

Running Lecture Outline: 707

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1 26-AUG-24

1.1 Order, Linear, and PDE vs ODE

2 28-AUG-24

2.1 Miscellaneous

I'm doing this to not fall asleep in class. Prof is Phillip Hutton. There are several ways to take the quiz. Quiz, office hours, etc. you can also take it in class. All quiz get one page cheat sheet.

2.2 More miscellany

Prof is doing some incredible projector gymnastics. He should record balance beam events.

2.3 Verifying solutions using initial conditions

To verify potential solutions, plug into the original diffeq. Use algebra (ha!) to make LHS = RHS. On the other hand, we can simply plug in various numbers for x and check for equivalency. Obviously, check for domains.

Example 2.1.

$$y' = xy^{\frac{1}{2}}$$

Potential Solution:

$$y = \frac{1}{16}x^4$$

Then,

$$\frac{dy}{dx} = \frac{1}{4}x^3$$

Then, plug into the original diffeq. We have:

$$\frac{1}{4}x^3 = x\left(\frac{1}{16}x^4\right)^{\frac{1}{2}}$$

or that

$$\frac{1}{4}x^3 = \frac{1}{4}x^3$$

as desired.

Example 2.2.

$$(y - x)\frac{dy}{dx} = y - x + 8$$

Potential Solution 1:

$$y = 2x + 4\sqrt{x+2}$$

Potential Solution 2:

$$y = x + 4\sqrt{x+2}$$

Case 1:

$$\frac{dy}{dx} = 2 + 2(x+2)^{-\frac{1}{2}}$$

Then, plug into the original diffeq. We have:

$$(2x + 4\sqrt{x+2} - x)(2 + 2(x+2)^{-\frac{1}{2}}) = 2x + 4\sqrt{x+2} - x + 8$$

Simplifying,

$$(x + 4\sqrt{x+2})(2 + 2(x+2)^{-\frac{1}{2}}) = x + 8 + 4\sqrt{x+2}$$

Consider the case that $x = 0$. Then,

$$(4\sqrt{2})(2 + 2(2)^{-\frac{1}{2}}) = 8 + 4\sqrt{2}$$

$$8\sqrt{2} + 8 = 8 + 4\sqrt{2}$$

or that

$$8\sqrt{2} = 4\sqrt{2}$$

which is clearly false.

Solution 2 works. You plug it in like above, but end with a true statement.

2.4 IVPs

Solving a diffeq yields a *general* solution with unknowns. Using initial values we can then solve for said unknowns. For n unknowns, we need n initial values.

Let's do an example!

Example 2.3. $y' = y$, where $y(0) = 3$. We know our general solution is

$$y = Ce^x$$

but what is C ? clearly, since $y(0) = 3$, and at $x = 0$, $y = c$, $3 = C$. Thus, the equation is really

$$y = 3e^x$$

Example 2.4. $y' + 2xy^2 = 0$, where $y(0) = 1$. The general solution to this is $y = \frac{1}{x+C}$. Plugging in at $x = 0$, we have $C = -1$. Final solution is $y = \frac{1}{x-1}$.

Example 2.5. $x'' + 16x = 0$, where $x(\frac{\pi}{2}) = -2$, $x'(\frac{\pi}{2}) = 1$. The general solution is

$$x = C_1 \cos 4t + C_2 \sin 4t$$

You plug in twice, you get $C_1 = -2$ and after the second step you get $C_2 = \frac{1}{4}$. Then plug in to general equation. Yay.

3 30-AUG-24

3.1 Integrating Factor

This is the most fun McIlwain review. When do we use this?

Theorem 1. *If you can write a differential equation to be of the form $\frac{dy}{dx} + p(x)y = f(x)$, you are eligible to use Integrating Factor.*

The algorithm for solving goes something like this:

$$\frac{dy}{dx} + p(x)y = f(x)$$

Multiply both sides by:

$$I_f = e^{\int p(x) dx}$$

You get:

$$e^{\int p(x) dx} \frac{dy}{dx} + e^{\int p(x) dx} p(x)y = e^{\int p(x) dx} f(x)$$

Using reverse chain rule:

$$\frac{d}{dx} [e^{\int p(x) dx} y] = e^{\int p(x) dx} f(x)$$

Integrating both sides, we get:

$$e^{\int p(x) dx} y = \int e^{\int p(x) dx} f(x)$$

This gets us:

$$y(x) = \frac{\int e^{\int p(x) dx} f(x)}{e^{\int p(x) dx}}$$

Example 3.1.

$$\frac{dy}{dx} = 5y$$

This seems separable, and it is. But if you were to use integrating factor, it goes like this:

$$\frac{dy}{dx} - 5y = 0$$

Note that this makes $p(t) = -5$

$$y = Ce^{5x}$$

Example 3.2.

$$\frac{dy}{dx} + y = e^{3x}$$

Note that this makes $p(x) = 1$, $f(x) = e^{3x}$

$$e^x \frac{dy}{dx} = e^{3x} e^x = e^{4x}$$

$$e^x y = \frac{1}{4} e^{4x} + C$$

$$y = \frac{\frac{1}{4} e^{4x} + C}{e^x}$$

or:

4 04-SEP-24

We have a quiz lol. Three questions, about 20-25 minutes.

4.1 Separation of Variables

Definition 1 (separable). A differential equation is separable if you can put it into the form $\frac{dy}{dx} = f(x)h(y)$, where f h are functions.

The steps to solving them are as follows:

$$\frac{dy}{dx} = f(x)h(y)$$

$$\frac{dy}{h(y)} = f(x)dx$$

$$\int \frac{dy}{h(y)} = \int f(x)dx$$

then, solve. Let's check for separability of some cases:

Example 4.1.

$$\frac{dy}{dx} - y = \cos x$$

$$\frac{dy}{dx} = \cos x + y$$

This does not satisfy the form specified in the definition, so it is *not separable*.

Example 4.2.

$$\frac{dy}{dx} = x^2 y^4 e^{5x-3y}$$

We can rewrite as:

$$\frac{dy}{dx} = (x^2 e^{5x})(y^4 e^{-3y})$$

This is separable, as it satisfies the above form.

Now, let's solve one:

Example 4.3.

$$(1-x)dy = -ydx$$

where $y(0) = 5$

Rewriting, we get:

$$\frac{1}{1-x}dx = \frac{-1}{y}dy$$

Integrating, we get:

$$-\ln 1 - x = -\ln y + C$$

When $y(0) = 5$, we have $0 = -\ln 5 + C$, so $C = \ln 5$. So,

$$-\ln 1 - x = -\ln y + \ln 5$$

and then:

$$\ln y = \ln 1 - x + \ln 5$$

Exponentiating,

$$e^{\ln y} = e^{\ln 1 - x + \ln 5}$$

$$y = 5(1 - x)$$

Example 4.4.

$$\frac{1}{y} \frac{dy}{dx} = 1 - x$$

where $y(0) = 2$. The joke is you don't actually need to use separation to do this. But you can.

5 06-SEP-24

5.1 Exact Equations

Exact equations are a specific form of differential equation.

Definition 2. For $f(x, y) = k$, where k is a constant, then $df = \frac{df}{dx}dx + \frac{df}{dy}dy = 0$.

Then, let us define $M(x, y) = \frac{df}{dx}$ and $N(x, y) = \frac{df}{dy}$. So, $M(x, y)dx + N(x, y)dy = 0$. Differentiating, we get:

$$\frac{dm}{dy} = \frac{d^2f}{dxdy} = \frac{dN}{dx}$$

Definition 3. If $M(x, y)dx + N(x, y)dy = 0$ and $\frac{dm}{dy} = \frac{d^2f}{dxdy} = \frac{dN}{dx}$, then $\frac{df}{dx} = M$ and $\frac{df}{dy} = N$.

This gives us a general algorithm for solving differential equations of some classes:

1. Put the DE into form $M(x, y)dx + N(x, y)dy = 0$
2. Then, identify $M(x, y)$ and $N(x, y)$
3. Then, test for exactness: that is, $\frac{dM}{dy} = \frac{dN}{dx}$. If true, we have an exact equation.
4. From $\frac{df}{dx} = M$, we have $df = Mdx$, which, when integrating, gets $f(x, y) = g(x, y) + h(y)$.
5. Similarly, from $\frac{df}{dy} = N$, we have $\frac{df}{dy} = \frac{dg}{dy} + \frac{dh}{dy} = N$, which, when integrating, gets $f(x, y) = g(x, y) + h(y)$. Think of $h(y)$ as a constant term.
6. This gets us $h(y) = \int N - \frac{dg}{dy}dy$. Then we substitute $h(y)$ into $f(x, y)$ and set $f(x, y) = C$.

I think an example may help more.

Example 5.1. $-2xydx = (x^2 - 1)dy$. Set up involves rewriting into the form, which gives us:

$$2xydx + (x^2 - 1)dy = 0$$

where $M = 2xy$, $N = x^2 - 1$. Then, we check if the equation is exact, which requires us to take the partials of both sides, that is $\frac{dM}{dy}$ and $\frac{dN}{dx}$. Since they are both $2x$, we're good to continue. Now, $\frac{df}{dx} = 2xy$, and then $f(x, y) = \int 2xydx$. We get $f(x, y) = x^2y + h(y)$. We now do the same thing for $\frac{df}{dy} = N$. That is, $\frac{df}{dy} = N$. That is,

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

, and so $\frac{dh}{dy} = -1$. Then, $\int dh = -\int dy$, and so $h(y) = -y + C$. Setting $f(x, y) = C$, we have $x^2y - y = C$.

Another example.

Example 5.2. $(x^2 + 2xy + y^2)dx + (2xy + x^2 - 1)dy = 0$ There's a cheeky sum of squares method for this. $M = (x^2 + 2xy + y^2)$ and $N = (2xy + x^2 - 1)$. Doing the test, we get $\frac{dM}{dy} = 2x + 2y = \frac{dN}{dx}$. This is true, by the wonders of the commutative property. Then, $\frac{df}{dx} = M = x^2 + 2xy + y^2$. Integrating, we get some silly little equation:

$$f(x, y) = \frac{1}{3}x^3 + x^2y + xy^2 + h(y)$$

. Then, if $\frac{df}{dy} = N$, we can solve for $h(y)$, as then $\frac{d}{dy}f(x, y) = x^2y + 2xy + -1$, and so $\frac{dh}{dy} = -1$, and then $h(y) = -y + C$. And then we set $f(x, y) = C$.

Another one. Cue DJ Khaled.

Example 5.3. $(x^3 + \cos y + \frac{1}{x})dy = (\frac{y}{x^2} - 3x^2y)dx$. Initially, N is on the left, M is on the right. More accurately,

$$(\frac{y}{x^2} - 3x^2y)dx - (x^3 + \cos y + \frac{1}{x})dy = 0$$

$\frac{dM}{dy} = \frac{1}{x^2} - 3x^2$. This is the same as $\frac{dN}{dx}$. Practice these differentiations, kids. Therefore, this is an exact equation.

$\frac{df}{dx} = M \implies f(x, y) = \frac{-y}{x} - x^3y + h(y)$. Similarly, $\frac{df}{dy} = N$ and $\frac{df}{dy} = \frac{-1}{x} - x^3 + \frac{dh}{dy} = -(x^3 + \cos y + \frac{1}{x})$. Then, solve for $h(y)$ and continue, and you're done.

6 09-SEP-24

6.1 Separation of Variables, but more

Example 6.1. Find the general solution to the differential equation:

$$\begin{aligned} e^{-2y}dy &= e^{3x}dx \\ -\frac{1}{2}e^{-2y} &= \frac{1}{3}e^{3x} + C \end{aligned}$$

Multiplying by -2 , we have:

$$e^{-2y} = \frac{-2}{3}e^{3x} + C$$

Taking natural logs:

$$\begin{aligned} \ln e^{-2y} &= \ln \frac{-2}{3}e^{3x} + C \\ -2y &= \ln \frac{-2}{3}e^{3x} + C \end{aligned}$$

6.2 Exact equations, but more

Example 6.2. Find the general solution of:

$$(\sin y - y \sin x)dx = -(\cos x + x \cos y)dy$$

First, get it into the form:

$$(\sin y - y \sin x)dx + (\cos x + x \cos y)dy = 0$$

Note that $M_y = \cos y - \sin x$ and $N_x = -\sin x + \cos y$. It is exact.

$$\int Mdx = x \sin y + \cos xy$$

Therefore, $\psi(x, y) = x \sin y + \cos xy + h(y)$. Then, we take the partial again:

$$\psi(x, y)_y = x \cos y + \cos x + h'(y)$$

Note that $N = \cos x + x \cos y$ and so $h'(y) = 0$. We get: $x \sin y + \cos xy = C$.

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7.1 Bernoulli Equations

So what is Bernoulli's equation?

Definition 4. Bernoulli equations are of the form:

$$\frac{dy}{dx} + p(x)y = f(x)y^n$$

Notice that this is nonlinear. So we have to make it linear, to make our life easier.

Here's the steps:

1. Put the differential equation in the form $\frac{dy}{dx} + p(x)y = f(x)y^n$, and then identify n .
2. Then, substitute $y = u^{\frac{1}{1-n}}$, which implies that $\frac{dy}{dx} = \frac{1}{1-n} u^{\frac{1}{1-n}-1} \frac{du}{dx}$.
3. This will be an ODE. We then solve for u using either separation of variables, integrating factor, or exact equations. It's usually integrating factor.
4. Then, once we solve for u , substitute back $u = y^{1-n}$, and then solve for $y(x)$.

Example 7.1. Let's solve:

$$x \frac{dy}{dx} + y = x^2 y^2$$

The first step is easy. To put it in the form $\frac{dy}{dx} + p(x)y = f(x)y^n$, we divide by x , which gives us:

$$\frac{dy}{dx} + \frac{1}{x}y = xy^2$$

Note that this makes $n = 2$. Then, we substitute for u :

$$y = u^{-1} \implies \frac{dy}{dx} = -u^{-2} \frac{du}{dx}$$

Continuing our evaluation, we get:

$$-u^{-2} \frac{du}{dx} + \frac{1}{x} \frac{1}{u} = x(u^{-1})^2$$

which gets us

$$\frac{du}{dx} - \frac{1}{x}u = -x$$

This is easy to solve using integrating factor. Note that $p(x) = -\frac{1}{x}$. We end up with $u(x) = -x^2 - Cx$. (Note that I would always write $+Cx$ here, but I'm following the professor's directive). Plugging it back in, we have $u = y^{-1}$. We end up with $y = (-x^2 - Cx)^{-1}$.

Another one.

Example 7.2. Let's solve:

$$x^2 \frac{dy}{dx} - 2xy = 3y^4$$

We divide by x^2 now, which gives us:

$$\frac{dy}{dx} - \frac{2}{x}y = \frac{3}{x^2}y^4$$

So, $n = 4$. Then, we substitute for u :

$$y = u^{-\frac{1}{3}} \implies \frac{dy}{dx} = -\frac{1}{3}u^{-\frac{4}{3}} \frac{du}{dx}$$

This gives us

$$-\frac{1}{3}u^{-\frac{4}{3}} \frac{du}{dx} - \frac{2}{x}u^{-\frac{1}{3}} = \frac{3}{x^2}u^{-\frac{4}{3}}$$

which gets us

$$\frac{du}{dx} + \frac{6}{x}u = -\frac{9}{x^2}$$

Integrating factor gets us $u(x) = C/x^6 - \frac{9}{5x}$. Since $u(x) = y^{-3}$, $y^{-3} = C/x^6 - \frac{9}{5x}$, which gets us:

$$y = (C/x^6 - \frac{9}{5x})^3$$

Example 7.3. Let's solve:

$$x^2 \frac{dy}{dx} - 2xy = 3y^4$$

We divide by x^2 now, which gives us:

$$\frac{dy}{dx} - \frac{2}{x}y = \frac{3}{x^2}y^4$$

So, $n = 4$. Then, we substitute for u :

$$y = u^{-\frac{1}{3}} \implies \frac{dy}{dx} = \frac{-1}{3}u^{-\frac{4}{3}} \frac{du}{dx}$$

This gives us

$$\frac{-1}{3}u^{-\frac{4}{3}} \frac{du}{dx} - \frac{2}{x}u^{-\frac{1}{3}} = \frac{3}{x^2}u^{-\frac{4}{3}}$$

which gets us

$$\frac{du}{dx} + \frac{6}{x}u = -\frac{9}{x^2}$$

Integrating factor gets us $u(x) = C/x^6 - \frac{9}{5x}$. Since $u(x) = y^{-3}$, $y^{-3} = C/x^6 - \frac{9}{5x}$, which gets us:

$$y = (C/x^6 - \frac{9}{5x})^{-\frac{1}{3}}$$

Another one.

Example 7.4. Let's solve:

$$x \frac{dy}{dx} + y - y^{-2} = 0$$

Step 1:

$$\frac{dy}{dx} + \frac{1}{x}y = \frac{1}{x}y^{-2}$$

So, $n = -2$. Substitute for u :

$$y = u^{\frac{1}{3}} \implies \frac{dy}{dx} = \frac{1}{3}u^{-\frac{2}{3}} \frac{du}{dx}$$

Then,

$$\frac{1}{3}u^{-\frac{2}{3}} \frac{du}{dx} + \frac{1}{x}u^{\frac{1}{3}} = \frac{1}{x}u^{-\frac{2}{3}}$$

which gets us

$$\frac{du}{dx} + \frac{3}{x}u = \frac{3}{x}$$

Integrating factor gets us $u(x) = \frac{C}{x^3} + 1$. So $y^3 = \frac{C}{x^3} + 1$, which gets us:

$$y = (\frac{C}{x^3} + 1)^{\frac{1}{3}}$$

8 13-SEP-24

8.1 Second order ODEs with constant coefficients

The form of this equation is:

$$a \frac{dy^2}{dx^2} + b \frac{dy}{dx} + cy = 0$$

where a, b, c are constants.

Here are the general steps:

1. Put the DE into the form $ay'' + by' + c = 0$, and then identify a, b, c
2. Then, find the roots to the characteristic equation $am^2 + bm + c = 0$, using the quadratic equation.
3. Your solution depends on your solutions to this characteristic equation m_1, m_2 .

Theorem 2. If $m_1, m_2 \in \mathbb{R}$ and $m_1 \neq m_2$, then the solution becomes

$$y = C_1 e^{m_1 x} + C_2 e^{m_2 x}$$

Theorem 3. If $m_1, m_2 \in \mathbb{R}$ and $m_1 = m_2$, then the solution becomes

$$y = C_1 e^{m_1 x} + C_2 x e^{m_1 x}$$

Theorem 4. If $m_1, m_2 = \alpha \pm i\beta$, then the solution becomes

$$y = e^{\alpha x} (C_1 \cos \beta x + C_2 \sin \beta x)$$

Here's an example:

Example 8.1.

$$2y'' + 12y = -10y' = 0$$

This is the same as

$$y'' + 5y' + 6 = 0$$

Solving the quadratic we get $m_1 = 2$ and $m_2 = 3$. By Theorem 2 we have $C_1 e^{-2x} + C_2 e^{-3x}$

Example 8.2.

$$y'' - 10y' + 25y = 0$$

Some work gets us $m_1 = m_2 = 5$. Using Theorem 3, we get $C_1 e^{5x} + C_2 x e^{5x}$

Example 8.3.

$$4y'' + 4y' + 17y = 0$$

where $y(0) = -1$ and $y'(0) = 2$ Using the silly quadratic formula, we get $m_{1,2} = \frac{-1}{2} \pm j2$ where $\alpha = \frac{-1}{2}$ and $\beta = 2$. Using Theorem 4, our general solution is

$$y = e^{\frac{-1}{2}x} (C_1 \cos 2x + C_2 \sin 2x)$$

Then, we solve for initial conditions. Using product rule, we get:

$$\frac{dy}{dx} = \frac{-1}{2} e^{\frac{-1}{2}x} (C_1 \cos 2x + C_2 \sin 2x)$$

We can then apply initial conditions. Using $y(0) = -1$ on the general solution, we have $-1 = C_1$. Plugging the second initial condition and $-1 = C_1$ into the equation for $\frac{dy}{dx}$ we get that $C_2 = \frac{3}{4}$.

We end up with:

$$y = e^{\frac{-1}{2}x} \left(-1 \cos 2x + \frac{3}{4} \sin 2x \right)$$

Example 8.4.

$$y'' - y' - 6y = 0$$

where $y(0) = 4$ $y'(0) = -3$ Using math, $m_1 = 3$, $m_2 = -2$. Using 2, we get the general solution is:

$$y = C_1 e^{3x} + C_2 e^{-2x}$$

We do some similar malarkey to find C_1 and C_2 . We end up with a systems of equations:

$$\begin{cases} C_1 + C_2 = 4 \\ 3C_1 - 2C_2 = -3 \end{cases}$$

We end up with $C_1 = 1$, $C_2 = 3$. I end up with:

$$y = e^{3x} - 3e^{-2x}$$

9 16-SEP-2024

9.1 Examples, again

Here's a Bernoulli's equation example:

Example 9.1. Give the general solution to $y' = e^x y^2 + y$. The form of Bernoulli is

$$y' - y = e^x y^2$$

So, $n = 2$. We then substitute, $y = u^{-1}$, and so $\frac{dy}{dx} = -u^{-2} \frac{du}{dx}$. Then,

$$u^{-2} \frac{du}{dx} - u^{-1} = e^x u^{-2}$$

This is solvable using integrating factor. We get $u = \frac{-1}{2}e^x + Ce^{-x}$. Since $y = u^{-1}$, $u = y^{-1}$. So, $y = (\frac{-1}{2}e^x + Ce^{-x})^{-1}$.

Let's do a second order ODE example.

Example 9.2.

$$y'' = 36y$$

We get that $m^2 - 36 = 0$, or that $m = \pm 6$. This gets us $C_1 e^{-6x} + C_2 e^{6x}$.

Another Bernoulli's.

Example 9.3.

$$3(1 - x^2)y' = 2xy(y^3 - 1)$$

In standard Bernoulli Form, we have:

$$y' + \frac{2x}{3(1 - x^2)}y = \frac{2x}{3(1 - x^2)}y^4$$

$n = 4$, and so $y = u^{-\frac{1}{3}}$. $\frac{dy}{dx} = -\frac{1}{3}u^{-\frac{4}{3}} \frac{du}{dx}$. Then, we rewrite and some small mental gymnastics. We have:

$$\frac{du}{dx} - \frac{2x}{1 - x^2}u = \frac{-2x}{1 - x^2}$$

Using integrating factor again, we get:

$$u = 1 + C(1 - x^2)$$

So, $y^{-3} = 1 + C(1 - x^2)$