Problem Set 7: Solutions (Fall Break Special)

Differential Equations

Fall 2024

Regular Questions: Review of course contents.

1. (Variation of Parameters). Solve the following third order differential equation of $y = y(t)$:
$$y''' - 4y' = e^{-2t}.$$

Solution:

First, we find the homogeneous case, that is:
$$y''' - 4y' = 0,$$
whose characteristic equation is $r^3 - 4r = 0$, so the roots are $r = 0, 2, -2$, hence the homogeneous solution is:
$$y(t) = C_1 + C_2e^{2t} + C_3e^{-2t}.$$
Given that the non-homogeneous part already exists in the equation, then our guess should be $y_p(t) = Ate^{-2t}$, which the derivatives as:
$$y_p'(t) = Ae^{-2t} - 2Ate^{-2t},$$
$$y_p''(t) = -4Ae^{-2t} + 4Ate^{-2t},$$
$$y_p'''(t) = 12Ae^{-2t} - 8Ate^{-2t}.$$
Note that when we plug into our equation, we have:
$$(12Ae^{-2t} - 8Ate^{-2t}) - 4(Ae^{-2t} - 2Ate^{-2t}) = e^{-2t}.$$
Note that the te^{-2t} term vanishes (why?), we now have:
$$8Ae^{-2t} = e^{-2t},$$
so we have that $A = 1/8$, so our general solution is:
$$y(t) = \boxed{C_1 + C_2e^{2t} + C_3e^{-2t} + \frac{1}{8}te^{-2t}}.$$
We invite diligent readers to attempt solving this problem using variation of parameters, as well, namely:
$$y_p(t) = y_1(t)\int_0^t \frac{W_1(s)g(s)}{W(s)}ds + y_2(t)\int_0^t \frac{W_2(s)g(s)}{W(s)}ds + y_3(t)\int_0^t \frac{W_3(s)g(s)}{W(s)}ds.$$

2. (Eigenvalues & Eigenvectors). Find all eigenvectors and eigenvalues of the following matrix:

(a)
$$A = \begin{pmatrix} 5 & -1 \\ 3 & 1 \end{pmatrix},$$

(b)
$$B = \begin{pmatrix} 1 & 0 & 0 \\ 2 & 1 & -2 \\ 3 & 2 & 1 \end{pmatrix}.$$

Solution:

(a) Here, we find the characteristic equation as:
$$0 = \begin{pmatrix} 5-\lambda & -1 \\ 3 & 1-\lambda \end{pmatrix} = (5-\lambda)(1-\lambda) - (-1)\cdot 3 = 8 - 6\lambda + \lambda^2 = (\lambda-2)(\lambda-4).$$
Hence, the eigenvalues are 2 and 4, and the eigenvalues, respectively, are:

i. For $\lambda_1 = \boxed{2}$, we have $A - 2\,\mathrm{Id}$ as $\begin{pmatrix} 3 & -1 \\ 3 & -1 \end{pmatrix}$, we want find $\boldsymbol{\xi}^{(1)}$ such that $\begin{pmatrix} 3 & -1 \\ 3 & -1 \end{pmatrix} .\boldsymbol{\xi}^{(1)} = \mathbf{0}$, that is $3\xi_1^{(1)} - \xi_2^{(1)} = 0$, so we have $\xi_2^{(1)} = 3\xi_1^{(1)}$, so we have $\boldsymbol{\xi}^{(1)} = \boxed{\begin{pmatrix} 1 \\ 3 \end{pmatrix}}$.

ii. For $\lambda_2 = \boxed{4}$, we have $A - 4\,\mathrm{Id}$ as $\begin{pmatrix} 1 & -1 \\ 3 & -3 \end{pmatrix}$, we want find $\boldsymbol{\xi}^{(2)}$ such that $\begin{pmatrix} 1 & -1 \\ 3 & -3 \end{pmatrix} .\boldsymbol{\xi}^{(2)} = \mathbf{0}$, that is $\xi_1^{(1)} - \xi_2^{(1)} = 0$, so we have $\xi_2^{(1)} = \xi_1^{(1)}$, so we have $\boldsymbol{\xi}^{(1)} = \boxed{\begin{pmatrix} 1 \\ 1 \end{pmatrix}}$.

(b) Here, we also find the characteristic equation as:
$$0 = \begin{pmatrix} 1-\lambda & 0 & 0 \\ 2 & 1-\lambda & -2 \\ 3 & 2 & 1-\lambda \end{pmatrix} = (1-\lambda)^3 - (1-\lambda)(-4) = (1-\lambda)\big((1-\lambda)^2 + 4\big).$$
Hence, the eigenvalues are 1, $1+2\mathrm{i}$ and $1-2\mathrm{i}$, and the eigenvalues, respectively, are:

i. For $\lambda_1 = \boxed{1}$, we have $B - \mathrm{Id}$ as $\begin{pmatrix} 0 & 0 & 0 \\ 2 & 0 & -2 \\ 3 & 2 & 0 \end{pmatrix}$, we want find $\boldsymbol{\xi}^{(1)}$ such that $\begin{pmatrix} 0 & 0 & 0 \\ 2 & 0 & -2 \\ 3 & 2 & 0 \end{pmatrix} .\boldsymbol{\xi}^{(1)} = \mathbf{0}$, that is $\xi_1^{(1)} - \xi_3^{(1)} = 0$ and $3\xi_1^{(1)} + 2\xi_2^{(1)} = 0$, so we have $\boldsymbol{\xi}^{(1)} = \boxed{\begin{pmatrix} 2 \\ -3 \\ 2 \end{pmatrix}}$.

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ii. For $\lambda_2 = \boxed{1+2i}$, we have $B-(1+2i)\,\mathrm{Id}$ as $\begin{pmatrix} -2i & 0 & 0 \\ 2 & -2i & -2 \\ 3 & 2 & -2i \end{pmatrix}$, we want find $\boldsymbol{\xi}^{(2)}$ such that $\begin{pmatrix} -2i & 0 & 0 \\ 2 & -2i & -2 \\ 3 & 2 & -2i \end{pmatrix}.\boldsymbol{\xi}^{(2)} = \mathbf{0}$, that is $\xi_1^{(2)} = 0$ and $i\xi_2^{(2)} + \xi_3^{(2)} = 0$, so we have $\boldsymbol{\xi}^{(2)} = \boxed{\begin{pmatrix} 0 \\ 1 \\ -i \end{pmatrix}}$.

iii. For $\lambda_3 = \boxed{1-2i}$, we have $B-(1-2i)\,\mathrm{Id}$ as $\begin{pmatrix} 2i & 0 & 0 \\ 2 & 2i & -2 \\ 3 & 2 & 2i \end{pmatrix}$, we want find $\boldsymbol{\xi}^{(3)}$ such that $\begin{pmatrix} 2i & 0 & 0 \\ 2 & 2i & -2 \\ 3 & 2 & 2i \end{pmatrix}.\boldsymbol{\xi}^{(3)} = \mathbf{0}$, that is $\xi_1^{(3)} = 0$ and $i\xi_2^{(3)} - \xi_3^{(3)} = 0$, so we have $\boldsymbol{\xi}^{(3)} = \boxed{\begin{pmatrix} 0 \\ 1 \\ i \end{pmatrix}}$.

3. (Linear Systems). Let $\mathbf{x} \in \mathbb{R}^2$, find the general solution of $\mathbf{x}$ if $\mathbf{x}$ satisfies:

$$\mathbf{x}' = \begin{pmatrix} 5 & -1 \\ 3 & 1 \end{pmatrix} .\mathbf{x}.$$

Solution:
Some readers might notice that this is the same matrix in the previous problem, we recall that the eigenvalues and eigenvectors, respectively, are:

$$\lambda_1 = 2, \qquad \boldsymbol{\xi}^{(1)} = \begin{pmatrix} 1 \\ 3 \end{pmatrix},$$

$$\lambda_2 = 4, \qquad \boldsymbol{\xi}^{(2)} = \begin{pmatrix} 1 \\ 1 \end{pmatrix}.$$

Hence, the solution to the linear system is:

$$\mathbf{x} = \boxed{C_1 \begin{pmatrix} 1 \\ 3 \end{pmatrix} e^{2t} + C_2 \begin{pmatrix} 1 \\ 1 \end{pmatrix} e^{4t}}.$$

Additional Questions: More challenging and fun problems related with the course.

1. (PDEs: Wave Equation). The following system of partial differential equations portraits the propagation of waves on a segment of the 1-dimensional string of length L, the displacement of string at $x \in [0, L]$ at time $t \in [0, \infty)$ is described as the function $u = u(x, t)$:

$$\begin{cases} \text{Differential Equation:} & \dfrac{\partial^2 u}{\partial t^2} - c^2 \dfrac{\partial^2 u}{\partial x^2} = 0, & \text{where } x \in (0, L) \text{ and } t \in [0, \infty); \\ \text{Initial Conditions:} & u(x, 0) = \sin\left(\dfrac{2\pi x}{L}\right), & \\ & \dfrac{\partial u}{\partial t}(x, 0) = \sin\left(\dfrac{5\pi x}{L}\right), & \text{where } x \in [0, L]; \\ \text{Boundary Conditions:} & u(0, t) = u(L, t) = 0, & \text{where } t \in [0, \infty); \end{cases}$$

where c is a constant and $g(x)$ has "good" behavior. Apply the method of separation, *i.e.*, $u(x, t) = v(x) \cdot w(t)$, and attempt to obtain a general solution that is *non-trivial*.
Hint: Use the fact that $\{\sin(n\pi x/L), \cos(n\pi x/L)\}_{n \in \mathbb{Z}^+}$ forms an orthonormal basis (cf. §5.2).

Solution:
With the method of separation, we insert the separations back to the system of equation to obtain:

$$v(x)w''(t) = c^2 v''(x)w(t).$$

Now, we apply the separation and set the common ratio to be λ:

$$\frac{v''(x)}{v(x)} = \frac{1}{c^2} \cdot \frac{w''(t)}{w(t)} = \lambda.$$

Reformatting the boundary condition gives use the following initial value problem:

$$\begin{cases} v''(x) - \lambda v(x) = 0, \\ v(0) = v(L) = 0. \end{cases}$$

As a second order linear ordinary differential equation, we discuss all following cases:

- If $\lambda = 0$, then $v(x) = a + Bx$ and by the initial condition, $A = B = 0$, which gives the trivial solution, *i.e.*, $v(x) = 0$;
- If $\lambda = \mu^2 > 0$, then we have $v(x) = Ae^{-\mu x} + Be^{\mu x}$ and again giving that $A = B = 0$, or the trivial solution;
- Eventually, if $\lambda = -\mu^2 < 0$, then we have the solution as:

$$v(x) = A\sin(\mu x) + B\cos(\mu x),$$

and the initial conditions gives us that:

$$\begin{cases} v(0) = B = 0, \\ v(L) = A\sin(\mu L) + B\cos(\mu L) = 0, \end{cases}$$

where A is arbitrary, $B = 0$, and $\mu L = m\pi$ positive integer m.
Overall, the only non-trivial solution would be:

$$v_m(x) = A\sin(\mu_m x), \text{ where } \mu_m = \frac{m\pi}{L}.$$

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Eventually, by inserting back $\lambda = -\mu_m^2$, we have $\lambda = -m^2\pi^2/L^2$, giving the solution to $w_m(t)$, another second order linear ordinary differential equation, as:

$$w_m(t) = C\cos(\mu_m ct) + D\sin(\mu_m ct), \text{ with } C, D \in \mathbb{R}.$$

By the *principle of superposition*, we can have our solution in the form:

$$u(x,t) = \sum_{m=1}^{\infty} [a_m \cos(\mu_m ct) + b_m \sin(\mu_m ct)] \sin(\mu_m x),$$

where our coefficients a_m and b_m have to be chosen to satisfy the initial conditions for $x \in [0, L]$:

$$u(x,0) = \sum_{m=1}^{\infty} a_m \sin(\mu_m x) = \sin\left(\frac{2\pi x}{L}\right),$$

$$\frac{\partial u}{\partial t}(x,0) = \sum_{m=1}^{\infty} c\mu_m b_m \sin(\mu_m x) = \sin\left(\frac{5\pi x}{L}\right).$$

Since we are hinted that $\{\sin(n\pi x/L), \cos(n\pi x/L)\}_{n\in\mathbb{Z}^+}$ forms an orthonormal basis, we now know that except for the following:

$$a_2 = 1 \text{ and } c\mu_5 b_5 = 1,$$

all the other coefficients are zero, so we have:

$$u(x,t) = \boxed{\cos\left(\frac{2\pi ct}{L}\right)\sin\left(\frac{2\pi x}{L}\right) + \frac{L}{5\pi c}\sin\left(\frac{5\pi ct}{L}\right)\sin\left(\frac{5\pi x}{L}\right)}.$$

2. (*Putnam 2023*: First Positive Root). Determine the smallest positive real number r such that there exists differentiable functions $f:\mathbb{R}\to\mathbb{R}$ and $g:\mathbb{R}\to\mathbb{R}$ satisfying:

   - $f(0)>0$,
   - $g(0)=0$,
   - $|f'(x)|\leq|g(x)|$ for all x,
   - $|g'(x)|\leq|f(x)|$ for all x, and
   - $f(r)=0$.

   You may give an answer <u>without</u> a rigorous proof, as the proof is out of scope of the course.
   Hint: Assume that the function "moves" the fastest when the cap of the derivatives are "moving" the fastest, then think of constructing a dynamical system relating f and g.

Solution:
Here, we first provide a "simplified" case, *i.e.*, we are constructing a dynamical system in which we pick equality for the inequality, that is:

$$\begin{cases}|f'(x)|=|g(x)|, \text{ and}\\ |g'(x)|=|f(x)|.\end{cases}$$

Without loss of generality, we may assume that f and g are non-negative before r, so the system becomes:

$$\begin{cases}f'=-g\\ g'=f\end{cases},$$

or equivalently, $\mathbf{y}=\begin{pmatrix}f\\g\end{pmatrix}$ that $\mathbf{y}=\begin{pmatrix}0&-1\\1&0\end{pmatrix}\mathbf{y}$. Clearly, we observe the eigenvalues are $\pm\mathrm{i}$ as the polynomial is $\lambda^2+1=0$. Moreover, the eigenvectors for $\lambda_1=\mathrm{i}$ is when $\begin{pmatrix}-\mathrm{i}&-1\\1&-\mathrm{i}\end{pmatrix}\boldsymbol{\xi}=\mathbf{0}$, in which we have $\boldsymbol{\xi}=y\begin{pmatrix}\mathrm{i}\\1\end{pmatrix}$, and that solution is:

$$\mathbf{y}=\begin{pmatrix}\mathrm{i}\\1\end{pmatrix}e^{ix}=\begin{pmatrix}\mathrm{i}\\1\end{pmatrix}(\cos x+\mathrm{i}\sin x)=\begin{pmatrix}-\sin x\\\cos x\end{pmatrix}+\mathrm{i}\begin{pmatrix}\cos x\\\sin x,\end{pmatrix}$$

and by conjugation, the solution should be:

$$\begin{pmatrix}f\\g\end{pmatrix}=C_1\begin{pmatrix}-\sin x\\\cos x\end{pmatrix}+C_2\begin{pmatrix}\cos x\\\sin x\end{pmatrix}.$$

Note that with the given initial condition that $g(0)=0$, this enforces $C_1=0$, thus $f(x)=C\cos x$ and $g(x)=C\sin x$, and we know that $f(r)$ is zero first at $r=\boxed{\pi/2}$.

The above version has some reasoning, but is not a rigorous proof at all, since this does not consider if r could be smaller than $\pi/2$. For students with interests, we provide the complete proof from the Putnam competition from Victor Lie, as follows.

Proof. Without loss of generality, we assume $f(x)>0$ for all $x\in[0,r)$ as it is the first positive zero. By the fundamental theorem of calculus, we have:

$$|f'(x)|\leq|g(x)|\leq\left|\int_0^x g(s)ds\right|\leq\int_0^x|g(s)|ds\leq\int_0^t|f(s)|ds.$$

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Now, as we denote $F(x) = \int_0^x f(s)ds$, we have:

$$f'(x) + F(x) \geq 0 \text{ for } x \in [0, r].$$

For the sake of contradiction, we suppose $r < \pi/2$, then we have:

$$f'(x) \cos x + F(x) \cos x \geq 0 \text{ for } x \in [0, r].$$

Notice that the left hand side is the derivative of $f(x) \cos x + F(x) \sin x$, so an integration on $[y, r]$ gives:

$$F(r) \sin r \geq f(y) \cos y + F(y) \sin(y).$$

With some rearranging, we can have:

$$F(r) \sin r \sec^2 y \geq f(y) \sec y + F(y) \sin y \sec^2 y$$

Again, we integrate both sides with respect to y on $[0, r]$, which gives:

$$F(r) \sin^2 r \geq F(r),$$

and this is impossible, so we have a contradiction.
Hence we must have $r \geq \pi/2$, and since we have noted the solution $f(x) = C \cos x$ and $g(x) = C \sin x$, we have proven that $r = \pi/2$ is the smallest case. $\square$

3. (Nilpotent Operator). Let M be a square matrix, M is defined to be *nilpotent* if:

$$M^k = 0 \text{ for some positive integer } k.$$

Similar to how we defined the exponential function analytically, the exponential function is also defined for matrices, let A be a square matrix, we define:

$$\exp(A) = \sum_{i=0}^{\infty} \frac{1}{i!} A^i.$$

(a) Show that $N = \begin{pmatrix} 0 & 2 & 3 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix}$ is nilpotent, then write down the result of $\exp(N)$.

Now, suppose that $N \in \mathcal{L}(\mathbb{R}^n)$ is a square matrix and is *nilpotent*.

(b) Suppose that $\mathrm{Id}_n \in \mathcal{L}(\mathbb{R}^n)$ is the identity matrix, prove that $\mathrm{Id}_n + N$ is invertible.
Hint: Use the differences of squares for matrices.

(c) If all the entries in N are rational, show that $\exp(N)$ has rational entries.

Solution:

(a) *proof of N is nilpotent.* Here, we want to do the matrix multiplication:

$$N^2 = \begin{pmatrix} 0 & 2 & 3 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} 0 & 2 & 3 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 2 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

$$N^3 = \begin{pmatrix} 0 & 0 & 2 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \cdot \begin{pmatrix} 0 & 2 & 3 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}.$$

Now, we have shown that $N^3 = 0$, or the zero matrix, hence N is nilpotent. □

Then, we want to calculate the matrix exponential, that is:

$$\exp(N) = \sum_{k=0}^{\infty} \frac{1}{k!} N^k = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 & 2 & 3 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{pmatrix} + \frac{1}{2} \begin{pmatrix} 0 & 0 & 2 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} = \boxed{\begin{pmatrix} 1 & 2 & 4 \\ 0 & 1 & 1 \\ 0 & 0 & 1 \end{pmatrix}}.$$

(b) *Proof.* Here, we recall the differences of squares still works when commutativity for multiplications fails, hence the we can still use it for matrix multiplication, namely, for all $m \in \mathbb{Z}^+$:

$$(\mathrm{Id}_n + N) \cdot (\mathrm{Id}_n - N) \cdot (\mathrm{Id}_n + N^2) \cdots (\mathrm{Id}_n + N^{2^m}) = \mathrm{Id}_n - N^{2^{m+1}}$$

Since N is *nilpotent*, this implies that we have some k such that $N^\ell = 0$ for all $\ell \geq k$. Meanwhile, note that $2^\ell \geq \ell$ for all positive integer ℓ. (This can be proven by induction.) Therefore, we select $m + 1 \geq k$ so that $N^{2m+1} = 0$, and we have:

$$(\mathrm{Id}_n + N) \cdot \left[(\mathrm{Id}_n - N) \cdot (\mathrm{Id}_n + N^2) \cdots (\mathrm{Id}_n + N^{2^m}) \right] = \mathrm{Id}_n,$$

thus $\mathrm{Id}_n + N$ is invertible. □

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(c) *Proof.* By the definition that N is nilpotent, we know that $N^m = 0$ for some finite positive integer m, hence, we can make the (countable) infinite sum into a finite sum:

$$\exp(N) = \sum_{k=0}^{\infty} \frac{1}{k!} N^k = \sum_{k=0}^{m} \frac{1}{k!} N^k,$$

thus all the entries are sum and non-zero divisions of rational numbers, while rational numbers are closed under addition and non-zero divisions, hence, all entries of $\exp(N)$ is rational. $\square$

Note that the elements of all n-by-n matrices can be considered as a *ring*, while *nilpotent* can be defined more generally for *rings*. We invite capable readers to investigate more properties of *nilpotent* elements of *rings* in the discipline of *Modern Algebra*.

4. (Convergence of Series.) As we dive into fundamentals of mathematics, it is inevitable to encounter *sequences* and their sums. Discuss about the following sequences if they converge or not. If they converge, find the explicit sum.

(a) $$\sum_{k=0}^{\infty} \frac{1}{k}.$$

(b) $$\sum_{k=0}^{\infty} \frac{1}{k!}.$$

(c) $$\sum_{k=0}^{\infty} \frac{1}{(4k+1)!}.$$

Solution:

(a) Diligent readers should observe that $\sum_{k=0}^{\infty} 1/k$ is a harmonic series, hence it $\boxed{\text{diverges}}$. Otherwise, we can simply notice that:

$$\begin{aligned}
\sum_{k=0}^{\infty} \frac{1}{k} &= \frac{1}{1} + \frac{1}{2} + \frac{1}{3} + \frac{1}{4} + \frac{1}{5} + \frac{1}{6} + \frac{1}{7} + \frac{1}{8} + \frac{1}{9} \cdots \\
&\geq \frac{1}{1} + \frac{1}{2} + \frac{1}{4} + \frac{1}{4} + \frac{1}{8} + \frac{1}{8} + \frac{1}{8} + \frac{1}{8} + \frac{1}{16} + \cdots \\
&= \frac{1}{1} + \frac{1}{2} + \left(\frac{1}{4} + \frac{1}{4}\right) + \left(\frac{1}{8} + \frac{1}{8} + \frac{1}{8} + \frac{1}{8}\right) + \left(\frac{1}{16} + \cdots\right) + \cdots \\
&= \frac{1}{1} + \frac{1}{2} + \frac{1}{2} + \frac{1}{2} + \cdots,
\end{aligned}$$

which diverges, hence our sequence $\sum_{k=0}^{\infty} 1/k$ must diverge.

(b) Here, we recall that the Taylor expansion of e^x at 0 is:

$$e^x = \sum_{k=0}^{\infty} \frac{1}{k!} e^0 (x-0)^k = \sum_{k=0}^{\infty} \frac{1}{k!} x^k.$$

Evaluating the above equation at 1 gives that:

$$\sum_{k=0}^{\infty} \frac{1}{k!} = e^1 = \boxed{e},$$

in which the sequence $\boxed{\text{converges}}$.

(c) For this part, we want to note the Taylor series of e^x, e^{-x}, $\sin x$ and $\cos x$ at 0 evaluated at $x = 1$ are, respectively:

$$\begin{array}{lclllllll}
e^1 & = & +\frac{1}{0!} & +\frac{1}{1!} & +\frac{1}{2!} & +\frac{1}{3!} & +\frac{1}{4!} & +\frac{1}{5!} & +\cdots \\
e^{-1} & = & +\frac{1}{0!} & -\frac{1}{1!} & +\frac{1}{2!} & -\frac{1}{3!} & +\frac{1}{4!} & -\frac{1}{5!} & +\cdots \\
\sin 1 & = & & +\frac{1}{1!} & & -\frac{1}{3!} & & +\frac{1}{5!} & -\cdots \\
\cos 1 & = & +\frac{1}{0!} & & -\frac{1}{2!} & & +\frac{1}{4!} & & -\cdots
\end{array}$$

Since the first series converges, we know that the later three series converges *absolutely*, so we are free to move around terms. Thus comparing vertically gives us that:

$$\sum_{k=0}^{\infty} \frac{1}{(4k+3)!} = \boxed{\frac{e^1 - e^{-1}}{4} + \frac{\sin 1}{2}}.$$