Separable differential equations (Sect. 1.3).

- Separable ODE.
- Solutions to separable ODE.
- Explicit and implicit solutions.
- Euler homogeneous equations.

Separable ODE.

Definition
Given functions $h, g : \mathbb{R} \to \mathbb{R}$, a first order ODE on the unknown function $y : \mathbb{R} \to \mathbb{R}$ is called *separable* iff the ODE has the form

$$h(y)\, y'(t) = g(t).$$

Remark:
A differential equation $y'(t) = f(t, y(t))$ is separable iff

$$y' = \frac{g(t)}{h(y)} \quad \Leftrightarrow \quad f(t,y) = \frac{g(t)}{h(y)}.$$

Example

$$y'(t) = \frac{t^2}{1 - y^2(t)}, \qquad y'(t) + y^2(t)\cos(2t) = 0.$$

Separable ODE.

Example

Determine whether the differential equation below is separable,

$$y'(t) = \frac{t^2}{1 - y^2(t)}.$$

Solution: The differential equation is separable, since it is equivalent to

$$\left(1 - y^2\right) y' = t^2 \quad \Rightarrow \quad \begin{cases} g(t) = t^2, \\ h(y) = 1 - y^2. \end{cases}$$

$\lhd$

Remark: The functions g and h are not uniquely defined. Another choice here is:

$$g(t) = c\, t^2, \quad h(y) = c\,(1 - y^2), \quad c \in \mathbb{R}.$$

Separable ODE.

Example

Determine whether The differential equation below is separable,

$$y'(t) + y^2(t)\, \cos(2t) = 0$$

Solution: The differential equation is separable, since it is equivalent to

$$\frac{1}{y^2}\, y' = -\cos(2t) \quad \Rightarrow \quad \begin{cases} g(t) = -\cos(2t), \\ h(y) = \dfrac{1}{y^2}. \end{cases}$$

$\lhd$

Remark: The functions g and h are not uniquely defined. Another choice here is:

$$g(t) = \cos(2t), \quad h(y) = -\frac{1}{y^2}.$$

Separable ODE.

Remark: Not every first order ODE is separable.

Example

- The differential equation $y'(t) = e^{y(t)} + \cos(t)$ is not separable.
- The linear differential equation $y'(t) = -\dfrac{2}{t}\, y(t) + 4t$ is not separable.
- The linear differential equation $y'(t) = -a(t)\, y(t) + b(t)$, with $b(t)$ non-constant, is not separable.

Separable differential equations (Sect. 1.3).

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Solutions to separable ODE.

Theorem (Separable equations)

If the functions $g, h : \mathbb{R} \to \mathbb{R}$ are continuous, with $h \neq 0$ and with primitives G and H, respectively; that is,

$$G'(t) = g(t), \qquad H'(u) = h(u),$$

then, the separable ODE

$$h(y)\, y' = g(t)$$

has infinitely many solutions $y : \mathbb{R} \to \mathbb{R}$ satisfying the algebraic equation

$$H(y(t)) = G(t) + c,$$

where $c \in \mathbb{R}$ is arbitrary.

Remark: Given functions g, h, find their primitives G, H.

Solutions to separable ODE.

Example

Find all solutions y to the equation $y'(t) = \dfrac{t^2}{1 - y^2(t)}$.

Solution: The equation is equivalent to

$$\left(1 - y^2\right) y'(t) = t^2 \quad \Rightarrow \quad g(t) = t^2, \quad h(y) = 1 - y^2.$$

Integrate on both sides of the equation,

$$\int \left[1 - y^2(t)\right] y'(t)\, dt = \int t^2\, dt + c.$$

The substitution $u = y(t)$, $du = y'(t)\, dt$, implies that

$$\int (1 - u^2)\, du = \int t^2\, dt + c \quad \Leftrightarrow \quad \left(u - \frac{u^3}{3}\right) = \frac{t^3}{3} + c.$$

Solutions to separable ODE.

Example

Find all solutions y to the equation $y'(t) = \dfrac{t^2}{1 - y^2(t)}$.

Solution: Recall: $\left(u - \dfrac{u^3}{3}\right) = \dfrac{t^3}{3} + c$.

Substitute the unknown function y back in the equation above,

$$\left(y - \frac{y^3}{3}\right) = \frac{t^3}{3} + c, \qquad c \in \mathbb{R}.$$

Remark: Recall the notation in the Theorem:

$$g(t) = t^2 \quad \Rightarrow \quad G(t) = \frac{t^3}{3},$$

$$h(y) = 1 - y^2 \quad \Rightarrow \quad H(y) = y - \frac{y^3}{3}.$$

Hence we recover the Theorem expression: $H(y(t)) = G(t) + c$.

Solutions to separable ODE.

Remarks:

- The equation $y(t) - \dfrac{y^3(t)}{3} = \dfrac{t^3}{3} + c$ is algebraic in y, since there is no y' in the equation.
- Every function y satisfying the algebraic equation

$$y(t) - \frac{y^3(t)}{3} = \frac{t^3}{3} + c,$$

  is a solution of the differential equation above.
- We now verify the previous statement: Differentiate on both sides with respect to t, that is,

$$y'(t) - 3\left(\frac{y^2(t)}{3}\right) y'(t) = 3\,\frac{t^2}{3} \quad \Rightarrow \quad (1 - y^2)\, y' = t^2.$$

Solutions to separable ODE.

Example

Find all solutions y to the equation $y'(t) + y^2(t)\cos(2t) = 0$.

Solution: The differential equation is separable,

$$\frac{y'(t)}{y^2(t)} = -\cos(2t) \quad \Rightarrow \quad g(t) = -\cos(2t), \quad h(y) = \frac{1}{y^2}.$$

Integrate on both sides of the equation,

$$\int \frac{y'(t)}{y^2(t)}\, dt = -\int \cos(2t)\, dt + c.$$

The substitution $u = y(t)$, $du = y'(t)\, dt$, implies that

$$\int \frac{du}{u^2} = -\int \cos(2t)\, dt + c \quad \Leftrightarrow \quad -\frac{1}{u} = -\frac{1}{2}\sin(2t) + c.$$

Solutions to separable ODE.

Example

Find all solutions y to the equation $y'(t) + y^2(t)\cos(2t) = 0$.

Solution: Recall: $-\frac{1}{u} = -\frac{1}{2}\sin(2t) + c$.

Substitute the unknown function y back in the equation above,

$$-\frac{1}{y(t)} = -\frac{1}{2}\sin(2t) + c, \qquad c \in \mathbb{R}.$$

Remark: Recall the notation in the Theorem:

$$g(t) = -\cos(2t) \quad \Rightarrow \quad G(t) = -\frac{1}{2}\sin(2t).$$

$$h(y) = \frac{1}{y^2} \quad \Rightarrow \quad H(y) = -\frac{1}{y}.$$

Hence we recover the Theorem expression: $H(y(t)) = G(t) + c$.

Separable differential equations (Sect. 1.3).

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Explicit and implicit solutions.

Definition

Assume the notation in the Theorem above. The solution y of a separable ODE is given in *implicit form* iff function y is given by

$$H\big(y(t)\big) = G(t) + c,$$

The solution is given in *explicit form* iff function H is invertible and

$$y(t) = H^{-1}\big(G(t) + c\big).$$

Example

(a) $y(t) - \dfrac{y^3(t)}{3} = \dfrac{t^3}{3} + c$ is in implicit form.

(b) $-\dfrac{1}{y(t)} = -\dfrac{1}{2}\sin(2t) + c$ is in implicit form.

(c) $y(t) = \dfrac{2}{\sin(2t) - 2c}$ is in explicit form.

Separable differential equations (Sect. 1.3).

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Euler homogeneous equations.

Definition
The first order ODE $y'(t) = f\big(t, y(t)\big)$ is called *Euler homogeneous* iff for every numbers $c, t, u \in \mathbb{R}$ the function f satisfies

$$f(ct, cu) = f(t, u).$$

Remark:

- The function f is invariant under the change of scale of its arguments.
- If $f(t, u)$ has the property above, it must depend only on u/t.
- Therefore, there exists $F : \mathbb{R} \to \mathbb{R}$ such that $f(t, u) = F\Big(\dfrac{u}{t}\Big)$.
- So, a first order ODE is Euler homogeneous iff it has the form

$$y'(t) = F\Big(\frac{y(t)}{t}\Big).$$

Euler homogeneous equations.

Example

Show that the equation below is Euler homogeneous,

$$(t-y)\,y' - 2y + 3t + \frac{y^2}{t} = 0.$$

Solution: Rewrite the equation in the standard form

$$(t-y)\,y' = 2y - 3t - \frac{y^2}{t} \quad \Rightarrow \quad y' = \frac{\left(2y - 3t - \dfrac{y^2}{t}\right)}{(t-y)}.$$

Divide numerator and denominator by t. We get,

$$y' = \frac{\left(2y - 3t - \dfrac{y^2}{t}\right)}{(t-y)} \frac{\left(\dfrac{1}{t}\right)}{\left(\dfrac{1}{t}\right)} \quad \Rightarrow \quad y' = \frac{2\left(\dfrac{y}{t}\right) - 3 - \left(\dfrac{y}{t}\right)^2}{\left[1 - \left(\dfrac{y}{t}\right)\right]}.$$

Euler homogeneous equations.

Example

Show that the equation below is Euler homogeneous,

$$(t-y)\,y' - 2y + 3t + \frac{y^2}{t} = 0.$$

Solution: Recall: $y' = \dfrac{2\left(\dfrac{y}{t}\right) - 3 - \left(\dfrac{y}{t}\right)^2}{\left[1 - \left(\dfrac{y}{t}\right)\right]}$.

We conclude that the ODE is Euler homogeneous, because the right-hand side of the equation above depends only on y/t.

Indeed, in our case:

$$f(t,y) = \frac{2y - 3t - (y^2/t)}{t-y}, \qquad F(x) = \frac{2x - 3 - x^2}{1-x},$$

and $f(t,y) = F(y/t)$. $\lhd$

Euler homogeneous equations.

Example

Determine whether the equation below is Euler homogeneous,

$$y' = \frac{t^2}{1 - y^3}.$$

Solution:

Divide numerator and denominator by t^3, we obtain

$$y' = \frac{t^2}{(1 - y^3)} \, \frac{\left(\dfrac{1}{t^3}\right)}{\left(\dfrac{1}{t^3}\right)} \quad \Rightarrow \quad y' = \frac{\left(\dfrac{1}{t}\right)}{\left(\dfrac{1}{t^3}\right) - \left(\dfrac{y}{t}\right)^3}.$$

Then, the differential equation is not Euler homogeneous. $\lhd$

Euler homogeneous equations.

Theorem

If the equation $y'(t) = f\big(t, y(t)\big)$ is Euler homogeneous, then the differential equation for the unknown $v(t) = \dfrac{y(t)}{t}$ is separable.

Remark: Euler homogeneous equations can be transformed into separable equations.

Proof: If $y' = f(t, y)$ is Euler homogeneous, then it can be written as $y' = F(y/t)$ for some function F. Introducing $v = y/t$,

$$y(t) = t\, v(t) \quad \Rightarrow \quad y'(t) = v(t) + t\, v'(t).$$

Introduce all these changes into the ODE, then

$$v + t\, v' = F(v) \quad \Rightarrow \quad v' = \frac{\big(F(v) - v\big)}{t}.$$

This last equation is separable. $\square$

Euler homogeneous equations.

Example

Find all solutions y of the equation $y' = \dfrac{t^2 + 3y^2}{2ty}$.

Solution: The equation is Euler homogeneous, since

$$y' = \frac{t^2 + 3y^2}{2ty} \, \frac{\left(\frac{1}{t^2}\right)}{\left(\frac{1}{t^2}\right)} \quad \Rightarrow \quad y' = \frac{1 + 3\left(\frac{y}{t}\right)^2}{2\left(\frac{y}{t}\right)}.$$

Therefore, we introduce the change of unknown $v = y/t$, so $y = t\,v$ and $y' = v + t\,v'$. Hence

$$v + t\,v' = \frac{1 + 3v^2}{2v} \quad \Rightarrow \quad t\,v' = \frac{1 + 3v^2}{2v} - v = \frac{1 + 3v^2 - 2v^2}{2v}$$

We obtain the separable equation $v' = \dfrac{1}{t}\left(\dfrac{1 + v^2}{2v}\right)$.

Euler homogeneous equations.

Example

Find all solutions y of the equation $y' = \dfrac{t^2 + 3y^2}{2ty}$.

Solution: Recall: $v' = \dfrac{1}{t}\left(\dfrac{1 + v^2}{2v}\right)$. We rewrite and integrate it,

$$\frac{2v}{1 + v^2}\, v' = \frac{1}{t} \quad \Rightarrow \quad \int \frac{2v}{1 + v^2}\, v'\, dt = \int \frac{1}{t}\, dt + c_0.$$

The substitution $u = 1 + v^2(t)$ implies $du = 2v(t)\, v'(t)\, dt$, so

$$\int \frac{du}{u} = \int \frac{dt}{t} + c_0 \quad \Rightarrow \quad \ln(u) = \ln(t) + c_0 \quad \Rightarrow \quad u = e^{\ln(t) + c_0}.$$

But $u = e^{\ln(t)} e^{c_0}$, so denoting $c_1 = e^{c_0}$, then $u = c_1 t$. Hence

$$1 + v^2 = c_1 t \quad \Rightarrow \quad 1 + \left(\frac{y}{t}\right)^2 = c_1 t \quad \Rightarrow \quad y(t) = \pm t\sqrt{c_1 t - 1}.$$