Calculus II
Integrals of involving radicals of quadratics

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Outline

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Integrals of form $\int R(x, \sqrt{ax^2 + bx + c})\mathrm{d}x$, R - rational function

Let $R(x, y)$ be an arbitrary rational expression in two variables (quotient of polynomials in two variables).

Question

Can we integrate $\int R\left(x, \sqrt{ax^2 + bx + c}\right)\mathrm{d}x$?

- Yes. We will learn how in what follows.
- The algorithm for integration is roughly:
  - Use linear substitution to transform to one of three integrals:
    $\int R(x, \sqrt{x^2 + 1})\mathrm{d}x$, $\int R(x, \sqrt{-x^2 + 1})\mathrm{d}x$, $\int R(x, \sqrt{x^2 - 1})\mathrm{d}x$.
  - Use trigonometric substitution or Euler substitution to transform to trigonometric or rational function integral (no radicals).
  - Solve as previously studied.
- We motivate why we need such integrals by examples such as computing the area of an ellipse.

Trigonometric Substitution

- To find the area of a circle or ellipse, one needs to compute $\int \sqrt{a^2 - x^2} \mathrm{d}x$.
- For $\int x\sqrt{a^2 - x^2} \mathrm{d}x$, the substitution $u = a^2 - x^2$ would work.
- For $\int \sqrt{a^2 - x^2} \mathrm{d}x$, we need a more elaborate substitution.
- Instead, substitute $x = a\sin\theta$.

$$\sqrt{a^2 - x^2} = \sqrt{a^2 - a^2\sin^2\theta} = \sqrt{a^2(1 - \sin^2\theta)} = \sqrt{a^2\cos^2\theta} = a|\cos\theta|.$$

- With $u = a^2 - x^2$, the new variable is a function of the old one.
- With $x = a\sin\theta$, the old variable is a function of the new one.

Linear substitutions to simplify radicals $\sqrt{ay^2 + by + c}$

- Using linear substitutions, radicals of form $\sqrt{ay^2 + by + c}$, $a \neq 0$, $b^2 - 4ac \neq 0$ can be transformed to (multiple of):
  - $\sqrt{x^2 + 1}$
  - $\sqrt{-x^2 + 1}$
  - $\sqrt{x^2 - 1}$.
- We already studied how to do that using completing the square when dealing with rational functions.

Recall: linear substitution is subst. of the form $u = px + q$.

Example

Use linear substitution to transform $\sqrt{x^2 + x + 1}$ to multiple of $\sqrt{u^2 + 1}$.

$$
\begin{aligned}
\sqrt{x^2 + x + 1} &= \sqrt{x^2 + 2 \cdot \frac{1}{2}x + \frac{1}{4} - \frac{1}{4} + 1} \\
&= \sqrt{\left(x + \frac{1}{2}\right)^2 + \frac{3}{4}} \\
&= \sqrt{\frac{3}{4}\left(\frac{4}{3}\left(x + \frac{1}{2}\right)^2 + 1\right)} \\
&= \frac{\sqrt{3}}{2}\sqrt{\left(\frac{2}{\sqrt{3}}\left(x + \frac{1}{2}\right)\right)^2 + 1} \\
&= \frac{\sqrt{3}}{2}\sqrt{u^2 + 1},
\end{aligned}
$$

where $u = \dfrac{2}{\sqrt{3}}\left(x + \dfrac{1}{2}\right) = \dfrac{2\sqrt{3}}{3}x + \dfrac{\sqrt{3}}{3}$.

Recall: linear substitution is subst. of the form $u = px + q$.

Example

Use linear subst. to transform $\sqrt{-2x^2 + x + 1}$ to multiple of $\sqrt{-u^2 + 1}$.

$$
\begin{aligned}
\sqrt{-2x^2 + x + 1} &= \sqrt{-2\left(x^2 - \tfrac{1}{2}x - \tfrac{1}{2}\right)} \\
&= \sqrt{-2\left(x^2 - 2\tfrac{1}{4}x + \tfrac{1}{16} - \tfrac{1}{16} - \tfrac{1}{2}\right)} \\
&= \sqrt{-2\left(\left(x - \tfrac{1}{4}\right)^2 - \tfrac{9}{16}\right)} \\
&= \sqrt{\tfrac{9}{8}\left(-\tfrac{16}{9}\left(x - \tfrac{1}{4}\right)^2 + 1\right)} \\
&= \tfrac{3}{\sqrt{8}}\sqrt{-\left(\tfrac{4}{3}\left(x - \tfrac{1}{4}\right)\right)^2 + 1} \\
&= \tfrac{3}{\sqrt{8}}\sqrt{-u^2 + 1},
\end{aligned}
$$

where $u = \tfrac{4}{3}\left(x - \tfrac{1}{4}\right) = \tfrac{4}{3}x - \tfrac{1}{3}$.

- Let R be a rational function in two variables.
- So far, with linear transformations we converted all integrals of the form $\int R(x, \sqrt{ax^2 + bx + c})\mathrm{d}x$ to one of the three forms:
  $\int R(x, \sqrt{x^2 + 1})\mathrm{d}x$, $\int R(x, \sqrt{-x^2 + 1})\mathrm{d}x$, $\int R(x, \sqrt{x^2 - 1})\mathrm{d}x$.
- Each of the above integrals can be transformed to a rational trigonometric integral using 3 pairs of substitutions:
  $x = \tan\theta$, $x = \cot\theta$; $x = \sin\theta$, $x = \cos\theta$; $x = \csc\theta$, $x = \sec\theta$.
- We studied that trigonometric integrals are converted to rational function integrals via $\theta = 2\arctan t$.
- The resulting 3 pairs of substitutions are called Euler substitutions:
  $x = \tan(2\arctan t)$, $x = \cot(2\arctan t)$; $x = \sin(2\arctan t)$,
  $x = \cos(2\arctan t)$; $x = \csc(2\arctan t)$, $x = \sec(2\arctan t)$.
- The Euler substitutions directly transform the integral to a rational function integral.
- We will demonstrate that the Euler substitutions are rational.

Trigonometric substitution and Euler substitution

Expression	Substitution	Variable range	Relevant identity
$\sqrt{x^2+1}$	$x = \tan\theta$	$\theta \in \left(-\frac{\pi}{2}, \frac{\pi}{2}\right)$	$1 + \tan^2\theta = \sec^2\theta$
	$x = \cot\theta$	$\theta \in (0, \pi)$	$1 + \cot^2\theta = \csc^2\theta$
$\sqrt{-x^2+1}$	$x = \sin\theta$	$\theta \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]$	$1 - \sin^2\theta = \cos^2\theta$
	$x = \cos\theta$	$\theta \in (0, \pi)$	$1 - \cos^2\theta = \cos^2\theta$
$\sqrt{x^2-1}$	$x = \csc\theta$	$\theta \in \left[0, \frac{\pi}{2}\right) \cup \left[\pi, \frac{3\pi}{2}\right)$	$\csc^2\theta - 1 = \cot^2\theta$
	$x = \sec\theta$	$\theta \in \left[0, \frac{\pi}{2}\right) \cup \left[\pi, \frac{3\pi}{2}\right)$	$\sec^2\theta - 1 = \tan^2\theta$

Euler substitution by applying in addition $\theta = 2\arctan t$

$\sqrt{x^2+1}$	$x = \frac{2t}{1-t^2}$	$-1 < t < 1$	(?)
	$x = \frac{1}{2}\left(\frac{1}{t} - t\right)$	$0 < t$	(?)
$\sqrt{-x^2+1}$	$x = \frac{2t}{1+t^2}$	$-1 \le t \le 1$	(?)
	$x = \frac{1-t^2}{1+t^2}$	$0 < t$	(?)
$\sqrt{x^2-1}$	$x = \frac{1}{2}\left(\frac{1}{t} + t\right)$	$t \in (-\infty, -1) \cup [0, 1)$	(?)
	$x = \frac{1+t^2}{1-t^2}$	$t \in (-\infty, -1) \cup [0, 1)$	(?)

Trigonometric substitution $x = \cot\theta$ for $\sqrt{x^2+1}$

The trigonometric substitution $x = \cot\theta$, $\theta \in (0,\pi)$ for $\sqrt{x^2+1}$:

$$
\begin{aligned}
\sqrt{x^2+1} &= \sqrt{\cot^2\theta + 1} \\
&= \sqrt{\frac{\cos^2\theta}{\sin^2\theta} + 1} \\
&= \sqrt{\frac{\cos^2\theta + \sin^2\theta}{\sin^2\theta}} \\
&= \sqrt{\frac{1}{\sin^2\theta}} = \frac{1}{\sqrt{\sin^2\theta}} \\
&= \frac{1}{\sin\theta} = \csc\theta \quad.
\end{aligned}
$$

$\left.\begin{array}{l} \text{when } \theta \in (0,\pi) \text{ we have} \\ \sin\theta \geq 0 \text{ and so} \\ \sqrt{\sin^2\theta} = \sin\theta \end{array}\right.$

Trigonometric substitution $x = \cot\theta$ for $\sqrt{x^2+1}$

The trigonometric substitution $x = \cot\theta$, $\theta \in (0, \pi)$ for $\sqrt{x^2+1}$:

$$\sqrt{x^2+1} \;=\; \frac{1}{\sin\theta} = \csc\theta \quad.$$

The differential dx can be expressed via dθ from $x = \cot\theta$. To summarize:

Definition

The trigonometric substitution $x = \cot\theta$, $\theta \in (0, \pi)$ for $\sqrt{x^2+1}$ is given by:

$$
\begin{aligned}
x &= \cot\theta \\
\sqrt{x^2+1} &= \frac{1}{\sin\theta} = \csc\theta \\
\mathrm{d}x &= -\frac{\mathrm{d}\theta}{\sin^2\theta} = -\csc^2\theta \textbf{?}\mathrm{d}\theta \\
\theta &= \operatorname{arccot} x \quad.
\end{aligned}
$$

Example

$$
\begin{aligned}
\int \frac{1}{x^2\sqrt{x^2+9}}\mathrm{d}x &= \int \frac{1}{x^2 3\sqrt{\left(\frac{x}{3}\right)^2+1}}\mathrm{d}x \\
&= \int \frac{1}{(3\cot\theta)^2 3\sqrt{\cot^2\theta+1}}\mathrm{d}(3\cot\theta) \\
&= \int \frac{1}{27\cot^2\theta\sqrt{\csc^2\theta}}\left(-3\csc^2\theta\right)\mathrm{d}\theta \\
&= \frac{1}{9}\int \frac{-\csc^2\theta}{\cot^2\theta\csc\theta}\mathrm{d}\theta \\
&= \frac{1}{9}\int \frac{-\sin\theta}{\cos^2\theta}\mathrm{d}\theta = \frac{1}{9}\int \frac{1}{\cos^2\theta}\mathrm{d}(\cos\theta) \\
&= \frac{1}{9}\int \frac{\mathrm{d}u}{u^2} = -\frac{1}{9u}+C = -\frac{\sec\theta}{9}+C \\
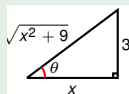&= -\frac{\sqrt{x^2+9}}{9x}+C
\end{aligned}
$$

$$
\begin{array}{l}
\text{Set} \\
\frac{x}{3} = \cot\theta \\
x = 3\cot\theta \\
\theta \in (0,\pi) \\
\theta \in (0,\pi) \Rightarrow \\
\csc\theta > 0
\end{array}
$$

Set $u = \cos\theta$

Euler subst. for $\sqrt{x^2+1}$ corresponding to $x = \cot\theta$

- $x = \cot\theta$ transforms $\mathrm{d}x, x, \sqrt{x^2+1}$ to trig form.
- $\theta = 2\arctan t, \ t > 0$ transforms $\mathrm{d}\theta, \cos\theta, \sin\theta$ to rational form.

What if we compose the above? We get the Euler substitution:

$$
\begin{aligned}
x &= \cot\theta \\[2mm]
&= \cot\left(2\arctan t\right) \qquad \left|\text{Recall: } \cot(2z) = \frac{\cos(2z)}{\sin(2z)} = \frac{1-\tan^2 z}{2\tan z}\right. \\[2mm]
&= \frac{1 - \tan^2(\arctan t)}{2\tan(\arctan t)} \\[2mm]
&= \frac{1 - t^2}{2t} \\[2mm]
&= \frac{1}{2}\left(\frac{1}{t} - t\right) \quad .
\end{aligned}
$$

Euler subst. for $\sqrt{x^2 + 1}$ corresponding to $x = \cot\theta$

- $x = \cot\theta$ transforms $dx, x, \sqrt{x^2+1}$ to trig form.
- $\theta = 2\arctan t$, $t > 0$ transforms $d\theta, \cos\theta, \sin\theta$ to rational form.

What if we compose the above? We get the Euler substitution:

$$x = \frac{1}{2}\left(\frac{1}{t} - t\right) \quad .$$

We can furthermore compute

$$
\begin{aligned}
\sqrt{x^2+1} &= \sqrt{\frac{1}{4}\left(\frac{1}{t} - t\right)^2 + 1} \\
&= \frac{1}{2}\sqrt{\left(\frac{1}{t} - t\right)^2 + 4} \quad \left| \left(\tfrac{1}{t} - t\right)^2 + 4 = \left(\tfrac{1}{t} + t\right)^2 \right.
\end{aligned}
$$

Euler subst. for $\sqrt{x^2+1}$ corresponding to $x = \cot\theta$

- $x = \cot\theta$ transforms $\mathrm{d}x, x, \sqrt{x^2+1}$ to trig form.
- $\theta = 2\arctan t, \ t > 0$ transforms $\mathrm{d}\theta, \cos\theta, \sin\theta$ to rational form.

What if we compose the above? We get the Euler substitution:

$$x \ = \ \frac{1}{2}\left(\frac{1}{t} - t\right) \quad .$$

We can furthermore compute

$$
\begin{aligned}
\sqrt{x^2+1} &= \sqrt{\frac{1}{4}\left(\frac{1}{t} - t\right)^2 + 1} \\
&= \frac{1}{2}\sqrt{\left(\frac{1}{t} + t\right)^2} \qquad \left| \begin{array}{l} \sqrt{\left(\frac{1}{t}+t\right)^2} = \frac{1}{t} + t \\ \text{because } t > 0 \end{array} \right. \\
&= \frac{1}{2}\left(\frac{1}{t} + t\right) \quad .
\end{aligned}
$$

Euler subst. for $\sqrt{x^2+1}$ corresponding to $x = \cot\theta$

- $x = \cot\theta$ transforms $dx, x, \sqrt{x^2+1}$ to trig form.
- $\theta = 2\arctan t, \ t > 0$ transforms $d\theta, \cos\theta, \sin\theta$ to rational form.

What if we compose the above? We get the Euler substitution:

$$x = \frac{1}{2}\left(\frac{1}{t} - t\right) \quad .$$

We can furthermore compute

$$\sqrt{x^2+1} = \frac{1}{2}\left(\frac{1}{t} + t\right) \quad .$$

Finally compute

$$\begin{aligned}
dx &= d\left(\frac{1}{2}\left(\frac{1}{t} - t\right)\right) = -\frac{1}{2}\left(\frac{1}{t^2} + 1\right)dt \\
t &= \frac{1}{2}\left(\frac{1}{t} + t\right) - \frac{1}{2}\left(\frac{1}{t} - t\right) = \sqrt{x^2+1} - x \quad .
\end{aligned}$$

Euler subst. for $\sqrt{x^2 + 1}$ corresponding to $x = \cot \theta$

- $x = \cot \theta$ transforms $dx, x, \sqrt{x^2 + 1}$ to trig form.
- $\theta = 2 \arctan t, \; t > 0$ transforms $d\theta, \cos\theta, \sin\theta$ to rational form.

What if we compose the above? We get the Euler substitution:

Definition

The Euler substitution for $\sqrt{x^2 + 1}$ corresponding to $x = \cot\theta$ is given by:

$$
\begin{aligned}
x &= \frac{1}{2}\left(\frac{1}{t} - t\right), \qquad t > 0 \\
\sqrt{x^2 + 1} &= \frac{1}{2}\left(\frac{1}{t} + t\right) \\
dx &= -\frac{1}{2}\left(\frac{1}{t^2} + 1\right)dt \\
t &= \sqrt{x^2 + 1} - x \quad.
\end{aligned}
$$
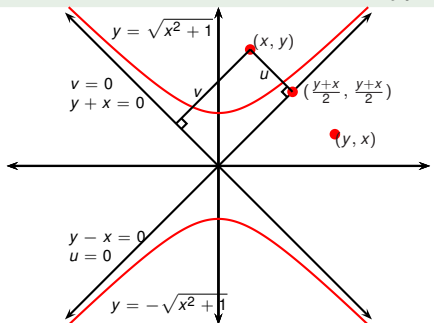
Euler substitution: $x = \frac{1}{2}\left(\frac{1}{t} - t\right)$, $\sqrt{x^2+1} = \frac{1}{2}\left(\frac{1}{t} + t\right)$,
$t = \sqrt{x^2+1} - x$, $\mathrm{d}x = -\frac{1}{2}\left(\frac{1}{t^2} + 1\right)\mathrm{d}t$. Recall $t > 0$.

Example

$$
\begin{aligned}
\int \sqrt{x^2+1}\,\mathrm{d}x &= -\int \frac{1}{2}\left(\frac{1}{t} + t\right)\frac{1}{2}\left(\frac{1}{t^2} + 1\right)\mathrm{d}t \\
&= -\frac{1}{4}\int \left(\frac{1}{t^3} + 2\frac{1}{t} + t\right)\mathrm{d}t \\
&= -\frac{1}{4}\left(-\frac{t^{-2}}{2} + 2\ln|t| + \frac{t^2}{2}\right) + C \\
&= \frac{1}{2}\left(\frac{1}{2}\left(t^{-1} - t\right)\frac{1}{2}\left(t^{-1} + t\right)\right) - \frac{1}{2}\ln t + C \\
&= \frac{1}{2}x\sqrt{x^2+1} - \frac{1}{2}\ln\left(\sqrt{x^2+1} - x\right) + C \\
&= \frac{1}{2}x\sqrt{x^2+1} + \frac{1}{2}\ln\frac{\sqrt{x^2+1} + x}{\left(\sqrt{x^2+1} - x\right)\left(\sqrt{x^2+1} + x\right)} + C \\
&= \frac{1}{2}x\sqrt{x^2+1} + \frac{1}{2}\ln\left(\sqrt{x^2+1} + x\right) + C
\end{aligned}
$$

Example

Find the area locked b-n the hyperbolas $y = \pm\sqrt{x^2+1}$ and $x = \pm 2\sqrt{2}$.

Signed distance b-n (x, y) and line $u = 0$ equals

$$\pm\sqrt{\left(x - \frac{(x+y)}{2}\right)^2 + \left(y - \frac{(x+y)}{2}\right)^2}$$
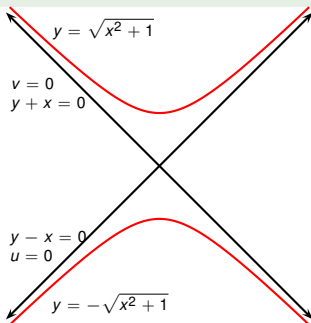$$= \pm\sqrt{\frac{1}{2}(y-x)^2} = \pm\frac{\sqrt{2}}{2}(y-x) = u.$$

We studied $v = \frac{\frac{1}{2}}{u}$ is called a hyperbola: why do we call $y = \sqrt{x^2+1}$ hyperbola? Compute:

$$\sqrt{x^2+1} = y$$
$$x^2+1 = y^2$$
$$y^2 - x^2 = 1$$
$$\frac{\sqrt{2}}{2}(y-x)\frac{\sqrt{2}}{2}(y+x) = \frac{1}{2}$$
$$uv = \frac{1}{2}$$
$$v = \frac{\frac{1}{2}}{u},$$

where $\begin{vmatrix} u = \frac{\sqrt{2}}{2}(y-x) \\ v = \frac{\sqrt{2}}{2}(y+x) \end{vmatrix}$. Consider an arbitrary point (x, y).

Example

Find the area locked b-n the hyperbolas $y = \pm\sqrt{x^2 + 1}$ and $x = \pm 2\sqrt{2}$.

Signed distance b-n (x, y) and line $u = 0$ equals u. Similarly compute that signed distance b-n (x, y) and the line $v = 0$ equals v.
$\Rightarrow y^2 - x^2 = 1$ is the hyperbola $v = \frac{1/2}{u}$ in the (u, v)-plane.
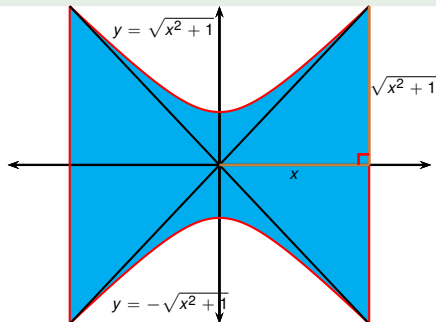
We studied $v = \frac{\frac{1}{2}}{u}$ is called a hyperbola: why do we call $y = \sqrt{x^2 + 1}$ hyperbola? Compute:

$$
\begin{aligned}
\sqrt{x^2 + 1} &= y \\
x^2 + 1 &= y^2 \\
y^2 - x^2 &= 1 \\
\tfrac{\sqrt{2}}{2}(y - x)\tfrac{\sqrt{2}}{2}(y + x) &= \tfrac{1}{2} \\
uv &= \tfrac{1}{2} \\
v &= \tfrac{\frac{1}{2}}{u},
\end{aligned}
$$

where $\begin{vmatrix} u = \frac{\sqrt{2}}{2}\,(y - x) \\ v = \frac{\sqrt{2}}{2}\,(y + x) \end{vmatrix}$. Consider an arbitrary point (x, y).

Example

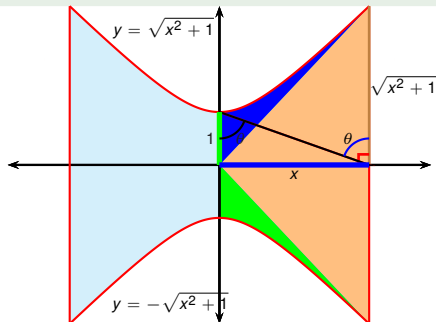Find the area locked b-n the hyperbolas $y = \pm\sqrt{x^2+1}$ and $x = \pm2\sqrt{2}$.

The area in question is:
$$\int\limits_{-2\sqrt{2}}^{2\sqrt{2}} 2\sqrt{x^2+1}\,\mathrm{d}x$$
$$= 2\left[x\sqrt{x^2+1}\right.$$
$$\left. + \ln\left(\sqrt{x^2+1}+x\right)\right]_0^{2\sqrt{2}}$$
$$= 2\left(2\sqrt{2}\sqrt{(2\sqrt{2})^2+1}\right.$$
$$\left. + \ln\left(\sqrt{(2\sqrt{2})^2+1}+2\sqrt{2}\right)\right)$$
$$= 12\sqrt{2} + 2\ln\left(3+2\sqrt{2}\right)$$
$$\approx 20.496$$

Example

Find the area locked b-n the hyperbolas $y = \pm\sqrt{x^2 + 1}$ and $x = \pm 2\sqrt{2}$.

- Recall: integral can be solved via $x = \tan\theta$.
- Geometric interpretation of θ?

The area in question is:

$$\int\limits_{-2\sqrt{2}}^{2\sqrt{2}} 2\sqrt{x^2 + 1}\,dx$$

$$= 2\left[x\sqrt{x^2 + 1}\right.$$

$$\left. + \ln\left(\sqrt{x^2 + 1} + x\right)\right]_0^{2\sqrt{2}}$$

$$= 2\left(2\sqrt{2}\sqrt{(2\sqrt{2})^2 + 1}\right.$$

$$\left. + \ln\left(\sqrt{(2\sqrt{2})^2 + 1} + 2\sqrt{2}\right)\right)$$

$$= 12\sqrt{2} + 2\ln\left(3 + 2\sqrt{2}\right)$$

$$\approx 20.496$$

Example

Find $\int \frac{x}{\sqrt{x^2+4}} \mathrm{d}x$.

- We could use the trig substitution $x = 2\tan\theta$.
- But there is an easier way:
- $u = x^2 + 4$.
- $\mathrm{d}u = 2x\mathrm{d}x$.
$$\int \frac{x}{\sqrt{x^2 + 4}}\mathrm{d}x = \frac{1}{2}\int \frac{\mathrm{d}u}{\sqrt{u}} = \sqrt{u} + C = \sqrt{x^2 + 4} + C$$

Trigonometric substitution $x = \cos\theta$ for $\sqrt{-x^2+1}$

The trigonometric substitution $x = \cos\theta$, $\theta \in [0, \pi]$ for $\sqrt{-x^2+1}$:

$$
\begin{aligned}
\sqrt{-x^2+1} &= \sqrt{1-\cos^2\theta} \\
&= \sqrt{\sin^2\theta} \\
&= \sin\theta \quad .
\end{aligned}
\quad
\left|
\begin{array}{l}
\text{when } \theta \in [0, \pi] \text{ we have} \\
\sin\theta \geq 0 \text{ and so } \sqrt{\sin^2\theta} = \sin\theta
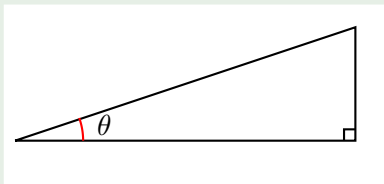\end{array}
\right.
$$

To summarize:

Definition

The trigonometric substitution $x = \cos\theta$, $\theta \in [0, \pi]$ for $\sqrt{-x^2+1}$ is given by:

$$
\begin{aligned}
x &= \cos\theta \\
\sqrt{-x^2+1} &= \sin\theta \\
dx &= -\sin\theta\, d\theta \\
\theta &= \arccos x \quad .
\end{aligned}
$$

Example

Evaluate $\int \frac{\sqrt{9-x^2}}{x^2}dx$.

- Let $x = 3\sin\theta$, where $-\pi/2 \le \theta \le \pi/2$.
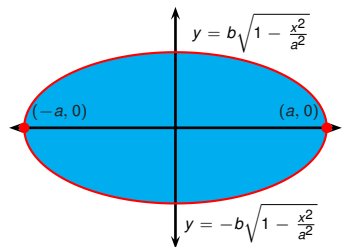
- Then $dx = 3\cos\theta d\theta$.

$$\sqrt{9-x^2} = \sqrt{9-9\sin^2\theta} = \sqrt{9\cos^2\theta} = 3|\cos\theta| = 3\cos\theta$$

$$
\begin{aligned}
\int \frac{\sqrt{9-x^2}}{x^2}dx &= \int \frac{3\cos\theta}{9\sin^2\theta}3\cos\theta d\theta = \int \cot^2\theta d\theta \\
&= \int(\csc^2\theta - 1)d\theta = -\cot\theta - \theta + C \\
&= -\frac{\sqrt{9-x^2}}{x} - \arcsin\left(\frac{x}{3}\right) + C
\end{aligned}
$$

Example

Find the area enclosed by the ellipse $\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$, $a, b > 0$.

The area in question is

$$\int\limits_{-a}^{a} 2b\sqrt{1 - \frac{x^2}{a^2}}\,dx$$

$$= 4\int\limits_{0}^{a} b\sqrt{1 - \frac{x^2}{a^2}}\,dx.$$

Express y via x:

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$$

$$\frac{y^2}{b^2} = 1 - \frac{x^2}{a^2}$$

$$y^2 = b^2\left(1 - \frac{x^2}{a^2}\right)$$

$$y = \pm b\sqrt{1 - \frac{x^2}{a^2}}$$

Example

Find the area enclosed by the ellipse $\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1$, $a, b > 0$.

$y = b\sqrt{1 - \frac{x^2}{a^2}}$

$y = -b\sqrt{1 - \frac{x^2}{a^2}}$
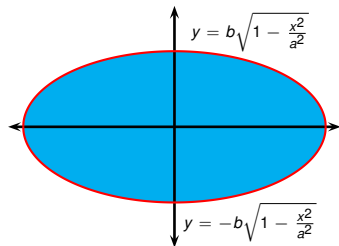
Trig subst.: set $x = a\sin\theta$, $\theta \in \left(0, \frac{\pi}{2}\right)$.

Compute: $\sqrt{1 - \frac{x^2}{a^2}} = \sqrt{1 - \frac{a^2\sin^2\theta}{a^2}} = \sqrt{1 - \sin^2\theta} = \cos\theta$. When $x = 0$, $\theta = 0$ and when $x = a$, $\theta = \frac{\pi}{2}$.

The area in question is

$$\int\limits_{-a}^{a} 2b\sqrt{1 - \frac{x^2}{a^2}}\mathrm{d}x$$

$$= 4\int\limits_{0}^{a} b\sqrt{1 - \frac{x^2}{a^2}}\mathrm{d}x$$

$$= 4b\frac{a\pi}{4} = \pi a b \quad .$$

$$\begin{aligned}
\int_0^a \sqrt{1 - \frac{x^2}{a^2}}\mathrm{d}x &= \int_0^{\frac{\pi}{2}} \cos\theta \,\mathrm{d}\left(a\sin\theta\right) \\
&= a\int_0^{\frac{\pi}{2}} \cos^2\theta\mathrm{d}\theta \\
&= a\int_0^{\frac{\pi}{2}} \frac{\cos(2\theta) + 1}{2}\mathrm{d}\theta \\
&= a\left[\frac{\sin(2\theta)}{4} + \frac{\theta}{2}\right]_{\theta=0}^{\theta=\frac{\pi}{2}} \\
&= a\left(0 + \frac{\pi}{4} - (0 + 0)\right) \\
&= \frac{a\pi}{4}
\end{aligned}$$

Example

Evaluate $\int \frac{x}{\sqrt{3-2x-x^2}} dx$.

- Complete the square under the root sign:
- $3 - 2x - x^2 = 3 + 1 - (x^2 + 2x + 1) = 4 - (x+1)^2$
- Substitute $u = x + 1$. Then $du = dx$ and $x = u - 1$.
- $\int \frac{x}{\sqrt{3-2x-x^2}} dx = \int \frac{x}{\sqrt{4-(x+1)^2}} dx = \int \frac{u-1}{\sqrt{4-u^2}} du$
- Let $u = 2\sin\theta$, where $-\pi/2 \leq \theta \leq \pi/2$. Then $du = 2\cos\theta d\theta$.
- $\sqrt{4 - u^2} = \sqrt{4 - 4\sin^2\theta} = \sqrt{4\cos^2\theta} = 2|\cos\theta| = 2\cos\theta$

$$\int \frac{x}{\sqrt{3-2x-x^2}} dx = \int \frac{u-1}{\sqrt{4-u^2}} du = \int \frac{2\sin\theta - 1}{2\cos\theta} 2\cos\theta d\theta$$
$$= \int (2\sin\theta - 1) d\theta = -2\cos\theta - \theta + C$$
$$= -\sqrt{4 - u^2} - \sin^{-1}\left(\frac{u}{2}\right) + C$$
$$= -\sqrt{3 - 2x - x^2} - \sin^{-1}\left(\frac{x+1}{2}\right) + C$$

Euler subst. for $\sqrt{-x^2 + 1}$ corresponding to $x = \cos\theta$

- $x = \cos\theta$ transforms $\mathrm{d}x, x, \sqrt{-x^2 + 1}$ to trig form.
- $\theta = 2\arctan t, \ t > 0$ transforms $\mathrm{d}\theta, \cos\theta, \sin\theta$ to rational form.

What if we compose the above? We get the Euler substitution:

$$
\begin{aligned}
x &= \cos\theta \\
&= \cos(2\arctan t) & \bigg| \ \cos(2z) = \frac{1 - \tan^2 z}{1 + \tan^2 z} \\
&= \frac{1 - \tan^2(\arctan t)}{1 + \tan^2(\arctan t)} \\
&= \frac{1 - t^2}{1 + t^2}
\end{aligned}
$$

Euler subst. for $\sqrt{-x^2+1}$ corresponding to $x = \cos\theta$

- $x = \cos\theta$ transforms $dx, x, \sqrt{-x^2+1}$ to trig form.
- $\theta = 2\arctan t, \ t > 0$ transforms $d\theta, \cos\theta, \sin\theta$ to rational form.

What if we compose the above? We get the Euler substitution:

$$
\begin{aligned}
x &= \frac{1-t^2}{1+t^2} \\
\hline
\sqrt{-x^2+1} &= \sqrt{1 - \left(\frac{1-t^2}{1+t^2}\right)^2} \\
&= \sqrt{\frac{(1+t^2)^2 - (1-t^2)^2}{(1+t^2)^2}} \qquad \Big|\ (1+t^2)^2 - (1-t^2)^2 = 4t^2 \\
&= \sqrt{\frac{4t^2}{(1+t^2)^2}} \qquad\qquad \Big|\ \sqrt{4t^2} = 2t \text{ because } t > 0 \\
&= \frac{2t}{1+t^2}
\end{aligned}
$$

Euler subst. for $\sqrt{-x^2+1}$ corresponding to $x = \cos\theta$

- $x = \cos\theta$ transforms $\mathrm{d}x, x, \sqrt{-x^2+1}$ to trig form.
- $\theta = 2\arctan t, \ t > 0$ transforms $\mathrm{d}\theta, \cos\theta, \sin\theta$ to rational form.

What if we compose the above? We get the Euler substitution:

$$x = \frac{1-t^2}{1+t^2}$$

$$\sqrt{-x^2+1} = \frac{2t}{1+t^2}$$

$$t = \frac{\sqrt{1-x}}{\sqrt{1+x}}\frac{\sqrt{1+x}}{\sqrt{1+x}} = \frac{\sqrt{-x^2+1}}{x+1} \qquad \text{we use } t > 0$$

$$\begin{aligned}
\mathrm{d}x &= \mathrm{d}\left(\frac{1-t^2}{1+t^2}\right) = \mathrm{d}\left(\frac{2-(1+t^2)}{1+t^2}\right) \\
&= \mathrm{d}\left(\frac{2}{1+t^2}-1\right) = -\frac{4t}{(1+t^2)^2}\mathrm{d}t
\end{aligned}$$

Euler subst. for $\sqrt{-x^2 + 1}$ corresponding to $x = \cos\theta$

- $x = \cos\theta$ transforms $\mathrm{d}x, x, \sqrt{-x^2 + 1}$ to trig form.
- $\theta = 2\arctan t, \ t > 0$ transforms $\mathrm{d}\theta, \cos\theta, \sin\theta$ to rational form.

What if we compose the above? We get the Euler substitution:

Definition

The Euler substitution for $\sqrt{-x^2 + 1}$ corresponding to $x = \cos\theta$ is given by:

$$
\begin{aligned}
x &= \frac{1 - t^2}{1 + t^2}, \qquad t > 0 \\
\sqrt{-x^2 + 1} &= \frac{2t}{1 + t^2} \\
\mathrm{d}x &= -\frac{4t}{(t^2 + 1)^2}\mathrm{d}t \\
t &= \frac{\sqrt{-x^2 + 1}}{x + 1} \quad .
\end{aligned}
$$

Trigonometric substitution $x = \sec\theta$ for $\sqrt{x^2-1}$

The trigonometric substitution $x = \sec\theta$, $\theta \in \left[0, \frac{\pi}{2}\right) \cup \left[\pi, \frac{3\pi}{2}\right)$:

$$
\begin{aligned}
\sqrt{x^2-1} &= \sqrt{\sec^2\theta - 1} \\
&= \sqrt{\frac{1}{\cos^2\theta} - 1} \\
&= \sqrt{\frac{\sin^2\theta}{\cos^2\theta}} \\
&= \sqrt{\tan^2\theta} \qquad \left| \begin{array}{l} \text{when } \theta \in \theta \in \left[0, \frac{\pi}{2}\right) \cup \left[\pi, \frac{3\pi}{2}\right) \text{ we have} \\ \tan\theta \geq 0 \text{ and so } \sqrt{\tan^2\theta} = \tan\theta \end{array} \right. \\
&= \tan\theta \quad .
\end{aligned}
$$

Trigonometric substitution $x = \sec\theta$ for $\sqrt{x^2 - 1}$

The trigonometric substitution $x = \sec\theta$, $\theta \in \left[0, \frac{\pi}{2}\right) \cup \left[\pi, \frac{3\pi}{2}\right)$:
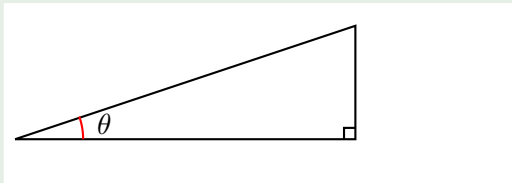
$$\sqrt{x^2 - 1} = \tan\theta \quad .$$

Definition

The trigonometric substitution $x = \sec\theta$, $\theta \in (0, \pi)$ for $\sqrt{x^2 + 1}$ is given by:

$$
\begin{aligned}
x &= \sec\theta = \frac{1}{\cos\theta} \qquad \theta \in \left[0, \frac{\pi}{2}\right) \cup \left[\pi, \frac{3\pi}{2}\right) \\
\sqrt{x^2 - 1} &= \tan\theta \\
\mathrm{d}x &= \frac{\sin\theta}{\cos^2\theta}\mathrm{d}\theta = \sec\theta\tan\theta\mathrm{d}\theta \\
\theta &= \operatorname{arcsec} x \quad .
\end{aligned}
$$

Example

Find $\int \frac{\mathrm{d}x}{\sqrt{x^2 - a^2}}$, $a > 0$.

- $x = a \sec \theta$,
  $0 < \theta < \pi/2$ or
  $\pi < \theta < 3\pi/2$.

- $\mathrm{d}x = a \sec \theta \tan \theta \mathrm{d}\theta$.
  $\sqrt{x^2 - a^2} = \sqrt{a^2 \sec^2 \theta - a^2} = \sqrt{a^2 \tan^2 \theta} = a|\tan \theta| = a \tan \theta$

$$
\begin{aligned}
\int \frac{\mathrm{d}x}{\sqrt{x^2 - a^2}} &= \int \frac{a \sec \theta \tan \theta \mathrm{d}\theta}{a \tan \theta} = \int \sec \theta \mathrm{d}\theta \\
&= \ln|\sec \theta + \tan \theta| + C = \ln\left| \frac{x}{a} + \frac{\sqrt{x^2 - a^2}}{a} \right| + C \\
&= \ln\left| x + \sqrt{x^2 - a^2} \right| + C_1
\end{aligned}
$$

Euler substitution $x = \sec\theta$, $\theta = 2\arctan t$

- $x = \sec\theta$ transforms $dx, x, \sqrt{x^2 - 1}$ to trig form.
- $\theta = 2\arctan t$, $t \in (-\infty, -1) \cup [0, 1)$ rationalizes $d\theta, \cos\theta, \sin\theta$.

What if we compose the above? We get the Euler substitution:

$$
\begin{aligned}
x &= \sec\theta = \frac{1}{\cos\theta} \\
&= \frac{1}{\cos(2\arctan t)} \\
&= \frac{1 + \tan^2(\arctan t)}{1 - \tan^2(\arctan t)} \\
&= \frac{1 + t^2}{1 - t^2} = \frac{2 - (1 - t^2)}{1 - t^2} \\
&= -1 + \frac{2}{1 - t^2}
\end{aligned}
\qquad \left| \; \cos(2z) = \frac{1 - \tan^2 z}{1 + \tan^2 z} \right.
$$

Euler substitution $x = \sec\theta$, $\theta = 2\arctan t$

- $x = \sec\theta$ transforms $dx, x, \sqrt{x^2-1}$ to trig form.
- $\theta = 2\arctan t$, $t \in (-\infty, -1) \cup [0, 1)$ rationalizes $d\theta, \cos\theta, \sin\theta$.

What if we compose the above? We get the Euler substitution:

$$
\begin{array}{rcl}
x & = & -1 + \dfrac{2}{1-t^2}
\end{array}
$$

$$
\begin{array}{rcll}
\sqrt{x^2-1} & = & \sqrt{\left(\dfrac{1+t^2}{1-t^2}\right)^2 - 1} & \\[4mm]
& = & \sqrt{\dfrac{(1+t^2)^2 - (1-t^2)^2}{(1-t^2)^2}} & \Big|\ (1+t^2)^2 - (1-t^2)^2 = 4t^2 \\[4mm]
& = & \sqrt{\dfrac{4t^2}{(1-t^2)^2}} & \Big|\ \begin{array}{l} t, 1-t^2 \text{ have same sign} \\ \text{when } t \in (-\infty, -1) \cup [0, 1) \end{array} \\[4mm]
& = & \dfrac{2t}{1-t^2} &
\end{array}
$$

Euler substitution $x = \sec\theta$, $\theta = 2\arctan t$

- $x = \sec\theta$ transforms $\mathrm{d}x, x, \sqrt{x^2 - 1}$ to trig form.
- $\theta = 2\arctan t$, $t \in (-\infty, -1) \cup [0, 1)$ rationalizes $\mathrm{d}\theta, \cos\theta, \sin\theta$.

What if we compose the above? We get the Euler substitution:

$$x = -1 + \frac{2}{1 - t^2}$$

$$\sqrt{x^2 - 1} = \frac{2t}{1 - t^2}$$

$$x = \frac{1 + t^2}{1 - t^2}$$

$$(1 - t^2)x = 1 + t^2$$

$$(1 + x)t^2 = x - 1$$

$$t^2 = \frac{x - 1}{x + 1}$$

$$t = \pm\sqrt{\frac{x - 1}{x + 1}}$$

Euler substitution $x = \sec\theta$, $\theta = 2\arctan t$

- $x = \sec\theta$ transforms $dx, x, \sqrt{x^2 - 1}$ to trig form.
- $\theta = 2\arctan t$, $t \in (-\infty, -1) \cup [0, 1)$ rationalizes $d\theta, \cos\theta, \sin\theta$.

What if we compose the above? We get the Euler substitution:

$$
\begin{aligned}
x &= -1 + \frac{2}{1 - t^2} \\[2mm]
\hline
\sqrt{x^2 - 1} &= \frac{2t}{1 - t^2} \\[2mm]
\hline
t &= \pm\sqrt{\frac{x - 1}{x + 1}} \\[2mm]
\hline
dx &= d\left(-1 + \frac{2}{1 - t^2}\right) \\[2mm]
&= \frac{4t}{(1 - t^2)^2}dt
\end{aligned}
$$

Euler substitution $x = \sec\theta$, $\theta = 2\arctan t$

- $x = \sec\theta$ transforms $dx, x, \sqrt{x^2 - 1}$ to trig form.
- $\theta = 2\arctan t$, $t \in (-\infty, -1) \cup [0, 1)$ rationalizes $d\theta, \cos\theta, \sin\theta$.

What if we compose the above? We get the Euler substitution:

Definition

The Euler substitution for $\sqrt{x^2 - 1}$ corresponding to $x = \sec\theta$ is given by:

$$
\begin{aligned}
x &= \frac{1 + t^2}{1 - t^2}, &\qquad t \in (-\infty, -1) \cup [0, 1) \\
\sqrt{x^2 - 1} &= \frac{2t}{1 - t^2} \\
dx &= \frac{4t}{(1 - t^2)^2} dt \\
t &= \pm\frac{\sqrt{x^2 - 1}}{x + 1} \quad .
\end{aligned}
$$

Rationalizing Substitutions

Some non-rational fractions can be changed into rational fractions by means of appropriate substitutions. In particular, when an integrand contains an expression of the form $\sqrt[n]{g(x)}$, the substitution $u = \sqrt[n]{g(x)}$ may be effective.

Example

Let $u = \sqrt{x+4}$. Then $u^2 = x + 4$, so $x = u^2 - 4$ and $dx = 2u\,du$.

$$
\begin{aligned}
\int \frac{\sqrt{x+4}}{x}dx &= \int \frac{u}{u^2 - 4} 2u\,du \\
&= 2 \int \frac{u^2}{u^2 - 4}du \\
&= 2 \int \left(1 + \frac{4}{u^2 - 4}\right) du && \text{long division} \\
&= 2 \int du + 8 \int \frac{du}{u^2 - 4} \\
&= 2 \int du + 8 \int \left(\frac{\frac{1}{4}}{u - 2} - \frac{\frac{1}{4}}{u + 2}\right) du && \text{partial fractions} \\
&= 2u + 2(\ln|u - 2| - \ln|u + 2|) + C \\
&= 2\sqrt{x+4} + 2\ln\left|\frac{\sqrt{x+4} - 2}{\sqrt{x+4} + 2}\right| + C
\end{aligned}
$$