3.6: Linear Independence and the Wronskian

Recall from linear algebra that two vectors \(v\) and \(w\) are called linearly dependent if there are nonzero constants \(c_1\) and \(c_2\) with
\[
\begin{align*}
c_1v + c_2w &= 0.
\end{align*}
\]

We can think of differentiable functions \(f(t)\) and \(g(t)\) as being vectors in the vector space of differentiable functions. The analogous definition is below.

Definition: Linear Dependence and Independence

Let \(f(t)\) and \(g(t)\) be differentiable functions. Then they are called linearly dependent if there are nonzero constants \(c_1\) and \(c_2\) with \(c_1f(t) + c_2g(t) = 0\) for all \(t\). Otherwise they are called linearly independent.

Example

\[
(1)(2\sin^2 t) + (-2)(1 - \cos^2(t)) = 0.
\]

Example

\[
(1)(2\sin^2 t) + (1 - \cos^2(t)) = 0.
\]

The functions \(f(t) = 2\sin^2 t\) and \(g(t) = 1 - \cos^2(t)\) are linearly dependent since
\[
\begin{align*}
(1)(2\sin^2 t) + (-2)(1 - \cos^2(t)) &= 0.
\end{align*}
\]

The functions \(f(t) = t\) and \(g(t) = t^2\) are linearly independent since otherwise there would be nonzero constants \(c_1\) and \(c_2\) such that
\[
\begin{align*}
c_1t + c_2t^2 &= 0.
\end{align*}
\]
for all values of \( t \). First let \( t = 1 \). Then

\[
[ \ c_1 + c_2 = 0. \nonumber \]

Now let \( t = 2 \). Then

\[
[\ 2c_1 + 4c_2 = 0 \nonumber \]

This is a system of 2 equations and two unknowns. The determinant of the corresponding matrix is

\[
[4 - 2 = 2. \nonumber \]

Since the determinant is nonzero, the only solution is the trivial solution. That is

\[
[ c_1 = c_2 = 0. \nonumber \]

The two functions are linearly independent.

In the above example, we arbitrarily selected two values for \( t \). It turns out that there is a systematic way to check for linear dependence. The following theorem states this way.

**Theorem**

Let \( f \) and \( g \) be differentiable on \( (a,b) \). If Wronskian \( W(f,g)(t_0) \) is nonzero for some \( t_0 \) in \( (a,b) \) then \( f \) and \( g \) are linearly independent on \( (a,b) \). If \( f \) and \( g \) are linearly dependent then the Wronskian is zero for all \( t \) in \( (a,b) \).

**Example \(~\text{PageIndex}~\{3\}\)**

Show that the functions \( f(t) = t \) and \( g(t) = e^{2t} \) are linearly independent.

**Solution**

We compute the Wronskian.

\[
[ f(t) = 1 \ g(t) = 2e^{2t} \nonumber \]

The Wronskian is

\[
[ (t)(2e^{2t}) - (e^{2t})(1) \nonumber \]

Now plug in \( t = 0 \) to get

\[
[ W(f, g)(0) = -1 \nonumber \]

which is nonzero. We can conclude that \( f \) and \( g \) are linearly independent.
Proof

If

\[ C_1 f(t) + C_2 g(t) = 0 \]

Then we can take derivatives of both sides to get

\[ C_1 f''(t) + C_2 g'(t) = 0 \]

This is a system of two equations with two unknowns. The determinant of the corresponding matrix is the Wronskian. Hence, if the Wronskian is nonzero at some \( t_0 \), only the trivial solution exists. Hence they are linearly independent.

\( \square \)

There is a fascinating relationship between second order linear differential equations and the Wronskian. This relationship is stated below.

Theorem: Abel's Theorem

Let \( (y_1) \) and \( (y_2) \) be solutions on the differential equation

\[ L(y) = y'' + p(t)y' + q(t)y = 0 \]

where \( (p) \) and \( (q) \) are continuous on \( ([a,b]) \). Then the Wronskian is given by

\[ W_{y_1, y_2}(t) = ce^{-\int p(t) dt} \]

where \( (c) \) is a constant depending on only \( (y_1) \) and \( (y_2) \), but not on \( (t) \). The Wronskian is either zero for all \( (t) \) in \( ([a,b]) \) or not in \( ([a,b]) \).

Proof

First the Wronskian

\[ W = y_1y'_2 - y_1y_2 \]

has derivative

\[ W' = y_1y''_2 - y''_1y_2 \]

Since \( (y_1) \) and \( (y_2) \) are solutions to the differential equation, we have

\[ y''_1 + p(t)y'_1 + q(t)y_1 = 0 \]
\[ y''_2 + p(t)y'_2 + q(t)y_2 = 0 \]
Multiplying the first equation by \((-y_2)\) and the second by \((y_1)\) and adding gives
\[ (y_1y''_2 - y''_1y_2) + p(t)(y_1y'_2 - y_1y_2) = 0. \]
This can be written as
\[ W' + p(t)W = 0. \]
This is a separable differential equation with
\[ \frac{dW}{W} = -p(t) \, dt. \]
Now integrate and Abel's theorem appears.

Example \(\PageIndex{4}\)

Find the Wronskian (up to a constant) of the differential equations
\[ y'' + \cos(t) \, y = 0. \]
Solution

We just use Abel's theorem, the integral of \(\cos t\) is \(\sin t\) hence the Wronskian is
\[ W(t) = ce^{\sin t}. \]
A corollary of Abel's theorem is the following

Corollary

Let \((y_1)\) and \((y_2)\) be solutions to the differential equation
\[ L(y) = y'' + p(t)y' + q(t)y = 0 \]
Then either \(W(y_1, y_2)\) is zero for all \(t\) or never zero.

Example \(\PageIndex{5}\)

Prove that
\[ y_1(t) = 1 - t \text{ and } y_2(t) = t^3 \]
cannot both be solutions to a differential equation.
\[ y'' + p(t)y + q(t) = 0 \]

for \( p(t) \) and \( q(t) \) continuous on \( [-1, 5] \).

**Solution**

We compute the Wronskian

\[ y'_1 = -1 \text{ and } y'_2 = 3t^2 \]

\[ W(y_1, y_2) = (1 - t)(3t^2) - (t^3)(-1) = 3t^2 - 2t^3. \]

Notice that the Wronskian is zero at \( t = 0 \) but nonzero at \( t = 1 \). By the above corollary, \( y_1 \) and \( y_2 \) cannot both be solutions.

---

**Contributors**

- **Larry Green** *(Lake Tahoe Community College)*