integral:

$$\int_a^b f(x) dx \tag{24}$$

, where a or b is infinite or $f(x)$ is discontinuous.

Example 1.5.1. We want to solve the integral:

$$\int_0^\infty e^{-x} dx$$

Evaluating the integral:

$$\begin{aligned} \int_0^\infty e^{-x} dx &= \lim_{b \rightarrow \infty} \int_0^b e^{-x} dx \\ &= \lim_{b \rightarrow \infty} -e^{-x} \Big|_0^b \\ &= \lim_{b \rightarrow \infty} -e^{-b} + 1 \\ &= 1 \end{aligned}$$

2 Hyperbolic Trigonometric Functions

Definiton 2.0.1 (Hyperbolic Sine). The hyperbolic sine function is defined as:

$$\sinh(x) = \frac{e^x - e^{-x}}{2}. \quad (25)$$

Definiton 2.0.2 (Hyperbolic Cosine). The hyperbolic cosine function is defined as:

$$\cosh(x) = \frac{e^x + e^{-x}}{2}. \quad (26)$$

Properties These combinations of exponential functions have properties similar to the trigonometric functions.

Derivatives The derivatives of the hyperbolic functions are:

$$\frac{d}{dx} \sinh(x) = \cosh(x), \quad (27)$$

$$\frac{d}{dx} \cosh(x) = \sinh(x). \quad (28)$$

Identities The hyperbolic functions satisfy the following identities:

$$\cosh^2(x) + \sinh^2(x) = 1, \quad (29)$$

$$\cosh(2x) = \cosh^2(x) + \sinh^2(x), \quad (30)$$

$$\sinh(2x) = 2 \sinh(x) \cosh(x). \quad (31)$$

Hyperbola The hyperbolic functions are related to the hyperbola $x^2 - y^2 = 1$. Simiar to the circle, the hyperbola can be parametrized by the hyperbolic functions (e.g. $x = \cosh(t)$, $y = \sinh(t)$).

Area The area of a sector of the hyperbola is given by:

$$A = t/2, \quad (32)$$

where t is the angle of the sector along the parametrization $\{(x, y) \mid x = \cosh(t), y = \sinh(t)\}$.

Catenary The hyperbolic cosine function describes the shape of a hanging chain or cable. The catenary is the curve formed by a chain hanging from two points. It is given by the equation:

$$a \cosh\left(\frac{x}{a}\right), \quad (33)$$

Definiton 2.0.3 (Hyperbolic Tangent). The hyperbolic tangent function is defined as:

$$\tanh(x) = \frac{\sinh(x)}{\cosh(x)} = \frac{e^x - e^{-x}}{e^x + e^{-x}}. \quad (34)$$

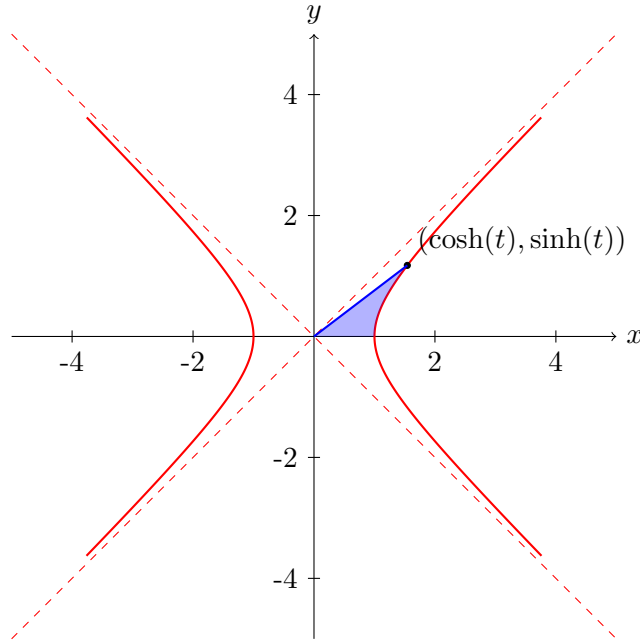


Figure 1: Sector of the hyperbola

Derivative The derivative of the hyperbolic tangent function resembles the derivative of the regular tangent function:

$$\frac{d}{dx} \tanh(x) = \operatorname{sech}^2(x). \quad (35)$$

Identities The hyperbolic tangent function satisfies the following identities:

$$\tanh(x) = \frac{\sinh(x)}{\cosh(x)}, \quad (36)$$

$$\operatorname{sech}^2(x) = 1 - \tanh^2(x). \quad (37)$$

Secant, Cosecant, Cotangent The hyperbolic secant, cosecant, and cotangent functions are defined similarly to the regular secant, cosecant, and cotangent functions. They are the **reciprocal** of the hyperbolic cosine, sine, and tangent functions, respectively.

Inverse Hyperbolic Functions The inverse hyperbolic functions are defined as the inverse of the hyperbolic functions. They are denoted by $\sinh^{-1}(x)$, $\cosh^{-1}(x)$, $\tanh^{-1}(x)$, etc.

$$\operatorname{arsinh} x = \ln \left(x + \sqrt{x^2 + 1} \right) \quad (38)$$

$$\operatorname{arcosh} x = \ln \left(x + \sqrt{x^2 - 1} \right) \quad (39)$$

$$\operatorname{artanh} x = \frac{1}{2} \ln \left(\frac{1+x}{1-x} \right) \quad (40)$$

$$\operatorname{arcsch} x = \ln \left(\frac{1}{x} + \sqrt{\frac{1}{x^2} + 1} \right) \quad (41)$$

$$\operatorname{arsech} x = \ln \left(\frac{1}{x} + \sqrt{\frac{1}{x^2} - 1} \right) \quad (42)$$

$$\operatorname{arcoth} x = \frac{1}{2} \ln \left(\frac{x+1}{x-1} \right) \quad (43)$$

3 Further Applications of Integrals

3.1 Arc Length

Arc Length Given the curve $C : y = f(x)$, the arc length of the curve between two points a and b , where $y'(x)$ is continuous, we would like to compute the arc length of the curve:

$$L = \int_C ds$$

Formula We can derive the formula for the arc length of a curve $y = f(x)$ between two points a and b as:

At x_i and x_{i+1} , the length of the segment is:

$$\begin{aligned} \Delta s &\approx \sqrt{(x_{i+1} - x_i)^2 + (y_{i+1} - y_i)^2} \\ &= \sqrt{\Delta_i x^2 + \Delta_i y^2} \end{aligned}$$

We also have, by MVT:

$$\begin{aligned} \frac{\Delta y}{\Delta x} &= y'(c) \\ \Delta y &= y'(c) \Delta x \\ \Delta s &\approx \sqrt{\Delta x^2 + (y'(c) \Delta x)^2} \\ &= \sqrt{1 + y'(c)^2} \Delta x \end{aligned}$$

3.2 Surface Area of Revolution

Taking a Riemann sum:

$$\begin{aligned} L &= \lim_{n \rightarrow \infty} \sum_{i=1}^n \sqrt{1 + y'(c_i)^2} \Delta x \\ &= \int_a^b \sqrt{1 + y'(x)^2} dx \end{aligned} \tag{44}$$

Example 3.1.1. Given $f(x) = x^{\frac{3}{2}}$ between $x = 0$ and $x = 44$, we would like to compute the arc length of the curve:

$$\begin{aligned} L &= \int_0^{44} \sqrt{1 + \left(\frac{3}{2}x^{\frac{1}{2}}\right)^2} dx \\ &= \int_0^{44} \sqrt{1 + \frac{9}{4}x} dx \\ &= \frac{8}{27} \left(1 + \frac{9}{4}x\right)^{\frac{3}{2}} \Big|_0^{44} = 296 \end{aligned}$$

3.2 Surface Area of Revolution

Surface Area of Revolution Given the curve $C : y = f(x)$, we would like to compute the surface area of the curve between two points a and b when rotated about the x -axis:

$$A = \int_C 2\pi y ds$$

Formula Deriving the formula for the surface area of a curve $y = f(x)$ between two points a and b is similar to the arc length formula:

At x_i and x_{i+1} , the length of the segment is:

$$\Delta s \approx \sqrt{\Delta_i x^2 + \Delta_i y^2}$$

The surface area of the segment is, by continuity:

$$A_i = \pi(y_i + y_{i+1})\Delta s = 2\pi y^* \Delta s \tag{45}$$

As the difference between y^* and y_i diminishes as $\Delta x \rightarrow 0$, taking a Riemann sum:

$$\begin{aligned} A &= \lim_{n \rightarrow \infty} \sum_{i=1}^n 2\pi y_i \sqrt{\Delta_i x^2 + \Delta_i y^2} \\ &= \int_a^b 2\pi y \sqrt{1 + y'(x)^2} dx \end{aligned} \tag{46}$$

3.3 Applications to Physics and Engineering

Example 3.2.1. Given $y = \sqrt{x}$ between $x = 0$ and $x = 1$, we would like to compute the surface area of the curve:

$$\begin{aligned} A &= \int_0^1 2\pi\sqrt{x}\sqrt{1 + \frac{1}{4x}} dx \\ &= \pi \int_0^1 \sqrt{4x + 1} dx \end{aligned}$$

Let $u = 4x + 1$, then $du = 4dx$:

$$\begin{aligned} &= \frac{\pi}{4} \int_1^5 \sqrt{u} du \\ &= \frac{\pi}{6} \left(5^{\frac{3}{2}} - 1 \right) \end{aligned}$$

3.3 Applications to Physics and Engineering

3.3.1 Hydrostatic Pressure and Force

Hydrostatic Pressure The hydrostatic pressure and Force is given by the Archimedes' principle:

$$P = \rho g \cdot d, \tag{47a}$$

$$F = \rho g \cdot d \cdot A \tag{47b}$$

Riemann Sum Given a tank rectangular with width defined by $w = f(x)$, we can take a horizontal slice, x^* , of the tank to compute the force exerted on the tank by the water:

$$F = \sum_{i=1}^n \rho g x_i f(x_i) \Delta x \tag{48}$$

Formula Given a tank rectangular with width defined by $w = f(x)$, where x is depth, we would like to compute the force exerted on the tank by the water:

$$F = \int_0^b \rho g x f(x) \cdot dx \tag{49}$$

, which is derived by considering dx as the depth a horizontal slice of the tank.

3.3.2 Center of Mass and Moments of Inertia

Properties of the Center of Mass The center of mass of a region R has the following properties:

1. **Symetry:** For all axis of symmetry, the center of mass lies on the axis.

3.4 Applications to Economics and Biology

2. **Additivity:** The center of mass of a region is the weighted average of the centers of mass of its parts. The weights are the areas of the parts.

$$\bar{x} = \sum_i \frac{A_i \bar{x}_i}{A} \quad (50)$$

Formula The centroid of a uniformly-dense region R bounded by $y = f(x)$, $x \in [a, b]$, $y \in [f(a), f(b)]$ is derived as follows:

We first have x_i^* and A_i as follows:

$$x_i^* = \frac{1}{2}(x_i + x_{i+1}) \quad A_i = f(x_i)\Delta x$$

For \bar{x} , we have:

$$A\bar{x} \approx \sum_i x_i^* A_i$$

Taking a Riemann sum:

$$\begin{aligned} A\bar{x} &= \lim_{n \rightarrow \infty} \sum_i x_i^* A_i \\ \bar{x} &= \frac{1}{A} \int_a^b x f(x) dx \end{aligned} \quad (51)$$

Similarly, for \bar{y} :

$$\begin{aligned} A\bar{y} &= \lim_{n \rightarrow \infty} \sum_i f(x_i^*) A_i \\ \bar{y} &= \frac{1}{A} \int_a^b \frac{1}{2}(f(x))^2 dx \end{aligned} \quad (52)$$

Theorem 3.3.1 (Pappus's Theorem). The volume of a solid of revolution is given by the product of the area of the region and the distance, R , traveled by the centroid of the region from the axis of rotation.

$$V = 2\pi R A \quad (53)$$

Example 3.3.2 (Elliptical Torus). Given an elliptical torus (tall donut) with major axis a and minor axis b , we would like to compute the volume of the torus:

$$\begin{aligned} V &= 2\pi R A \\ &= 2\pi R \cdot \pi ab = 2\pi^2 ab R \end{aligned}$$

This could be, alternatively, shown via the washer method and the shell method.

3.4 Applications to Economics and Biology

“Biologists are so bad at math” - Prof. Davis as he proceeds to erase the board and skip to the next section.

4 Parametric Equations and Polar Coordinates

4.1 Curves Defined by Parametric Equations

Parametric Equations For $t \in \mathbb{R}$, we have:

$$x = x(t), \quad y = y(t) \tag{54}$$

Example 4.1.1 (Newton's Laws of Motion). Given $\ddot{x} = 0$, $\ddot{y} = -g$, we have:

$$\begin{aligned} x(t) &= A_1 t + A_2, \\ y(t) &= -\frac{1}{2} g t^2 + B_1 t + B_2 \end{aligned}$$

At initial conditions $t = 0$, we have $x(0) = 0$, $y(0) = 0$, $\dot{x}(0) = v_0 \cos(\theta)$, $\dot{y}(0) = v_0 \sin(\theta) - \frac{1}{2} g t^2$.

Example 4.1.2 (Ellipse). Given $x = a \cos(t)$, $y = b \sin(t)$, we have:

$$\begin{aligned} x^2 &= a^2 \cos^2(t), \\ y^2 &= b^2 \sin^2(t) \end{aligned}$$

, which satisfies $x^2/a^2 + y^2/b^2 = 1$.

Intersections of Parametric Curves Given two parametric curves C_1 , C_2 , defined by:

$$\begin{aligned} C_1 : x_1 &= x_1(t), \quad y_1 = y_1(t) \\ C_2 : x_2 &= x_2(t), \quad y_2 = y_2(t) \end{aligned}$$

, we can find the intersection points by solving the system of equations:

$$\begin{aligned} x_1(t) &= x_2(t) \\ y_1(t) &= y_2(t) \end{aligned}$$

Example 4.1.3. Given $x_1 = 2t + t$, $y_1 = 5 - 4t$, $x_2 = 3 - 5 \cos(\pi t)$, $y_2 = 1 + 5 \sin(\pi t)$, we have:

$$\begin{aligned} 2t + 1 &= 3 - 5 \cos(\pi t) \\ 5 - 4t &= 1 + 5 \sin(\pi t) \end{aligned}$$

4.2 Calculus with Parametric Curves

Tangents The tangent to a parametric curve C at a point t is given by:

$$\frac{dy}{dx} = \frac{dy/dt}{dx/dt} = \frac{y'(t)}{x'(t)} \tag{55}$$

Equation of the Tangent The equation of the tangent to a parametric curve C at a point t_0 is given by:

$$y'(t_0)(x - x(t_0)) - x'(t_0)(y - y(t_0)) = 0 \quad (56)$$

Hence, if $x'(t_0) = 0$, we have a vertical tangent; if $y'(t_0) = 0$, we have a horizontal tangent. However, if $x'(t_0) = 0$ and $y'(t_0) = 0$, we have no information.

Example 4.2.1. Let $x = \sin 2t$, $y = \sin t$, we have:

$$\begin{aligned} x'(t) &= 2 \cos 2t, \\ y'(t) &= \cos t \end{aligned}$$

Vertical Tangent: $2 \cos 2t = 0 \Rightarrow t = \frac{\pi}{4} + \frac{n\pi}{2}$. **Horizontal Tangent:** $\cos t = 0 \Rightarrow t = \frac{\pi}{2} + n\pi$. At $t = 0$ we have $x' = y' = 0$. Thus, we have no information. On the graph, we see that the curve intersects itself at $t = 0$.

Area under Parametric Curve The area under a parametric curve C between t_1 and t_2 is given by:

$$A = \int_{x(t_1)}^{x(t_2)} y(x) dx = \int_{t_1}^{t_2} y(t)x'(t) dt \quad (57)$$

Definiton 4.2.2 (Orientation). The orientation of a parametric curve C is given by the direction of the curve as t increases. If the enclosed area is to the left of the trace of t (counter-clockwise) the orientation is positive; otherwise, it is negative.

The sign of the area of a parametric curve C is given by the orientation of the curve.

Area of Closed Curves The area of a closed parametric curve C is given by:

$$A = \oint_C dA = \int_{t_1}^{t_2} y(t)x'(t) dt = \int_{t_1}^{t_2} x(t)y'(t) dt \quad (58)$$

, where

$$x(t_1) = x(t_2), \quad y(t_1) = y(t_2) \quad \text{and} \quad t_2 \text{ is the smallest } t > t_1 \text{ to satisfy the condition.}$$

Arc Length The arc length of a parametric curve C is given by:

$$L = \int_a^b \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} dt \quad (59)$$

Example 4.2.3. Given $x = t \cos t$, $y = t \sin t$, we have:

$$\begin{aligned} \frac{dx}{dt} &= \cos t - t \sin t, \\ \frac{dy}{dt} &= \sin t + t \cos t \end{aligned}$$

Thus, the arc length is given by:

$$\begin{aligned} L &= \int_0^{2\pi} \sqrt{(\cos t - t \sin t)^2 + (\sin t + t \cos t)^2} dt \\ &= \int_0^{2\pi} \sqrt{1 + t^2} dt \end{aligned}$$

Using the substitution $t = \tan \theta$, we have:

$$= \pi \sqrt{1 + 4\pi^2} + \frac{1}{2} \ln(2\pi + \sqrt{1 + 4\pi^2})$$

Surface Area of Revolution The surface area of a parametric curve C rotated about the x -axis is given by:

$$A = \int_a^b 2\pi y(t) ds$$

From the arc length formula, we have $ds = \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} dt$, thus:

$$= \int_a^b 2\pi y(t) \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} dt \quad (60)$$

Similarly, the surface area of a parametric curve C rotated about the y -axis is given by:

$$A = \int_a^b 2\pi x(t) \sqrt{\left(\frac{dx}{dt}\right)^2 + \left(\frac{dy}{dt}\right)^2} dt \quad (61)$$

Example 4.2.4 (Surface Area of of a Ellipse). Given $x = a \sin t$, $y = b \cos t$, we have:

$$\begin{aligned} \frac{dx}{dt} &= a \cos t, \\ \frac{dy}{dt} &= -b \sin t \end{aligned}$$

Thus, the surface area of the ellipse is given by:

$$\begin{aligned} A &= \int_0^{2\pi} 2\pi b \cos t \sqrt{a^2 \cos^2 t + b^2 \sin^2 t} dt \\ &= 2\pi b \int_0^{2\pi} \sqrt{a^2(1 - \sin^2 t) + b^2 \sin^2 t} dt \\ &= 2\pi b \int_0^{2\pi} \sqrt{a^2 + b^2 - (a^2 - b^2) \sin^2 t} dt \end{aligned}$$

This has no analytical solution, but can be solved numerically. Typically, we take $\epsilon = \sqrt{\frac{a^2 - b^2}{a^2}}$.

A Trigonometric Derivatives

Trigonometric Function	Inverse Trigonometric Function
$\frac{d}{dx} \sin(x) = \cos(x)$	$\frac{d}{dx} \arcsin(x) = \frac{1}{\sqrt{1-x^2}}$
$\frac{d}{dx} \cos(x) = -\sin(x)$	$\frac{d}{dx} \arccos(x) = \frac{-1}{\sqrt{1-x^2}}$
$\frac{d}{dx} \tan(x) = \sec^2(x)$	$\frac{d}{dx} \arctan(x) = \frac{1}{1+x^2}$
$\frac{d}{dx} \cot(x) = -\csc^2(x)$	$\frac{d}{dx} \operatorname{arccot}(x) = \frac{-1}{1+x^2}$
$\frac{d}{dx} \sec(x) = \sec(x)\tan(x)$	$\frac{d}{dx} \operatorname{arcsec}(x) = \frac{1}{ x \sqrt{x^2-1}}$
$\frac{d}{dx} \csc(x) = -\csc(x)\cot(x)$	$\frac{d}{dx} \operatorname{arccsc}(x) = \frac{-1}{ x \sqrt{x^2-1}}$
Hyperbolic Function	Inverse Hyperbolic Function
$\frac{d}{dx} \sinh(x) = \cosh(x)$	$\frac{d}{dx} \operatorname{arsinh}(x) = \frac{1}{\sqrt{x^2+1}}$
$\frac{d}{dx} \cosh(x) = \sinh(x)$	$\frac{d}{dx} \operatorname{arcosh}(x) = \frac{1}{\sqrt{x^2-1}} \quad (x > 1)$
$\frac{d}{dx} \tanh(x) = \operatorname{sech}^2(x)$	$\frac{d}{dx} \operatorname{artanh}(x) = \frac{1}{1-x^2} \quad (x < 1)$
$\frac{d}{dx} \coth(x) = -\operatorname{csch}^2(x)$	$\frac{d}{dx} \operatorname{arcoth}(x) = \frac{1}{1-x^2} \quad (x > 1)$
$\frac{d}{dx} \operatorname{sech}(x) = -\operatorname{sech}(x)\tanh(x)$	$\frac{d}{dx} \operatorname{arsech}(x) = \frac{-1}{x\sqrt{1-x^2}} \quad (0 < x \leq 1)$
$\frac{d}{dx} \operatorname{csch}(x) = -\operatorname{csch}(x)\coth(x)$	$\frac{d}{dx} \operatorname{arcsch}(x) = \frac{-1}{ x \sqrt{x^2+1}}$