Fri Mar 9

5.3 Solving constant coefficient homogeneous linear differential equations: complex roots in the characteristic polynomial

Announcements: another magic day... your labs yesterday told you the recipe for finding solutions to homog. linear const. coeff DE's, when the roots of characteristic polynomial are complex

$r = a \pm ib$ root $\longrightarrow y(x) = e^{ax}\cos bx,\ e^{ax}\sin bx$

$y(x) = e^{rx}$

• first, finish Wed

'til 10:47

Warm-up Exercise: Recall Taylor-McLaurin series from Calculus 2:

$$f(x) = f(0) + f'(0)x + \frac{1}{2!}f''(0)x^2 + \frac{1}{3!}f'''(0)x^3 + \ldots$$

(The series on the right is created to match $f(0), f'(0), f''(0), \ldots$)

Recover the McLaurin series for

a) $e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \frac{x^4}{4!} + \ldots$ $\qquad 3! = 3\cdot2\cdot1$ etc.

See notes below

b) $\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \frac{x^6}{6!} + \ldots$

even function so even powers

c) $\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \ldots$

odd function so odd powers

(finishing up on Friday, from Wednesday's notes, before proceeding to complex roots)

Here's the general algorithm: If

$$p(r) = (r - r_1)^{k_1} (r - r_2)^{k_2} \dots (r - r_m)^{k_m}$$

then (as before) $e^{r_1 x}, e^{r_2 x}, \dots, e^{r_m x}$ are independent solutions, but since $m < n$ there aren't enough of them to be a basis. Here's how you get the rest: For each $k_j > 1$, you actually get independent solutions

$$e^{r_j x}, x e^{r_j x}, x^2 e^{r_j x}, \dots, x^{k_j - 1} e^{r_j x}.$$

This yields k_j solutions for each root r_j, so since $k_1 + k_2 + \dots + k_m = n$ you get a total of n solutions to the differential equation. There's a good explanation in the text as to why these additional functions actually do solve the differential equation, see pages 316-318 and the discussion of "polynomial differential operators". I've also made a homework problem in which you can explore these ideas. Using the limiting method we discussed earlier, it's not too hard to show that all n of these solutions are indeed linearly independent, so they are in fact a basis for the solution space to $L(y) = 0$.

Exercise 3) Explicitly antidifferentiate to show that the solution space to the differential equation for $y(x)$

$$y^{(4)} - y^{(3)} = 0$$

agrees with what you would get using the repeated roots algorithm in Case 2 above. Hint: first find $v = y'''$, using $v' - v = 0$, then antidifferentiate three times to find y_H. When you compare to the repeated roots algorithm, note that it includes the possibility $r = 0$ and that $e^{0x} = 1$.

$L(y) = y^{(4)} - y^{(3)} = 0$

$y = e^{rx}$: $L(e^{rx}) = (e^{rx})^{(4)} - (e^{rx})^{(3)}$

$= r^4 e^{rx} - r^3 e^{rx}$

$= e^{rx}(r^4 - r^3) \overset{\text{want}}{=} 0$

$r^4 - r^3 = 0$

$r^3 (r-1)$

$(r-0)^3 (r-1) = 0$

basis of solutions:

recipe: e^x, 1, x, x^2

$r=1$; $1 \uparrow e^{0x}$, $x \uparrow xe^{0x}$, $x^2 \uparrow x^2 e^{0x}$

Chapter 1

$v = y'''$ then DE says

$v' - v = 0$

$e^{-x}(v' - v) = 0$

$\frac{d}{dx}(e^{-x} v) = 0$

$e^{-x} v = C$

$v = Ce^x$

$y''' = Ce^x$

$y'' = Ce^x + D$

$y' = Ce^x + Dx + E$

S: $y = Ce^x + \frac{D}{2}x^2 + Ex + F$

Case 3) Complex number roots - this will be our surprising and fun topic on Friday. Our analysis will explain exactly how and why trig functions and mixed exponential-trig-polynomial functions show up as solutions for some of the homogeneous DE's you worked with in your homework and lab for this past week. This analysis depends on Euler's formula, one of the most beautiful and useful formulas in mathematics:

$$e^{i\theta} = \cos(\theta) + i \sin(\theta)$$

for $i^2 = -1$.

5.3 continued. How to find the solution space for n^{th} order linear homogeneous DE's with constant coefficients, and why the algorithms work.

$L(y) = y^{(n)} + a_{n-1} y^{(n-1)} + \dots + a_1 y' + a_0 y = 0$

Strategy: In all cases we first try to find a basis for the n-dimensional solution space made of or related to exponential functions....trying $y(x) = e^{rx}$ yields

$$L(y) = e^{rx}\left(r^n + a_{n-1}r^{n-1} + \dots + a_1 r + a_0\right) = e^{rx} p(r) \, .$$

The characteristic polynomial $p(r)$ and how it factors are the keys to finding the solution space to $L(y) = 0$. There are three cases, of which the first two (distinct and repeated real roots) are in yesterday's notes.

Case 3) $\boxed{p(r) \text{ has complex number roots.}}$ This is the hardest, but also most interesting case.The punch line is that exponential functions e^{rx} still work, except that $r = a \pm b\,i$; but, rather than use those complex exponential functions to construct solution space bases we decompose them into real-valued solutions that are products of exponential and trigonometric functions.

punchline in lab: if $r = a \pm bi$ is complex root then $y_1 = e^{ax}\cos bx$, $e^{ax}\sin bx$ are real soltns.

Magic What do these have to do with $e^{(a+bi)x}$, $e^{(a-bi)x}$

To understand how this all comes about, we need to learn Euler's formula . This also lets us review some important Taylor's series facts from Calc 2. As it turns out, complex number arithmetic and complex exponential functions actually are important in many engineering and science applications.

Recall the Taylor-Maclaurin formula from Calculus

$$f(x) \sim f(0) + f'(0)x + \frac{1}{2!}f''(0)x^2 + \frac{1}{3!}f'''(0)x^3 + ... + \frac{1}{n!}f^{(n)}(0)x^n + ...$$

(Recall that the partial sum polynomial through order n matches f and its first n derivatives at $x_0 = 0$. When you studied Taylor series in Calculus you sometimes expanded about points other than $x_0 = 0$. You also needed error estimates to figure out on which intervals the Taylor polynomials actually coverged back to f.)

Warm-up.

Exercise 1) Use the formula above to recall the three very important Taylor series for

converge for all x

1a) $e^x = 1 + 1x + \frac{1}{2!}x^2 + \frac{1}{3!}x^3 + \dots + \frac{1}{n!}x^n + \dots$

$f(0)=1 \quad f'(0)=1, \quad f''(0)=1, \quad \dots$

$f(x)=e^x, \quad f'(x)=e^x, \quad f''(x)=e^x, \dots$

1b) $\cos(x) = 1 - \frac{1}{2!}x^2 + \frac{1}{4!}x^4 - \frac{1}{6!}x^6 + \dots$

$f(0)=1, \quad f'(0)=0, \quad f''(0)=-1 \quad f'''(0)=0 \quad f^{(4)}(0)=1$, repeat

$f(x)=\cos x, \quad f'(x)=-\sin x, \quad f''(x)=-\cos x, \quad f'''(x)=\sin x, \quad f^{(4)}(x)=\cos x$, repeat!

1c) $\sin(x) = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \dots$

$f(0)=0 \quad f'(0)=1 \quad f''(0)=0 \quad f'''(0)=-1 \quad f^{(4)}(0)=0$, repeat

$f(x)=\sin x, \quad f'(x)=\cos x, \quad f''(x)=-\sin x, \quad f'''(x)=-\cos x, \quad f^{(4)}(x)=\sin x$, repeat

In Calculus you checked that these series actually converge and equal the given functions, for all real numbers x.

Exercise 2) Let $x = i\,\theta$ and use the Taylor series for e^x as the definition of $e^{i\,\theta}$ in order to derive Euler's formula:

$i = \sqrt{-1} \quad i^2 = -1$

$i^3 = i^2 i = -i$

$$e^{i\,\theta} = \cos(\theta) + i\sin(\theta)\ .$$

$i^4 = (i^2)(i^2) = 1$

$x = i\theta \qquad e^{i\theta} = 1 + i\theta + \frac{1}{2!}(i\theta)^2 + \frac{1}{3!}(i\theta)^3 + \frac{1}{4!}(i\theta)^4 + \dots$

$= 1 + i\theta - \frac{1}{2!}\theta^2 - \frac{i}{3!}\theta^3 + \frac{1}{4!}\theta^4 + \frac{i}{5!}\theta^5 - \frac{1}{6!}\theta^6$

$i^3 = i^2 \cdot i = (-1)i$

$$\boxed{e^{i\theta} = \cos\theta + i\sin\theta}$$

e.g. $\theta = \pi$: $e^{i\pi} = -1$

the best formula there is.

From Euler's formula it makes sense to define

$$e^{a+bi} := e^a e^{bi} = e^a(\cos(b) + i\sin(b))$$

for $a, b \in \mathbb{R}$. So for $x \in \mathbb{R}$ we also get

$$e^{(a+bi)x} = e^{ax}(\cos(bx) + i\sin(bx)) = e^{ax}\cos(bx) + i\,e^{ax}\sin(bx)\,.$$

For a complex function $f(x) + i\,g(x)$ we define the derivative by

$$D_x(f(x) + i\,g(x)) := f'(x) + i\,g'(x)\,.$$

It's straightforward to verify (but would take some time to check all of them) that the usual differentiation rules, i.e. sum rule, product rule, quotient rule, constant multiple rule, all hold for derivatives of complex functions. The following rule pertains most specifically to our discussion and we should check it:

<u>Exercise 3)</u> Check that $D_x\left(e^{(a+bi)x}\right) = (a+bi)e^{(a+bi)x}$, i.e.

$$D_x e^{rx} = r\,e^{rx}$$

even if r is complex. (So also $D_x^2 e^{rx} = D_x r\,e^{rx} = r^2 e^{rx}$, $D_x^3 e^{rx} = r^3 e^{rx}$, etc.)

$$D_x e^{rx} = re^{rx}$$

$$D_x\left(e^{(a+bi)x}\right) = D_x\left(e^{ax}(\cos bx + i\sin bx)\right) \quad \text{Euler.}$$

$$= D_x\left(e^{ax}\cos bx\right) + i\,D_x\left(e^{ax}\sin bx\right)$$

$$= -b\,e^{ax}\sin bx + a e^{ax}\cos bx$$

$$+\, i\left(a e^{ax}\sin bx + b e^{ax}\cos bx\right)$$

$$\overset{?}{=} (a+bi)\,e^{(a+bi)x}$$

$$= (a+bi)(e^{ax})(\cos bx + i\sin bx)$$

$$(a\cos bx - b\sin bx)\,e^{ax}$$

$$i\left[e^{ax}(a\sin bx) + b e^{ax}\cos bx\right]$$

Now return to our differential equation questions, with

$$L(y) := y^{(n)} + a_{n-1}y^{(n-1)} + \ldots + a_1 y' + a_0 y \,.$$

Then even for complex $r = a + b\,i \quad (a, b \in \mathbb{R})$, our work above shows that

$$L\left(e^{r\,x}\right) = e^{r\,x}\left(r^n + a_{n-1}r^{n-1} + \ldots + a_1 r + a_0\right) = e^{r\,x}\,p(r)\,.$$

So if $r = a + b\,i$ is a complex root of $p(r)$ then $e^{r\,x}$ is a complex-valued function solution to $L(y) = 0$.
But L is linear, and because of how we take derivatives of complex functions, we can compute in this case that

$e^{(a+bi)x} = e^{ax}\cos bx$
$+ i e^{ax}\sin bx$

$$0 + 0\,i = L\left(e^{r\,x}\right) = L\left(e^{a\,x}\cos(b\,x) + i\,e^{a\,x}\sin(b\,x)\right)$$

$$= L\left(e^{a\,x}\cos(b\,x)\right) + i\,L\left(e^{a\,x}\sin(b\,x)\right)\,.$$

Equating the real and imaginary parts in the first expression to those in the final expression (because that's what it means for complex numbers to be equal) we deduce

$$0 = L\left(e^{a\,x}\cos(b\,x)\right)$$
$$0 = L\left(e^{a\,x}\sin(b\,x)\right)\,.$$

<u>Upshot:</u> If $r = a + b\,i$ is a complex root of the characteristic polynomial $p(r)$ then

$$y_1 = e^{a\,x}\cos(b\,x)$$
$$y_2 = e^{a\,x}\sin(b\,x)$$

are two solutions to $L(y) = 0$. (The conjugate root $a - b\,i$ would give rise to y_1, $-y_2$, which have the same span.

$z_1 = e^{ax}\cos(-bx) = e^{ax}\cos bx$
$z_2 = e^{ax}\sin(-bx) = -e^{ax}\sin bx$

downside: algebra messier
upside: got solns from $a+bi$, don't worry abt $a-bi$

Case 3) Let L have characteristic polynomial

$$p(r) = r^n + a_{n-1} r^{n-1} + \ldots + a_1 r + a_0$$

with real constant coefficients $a_{n-1}, \ldots, a_1, a_0$. If $(r - (a + b\,i))^k$ is a factor of $p(r)$ then so is the conjugate factor $(r - (a - b\,i))^k$. Associated to these two factors are $2\,k$ real and independent solutions to $L(y) = 0$, namely

$$\begin{gathered} e^{a x}\cos(b\,x),\ e^{a x}\sin(b\,x) \\ x\,e^{a x}\cos(b\,x),\ x\,e^{a x}\sin(b\,x) \\ \vdots \qquad\qquad \vdots \\ x^{k-1}e^{a x}\cos(b\,x),\ x^{k-1}e^{a x}\sin(b\,x) \end{gathered}$$

Combining cases 1,2,3, yields a complete algorithm for finding the general solution to $L(y) = 0$, as long as you are able to figure out the factorization of the characteristic polynomial $p(r)$.

Exercise 4) Find a basis for the solution space of functions $y(x)$ that solve

$$y'' + 9\,y = 0\,.$$

(You were told a basis in the last problem of last week's lab....now you know where it came from.)

$p(r) = r^2 + 9 = 0$ $\quad r^2 = -9$

$r = \pm 3i$

$= a \pm bi$ $\quad a = 0$, $b = 3$

$r = a \pm bi$

$y_1 = e^{ax}\cos bx$

$y_2 = e^{ax}\sin bx$

$e^{0x}\cos 3x = \cos 3x$

$e^{0x}\sin 3x = \sin 3x$

Exercise 5) Find a basis for the solution space of functions $y(x)$ that solve

$$y'' + 6\,y' + 13\,y = 0\,.$$

Exercise 6) Suppose a 7^{th} order linear homogeneous DE has characteristic polynomial

$$p(r) = \left(r^2 + 6\,r + 13\right)^2 (r - 2)^3\,.$$

What is the general solution to the corresponding homogeneous DE?