To solve differential equations:

First order differential equation:

Method 1: Separate variables.

Method 2: If linear $[y' + p(t)y = g(t)]$, multiply equation by an integrating factor $u = e^{\int p(t)dt}$.

$$y'u + p(t)uy = ug(t)$$
$$(uy)' = ug(t)$$

Second order differential equation:

Method 1: If there is no independent variable (t) OR if there is no dependent variable (y), transform into first order differential equation:

let $v = \frac{dy}{dt} = y'$. Then $v' =$ ________________

If there are 3 variables, note: $\frac{dv}{dt} = \frac{dv}{dy}\frac{dy}{dt} = v\frac{dv}{dy}$

Method 2 (linear equation with constant coefficients): If the second order differential equation is

$$ay'' + by' + cy = 0,$$
then $y = e^{rt}$ is a solution

Need to have two independent solutions.

$ay'' + by' + cy = 0, \quad y = e^{rt}$, then
$ar^2e^{rt} + bre^{rt} + ce^{rt} = 0$ implies $ar^2 + br + c = 0$,

Suppose $r = r_1, r_2$ are solutions to $ar^2 + br + c = 0$

If $r_1 \neq r_2$, then $b^2 - 4ac \neq 0$. Hence a general solution is $y = c_1e^{r_1t} + c_2e^{r_2t}$

If $b^2 - 4ac > 0$, general solution is $y = c_1e^{r_1t} + c_2e^{r_2t}$.

If $b^2 - 4ac < 0$, change format to linear combination of real-valued functions instead of complex valued functions by using Euler's formula.

general solution is $y = c_1e^{dt}cos(nt) + c_2e^{dt}sin(nt)$ where $r = d \pm in$

If $b^2 - 4ac = 0$, $r_1 = r_2$, so need 2nd (independent) solution: te^{r_1t}

Hence general solution is $y = c_1e^{r_1t} + c_2te^{r_1t}$.

Initial value problem: use $y(0) = y_0$, $y'(0) = y_0'$ to solve for c_1, c_2 to find unique solution.

Derivation of general solutions:

If $b^2 - 4ac > 0$ we guessed e^{rt} is a solution and noted that any linear combination of solutions is a solution to a homogeneous linear differential equation.

If $b^2 - 4ac < 0$, :

Changed format of $y = c_1 e^{r_1 t} + c_2 e^{r_2 t}$ to linear combination of real-valued functions instead of complex valued functions by using Euler's formula:

$$e^{it} = cos(t) + isin(t)$$

Hence $e^{(d+in)t} = e^{dt}e^{int} = e^{dt}[cos(nt) + isin(nt)]$

Let $r_1 = d + in$, $r_2 = d - in$

$$y = c_1 e^{r_1 t} + c_2 e^{r_2 t}$$

$$= c_1 e^{dt}[cos(nt)+isin(nt)]+c_2 e^{dt}[cos(-nt)+isin(-nt)]$$

$$= c_1 e^{dt} cos(nt)+ic_1 e^{dt} sin(nt)+c_2 e^{dt} cos(nt)-ic_2 e^{dt} sin(nt)$$

$$=(c_1 + c_2)e^{dt} cos(nt) + i(c_1 - c_2)e^{dt} sin(nt)$$

$$= k_1 e^{dt} cos(nt) + k_2 e^{dt} sin(nt)$$

If $b^2 - 4ac = 0$, then $r_1 = r_2$.
Hence one solution is $y = e^{r_1 t}$ Need second solution.

If $y = e^{rt}$ is a solution, $y = ce^{rt}$ is a solution.

How about $y = v(t)e^{rt}$?

$$y' = v'(t)e^{rt} + v(t)re^{rt}$$

$$y'' = v''(t)e^{rt} + v'(t)re^{rt} + v'(t)re^{rt} + v(t)r^2e^{rt}$$

$$= v''(t)e^{rt} + 2v'(t)re^{rt} + v(t)r^2e^{rt}$$

$$ay'' + by' + cy = 0$$

$$a(v''(t)e^{rt} + 2v'(t)re^{rt} + v(t)r^2e^{rt}) + b(v'(t)e^{rt} + v(t)re^{rt}) + c(v(t)e^{rt}) = 0$$

$$a(v''(t) + 2v'(t)r + v(t)r^2) + b(v'(t) + v(t)r) + cv(t) = 0$$

$$av''(t) + 2av'(t)r + av(t)r^2 + bv'(t) + bv(t)r + cv(t) = 0$$

$$av''(t) + (2ar + b)v'(t) + (ar^2 + br + c)v(t) = 0$$

$$av''(t) + (2a(\tfrac{-b}{2a}) + b)v'(t) + 0 = 0$$

Since $ar^2 + br + c = 0$ and $r = \frac{-b}{2a}$

$av''(t) + (-b + b)v'(t) = 0$

$av''(t) = 0$

Hence $v''(t) = 0$

$v'(t) = k_1$

$v(t) = k_1 t + k_2$

Hence $v(t)e^{r_1 t} = (k_1 t + k_2)e^{r_1 t}$ is a soln

Hence $te^{r_1 t}$ is a nice second solution.

Hence general solution is $y = c_1 e^{r_1 t} + c_2 t e^{r_1 t}$

3.6 Nonhomogeneous Equations: $ay'' + by' + cy = g(t)$

Method of Undetermined Coefficients.