CHAPTER 6

Section 6.4

1. (a)
$$\lim_{n\to\infty}\frac{n^2+1}{n^3+1}=\lim_{n\to\infty}\frac{(1/n^2)+1/n^3}{1+1/n^3}=\frac{0}{1}=0$$
(b)
$$\lim_{n\to\infty}\frac{\ln n}{n}=\lim_{n\to\infty}\frac{d(\ln n)/dn}{d(n)/dn}=\lim_{n\to\infty}\frac{1/n}{1}=\frac{0}{1}=0$$
(c)
$$\lim_{n\to\infty}\frac{n}{2^n}=\lim_{n\to\infty}\frac{1}{2^n\ln 2}=\frac{1}{\infty}=0$$
(d)
$$\begin{aligned}\lim_{n\to\infty}n\ln\left(1+\frac{1}{n}\right)=\lim_{n\to\infty}\frac{\ln(1+1/n)}{n^{-1}}&=\lim_{n\to\infty}\frac{d\left[\ln(1+1/n)\right]/dn}{d\left(n^{-1}\right)/dn}\\&=\lim_{n\to\infty}\frac{1/\left(n^2+n\right)}{1/n^2}\\&=\lim_{n\to\infty}\frac{1}{1+1/n}\\&=\frac{1}{1+0}=1\end{aligned}$$
(e)
$$\lim_{n\to\infty}s_n=1\text{ for }n=1,2,3,\cdots\implies\lim_{n\to\infty}s_n=1$$

2. (a)
$$\overline{\lim}_{n\to\infty}\cos n\pi=1\qquad\qquad\underline{\lim}_{n\to\infty}\cos n\pi=-1\tag{1}$$
(b)
$$\overline{\lim}_{n\to\infty}\sin\frac{1}{5}n\pi\approx0.951\qquad\qquad\underline{\lim}_{n\to\infty}\sin\frac{1}{5}n\pi\approx-0.951$$
(c)
$$\overline{\lim}_{n\to\infty}n\sin\frac{1}{2}n\pi=\infty\qquad\qquad\underline{\lim}_{n\to\infty}n\sin\frac{1}{2}n\pi=-\infty$$

3. (a) A sequence
$$s_n=1+\cos n\pi$$
has limits
$$\overline{\lim}_{n\to\infty}s_n=2\qquad\qquad\underline{\lim}_{n\to\infty}s_n=0$$

(b) A sequence

$$s_n = -n^2 \sin^2\left(\frac{1}{2}n\pi\right)$$

has limits

$$\overline{\lim}_{n\to\infty} s_n = 0 \qquad\qquad \underline{\lim}_{n\to\infty} s_n = -\infty$$

(c) A sequence

$$s_n = n$$

has limits

$$\overline{\lim}_{n\to\infty} s_n = \underline{\lim}_{n\to\infty} s_n = \infty$$

4. Let a sequence $s_n = 1/n$ be given. Now this sequence converges, since

$$s = \lim_{n\to\infty} \frac{1}{n} = 0$$

Hence, for every $\epsilon > 0$ an N can be found such that

$$|s_n - s| < \frac{\epsilon}{2}$$

for all $n > N$. Hence, for all $m, n > N$

$$|s_m - s_n| = |s_m - s + s - s_n| \leq |s_m - s| + |s - s_n| < \frac{\epsilon}{2} + \frac{\epsilon}{2} = \epsilon$$

and so condition (6.10) is satisfied.

5. In order to define e to 2 decimal places from its definition

$$e = \lim_{n\to\infty}\left(1 + \frac{1}{n}\right)^n$$

we let $\epsilon = 0.00828$ in order to find a value N such that (6.5)

$$|s_n - s| < \epsilon \quad \text{for } n > N$$

Inserting in the condition above then gives

$$\left|\left(1 + \frac{1}{n}\right)^n - e\right| < 0.00828$$

which is satisfied for $n = 164$. Hence,

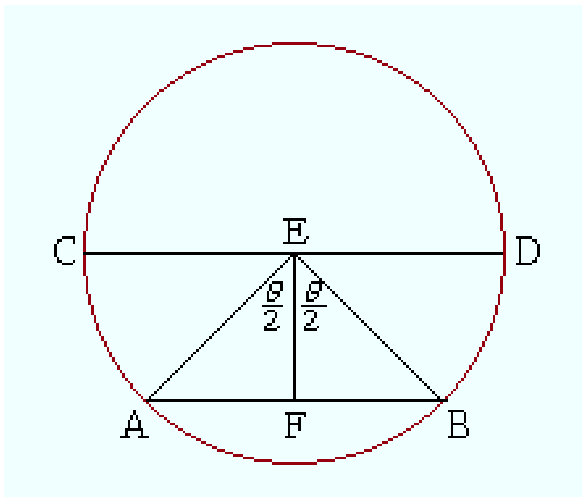
$$e \approx \left(1 + \frac{1}{164}\right)^{164} \approx 2.71$$

6.

$$\overline{\lim}_{n\to\infty} x^n = \infty \qquad \text{for } |x| > 1$$
$$\overline{\lim}_{n\to\infty} x^n = 1 \qquad \text{for } x = \pm 1$$
$$\overline{\lim}_{n\to\infty} x^n = 0 \qquad \text{for } |x| < 1$$

$$\underline{\lim}_{n\to\infty} x^n = -\infty \qquad \text{for } x < -1$$
$$\underline{\lim}_{n\to\infty} x^n = -1 \qquad \text{for } x = -1$$
$$\underline{\lim}_{n\to\infty} x^n = 0 \qquad \text{for } |x| < 1$$
$$\underline{\lim}_{n\to\infty} x^n = 1 \qquad \text{for } x = 1$$
$$\underline{\lim}_{n\to\infty} x^n = \infty \qquad \text{for } x > 1$$

7.



Assuming the figure above represents the unit circle, it follows that $AE = BE = 1$ and that the area of the polygon AEB is given by

$$A(AEB) = \frac{1}{2}AB \times EF = AF \times EF = AE \sin\frac{\theta}{2} \times AE\cos\frac{\theta}{2} = \sin\frac{\theta}{2}\cos\frac{\theta}{2} = \frac{\sin\theta}{2}$$

The area of the unit circle may then be approximated as the sum of the areas of n such polygons in the limit $n \to \infty$:

$$A_{S_1} = s_n = \lim_{n\to\infty} \frac{n}{2}\sin\frac{2\pi}{n} = \lim_{n\to\infty} \pi\frac{n}{2\pi}\sin\frac{2\pi}{n}$$

Now using the fact that $\lim_{x\to 0}\sin(x)/x = 1$ and setting $x = 2\pi/n$ we find

$$A_{S_1} = s_n = \lim_{n\to\infty} \pi\frac{n}{2\pi}\sin\frac{2\pi}{n} = \lim_{x\to 0}\pi\frac{\sin x}{x} = \pi$$

Hence, since the sequence s_n is bounded and has limit π, it is monotone increasing.

Section 6.7

1. (a) Since

$$\overline{\lim}_{n\to\infty} \sin\left(\frac{n^2\pi}{2}\right) = 1 \neq 0$$

then by the nth term test $\sum_{n=1}^{\infty} \sin(n^2\pi/2)$ diverges.

(b) Since

$$\lim_{n\to\infty} \frac{2^n}{n^3} = \lim_{n\to\infty} \frac{2^{n-1}}{3n} = \lim_{n\to\infty} \frac{(n-1)\,2^{n-2}}{3} = \infty \neq 0$$

employing *L'Hospital's rule*, then by the nth term test $\sum_{n=1}^{\infty} 2^n/n^3$ diverges.

2. (a) Since $n^3 > n$ for $n > 0$ it follows that

$$\frac{1}{n^3-1} = \left|\frac{1}{n^3-1}\right| < \frac{1}{n-1}$$

for $n = 2, 3, \ldots$. Now since

$$\lim_{n\to\infty} \frac{1}{n-1} = \lim_{n\to\infty} \frac{1/n}{1-(1/n)} = 0$$

then $\sum_{n=2}^{\infty} 1/(n-1)$ converges and hence, by the comparison test for convergence $\sum_{n=2}^{\infty} 1/(n^3-1)$ is absolutely convergent.

(b) Since $|\sin n| < 1$ for $n \geq 1$ it follows that

$$\left|\frac{\sin n}{n^2}\right| < \frac{1}{n^2}$$

for $n = 1, 2, \ldots$. Now since

$$\lim_{n\to\infty} \frac{1}{n^2} = 0$$

then $\sum_{n=1}^{\infty} 1/n^2$ converges and hence, by the comparison test for convergence $\sum_{n=1}^{\infty} \sin(n)/n^2$ is absolutely convergent.

3. (a) Since $n+5 > n$ and $n^2-3n-5 < n^2$ for $n \geq 1$ it follows that

$$\frac{n+5}{n^2-3n-5} > \frac{n}{n^2} = \frac{1}{n}$$

for $n = 1, 2, \ldots$. Now since $\sum_{n=1}^{\infty} 1/n$ is the *harmonic series*, which diverges, it follows by the comparison test for divergence that $\sum_{n=1}^{\infty}(n+5)/(n^2-3n-5)$ diverges as well.

(b) Since $\sqrt{n}\ln n < n \ln n$ for $n \geq 2$ it follows that

$$\frac{1}{\sqrt{n}\ln n} > \frac{1}{n \ln n}$$

for $n = 2, 3, \ldots$. Using the inequality $\ln(1+x) \leq x$ we may continue to write

$$\frac{1}{n \ln n} \geq \frac{\ln(1+1/n)}{\ln n} \geq \ln\left(1 + \frac{\ln(1+1/n)}{\ln n}\right) \geq \ln \frac{\ln(1+n)}{\ln n}$$

In summary, we find

$$\frac{1}{\sqrt{n}\ln n} > \ln \frac{\ln(1+n)}{\ln n} = \ln\ln(1+n) - \ln\ln n$$

Now let us consider the series

$$\sum_{n=2}^{N} \ln\ln(1+n) - \ln\ln n = \ln\ln(1+N) - \ln\ln 2$$

Hence, when $N \to \infty$

$$\sum_{n=2}^{\infty} \ln\ln(1+n) - \ln\ln n = \lim_{N\to\infty} \ln\ln(1+N) - \ln\ln 2 = \infty$$

And so by the comparison test for divergence we may conclude that $\sum_{n=2}^{\infty} 1/(\sqrt{n}\ln n)$ diverges as well.

4. (a) Let $y = f(x) = 1/(x^2+1)$. As such, $f(x)$ is defined and continuous for $c \leq x < \infty$, $f(x)$ decreases as x increases and $\lim_{x\to\infty} f(x) = 0$. The improper integral $\int_c^\infty f(x)\,dx$ with $c = 1$ then evaluates to

$$\int_1^\infty \frac{dx}{x^2+1} = \lim_{b\to\infty} \int_1^b \frac{dx}{x^2+1} = \lim_{b\to\infty} \int_{\pi/4}^{\tan^{-1} b} du = \lim_{b\to\infty} u\Big|_{\pi/4}^{\tan^{-1} b} = \lim_{b\to\infty} \tan^{-1} b - \frac{\pi}{4}$$
$$= \frac{\pi}{2} - \frac{\pi}{4} = \frac{\pi}{4}$$

where we have used the substitution $x = \tan u$. Hence, by the integral test, since the improper integral $\int_1^\infty f(x)\,dx$ converges so will the series $a_n = f(n) = \sum_{n=1}^{\infty} 1/(n^2+1)$.

(b) let $y = f(x) = 1/(x \ln^2 x)$. As such, $f(x)$ is defined and continuous for $c \leq x < \infty$, $f(x)$ decreases as x increases and $\lim_{x\to\infty} f(x) = 0$. The improper integral $\int_c^\infty f(x)\,dx$ with $c = 2$ then evaluates to

$$\int_2^\infty \frac{dx}{x\ln^2 x} = \lim_{b\to\infty} \int_2^b \frac{dx}{x \ln^2 x} = \lim_{b\to\infty} \int_{\ln 2}^{\ln b} \frac{du}{u^2} = \lim_{b\to\infty} -\frac{1}{u}\Big|_{\ln 2}^{\ln b} = \frac{1}{\ln 2} - \lim_{b\to\infty} \frac{1}{\ln b}$$
$$= \frac{1}{\ln 2} - 0 = \frac{1}{\ln 2}$$

where we have used the substitution $u = \ln x$. Hence, by the integral test, since the improper integral $\int_2^\infty f(x)\,dx$ converges so will the series $a_n = f(n) = \sum_{n=2}^\infty 1/(n \ln^2 n)$.

5. (a) Let $y = f(x) = x/(x^2+1)$. As such, $f(x)$ is defined and continuous for $c \le x < \infty$, (fx) decreases as x increases and $\lim_{x\to\infty} f(x) = 0$. The improper integral $\int_c^\infty f(x)\,dx$ with $c = 1$ then evaluates to

$$\begin{aligned}
\int_1^\infty \frac{x}{x^2+1}\,dx = \lim_{b\to\infty} \int_1^b \frac{x}{x^2+1}\,dx = \lim_{b\to\infty} \frac{1}{2}\int_2^{b^2+1} \frac{du}{u} &= \lim_{b\to\infty} \left.\frac{\ln u}{2}\right|_2^{b^2+1} \\
&= \lim_{b\to\infty} \frac{\ln|b^2+1| - \ln 2}{2} \\
&= \infty - \frac{\ln 2}{2} = \infty
\end{aligned}$$

where we have used the substitution $u = x^2 + 1$. Hence, by the integral test, since the improper integral $\int_1^\infty f(x)\,dx$ diverges so will the series $a_n = f(n) = \sum_{n=1}^\infty n/(n^2+1)$.

(b) Let $y = f(x) = 1/(x \ln x \ln\ln x)$. As such, $f(x)$ is defined and continuous for $c \le x < \infty$, $f(x)$ decreases as x increases and $\lim_{x\to\infty} f(x) = 0$. The improper integral $\int_c^\infty f(x)\,dx$ with $c = 10$ then evaluates to

$$\begin{aligned}
\int_{10}^\infty \frac{dx}{x\ln x \ln\ln x} = \lim_{b\to\infty}\int_{10}^b \frac{dx}{x\ln x\ln\ln x} &= \lim_{b\to\infty}\int_{\ln 10}^{\ln b} \frac{du}{u\ln u} \\
&= \lim_{b\to\infty}\int_{\ln\ln 10}^{\ln\ln b} \frac{dv}{v} \\
&= \lim_{b\to\infty} \ln v\Big|_{\ln\ln 10}^{\ln\ln b} \\
&= \lim_{b\to\infty} \ln\ln\ln b - \ln\ln\ln 10 \\
&= \infty - \ln\ln\ln 10 = \infty
\end{aligned}$$

where we have used the substitutions $u = \ln x$ and $v = \ln u$. Hence, by the integral test, since the improper integral $\int_{10}^\infty f(x)\,dx$ diverges so will the series $a_n = f(n) = \sum_{n=10}^\infty 1/(n \ln n \ln\ln n)$.

6. (a) Let $a_n = (-1)^n/n!$. As such we find

$$\lim_{n\to\infty}\left|\frac{a_{n+1}}{a_n}\right| = L = \lim_{n\to\infty}\left|\frac{n!}{(-1)^n}\frac{(-1)^{n+1}}{(n+1)!}\right| = \lim_{n\to\infty}\left|-\frac{1}{n+1}\right| = \lim_{n\to\infty}\frac{1}{n+1} = \frac{1}{\infty} = 0$$

Hence, $L < 1$ and so according to the ratio test the series $\sum_{n+1}^\infty (-1)^n/n!$ is absolutely convergent.

(b) Let $a_n = 2^n + 1/(3^n + n)$. As such we find

$$\begin{aligned}
\lim_{n\to\infty}\left|\frac{a_{n+1}}{a_n}\right| = L = \lim_{n\to\infty}&\left|\frac{3^n+n}{2^n+1}\frac{2^{n+1}+1}{3^{n+1}+n+1}\right| \\
= \lim_{n\to\infty}&\left|\frac{3^n\left(1+n/3^n\right)}{2^n\left(1+1/2^n\right)}\frac{2^{n+1}\left(1+1/2^{n+1}\right)}{3^{n+1}\left[1+\left(n/3^{n+1}\right)+\left(1/3^{n+1}\right)\right]}\right| \\
= \frac{2}{3}\lim_{n\to\infty}&\left|\frac{\left(1+n/3^n\right)\left(1+1/2^{n+1}\right)}{\left(1+1/2^n\right)\left(1+n/3^{n+1}+1/3^{n+1}\right)}\right| \\
= \frac{2}{3}&\frac{(1+0)\cdot(1+0)}{(1+0)\cdot(1+0+0)} = \frac{2}{3}
\end{aligned}$$

where we have used the fact that

$$\lim_{x\to\infty}\frac{x}{a^x} = \lim_{x\to\infty}\frac{1}{xa^{x-1}} = \frac{1}{\infty} = 0$$

using *L'Hospital's rule*. Hence, $L < 1$ and so according to the ratio test the series $\sum_{n+1}^{\infty} 2^n + 1/(3^n + n)$ is absolutely convergent.

7. (a) Let $a_n = 1/\ln n$. Then for $2 \le n < \infty$ we find

$$a_n = \frac{(-1)^n}{\ln n} = \frac{1}{\ln n}$$

Now since $\ln n$ is monotonically increasing for $2 \le n < \infty$ we may conclude that $a_n = 1/\ln n$ is monotonically decreasing for $2 \le n < \infty$ and so $a_{n+1} \le a_n$. Furthermore

$$\lim_{n\to\infty} a_n = \lim_{n\to\infty}\frac{1}{\ln n} = \frac{1}{\infty} = 0$$

provided $n \ge 2$ and so by the alternating series test we may conclude that the series $\sum_{n=2}^{\infty}(-1)^n/\ln n$ converges.

(b) Let $f(x) = \ln x/x$. Hence,

$$\frac{d}{dx}f(x) = \frac{d}{dx}\frac{\ln x}{x} = \frac{1-\ln x}{x^2}$$

Note that the derivative of $f(x)$ becomes negative when $x > e \approxeq 2.71828$ and hence, that $f(x)$ becomes monotonically decreasing when $e < x < \infty$. As such, the terms of the sequence $a_n = f(n) = \ln n/n$ are decreasing (i.e. $a_{n+1} \le a_n$) when $3 \le n < \infty$. Furthermore

$$\lim_{n\to\infty} a_n = \lim_{n\to\infty}\frac{\ln n}{n} = \lim_{n\to\infty}\frac{1}{n} = \frac{1}{\infty} = 0$$

using *L'Hospital's rule*. As such, by the alternating series test we may conclude that the series $\sum_{n=3}^{\infty}(-1)^n \ln n/n$ converges.

8. (a) Let $a_n = 1/n^n$. Then

$$\lim_{n\to\infty} \sqrt[n]{|a_n|} = R = \lim_{n\to\infty} \sqrt[n]{n^{-n}} = \lim_{n\to\infty} \frac{1}{n} = \frac{1}{\infty} = 0$$

provided $n \geq 1$. Hence, since $R < 1$ it follows from the root test that the series $\sum_{n=1}^{\infty} 1/n^n$ is absolutely convergent.

(b) Let $a_n = [n/(n+1)]^{n^2}$. Then

$$\lim_{n\to\infty} \sqrt[n]{|a_n|} = R = \lim_{n\to\infty} \sqrt[n]{\left(\frac{n}{n+1}\right)^{n^2}} = \lim_{n\to\infty} \left(\frac{n}{n+1}\right)^n = \frac{1}{e}$$

provided $n \geq 1$. Hence, since $R < 1$ it follows from the root test that the series $\sum_{n=1}^{\infty} [n/(n+1)]^{n^2}$ is absolutely convergent.

9. (a) Let the series

$$\sum_{n=1}^{\infty} \frac{1}{(n+2)(n+1)} = \sum_{n=1}^{\infty} \left(\frac{n+1}{n+2} - \frac{n}{n+1}\right)$$

be given. To show that this series converges we consider the partial sum

$$S_n = \frac{2}{3} - \frac{1}{2} + \frac{3}{4} - \frac{2}{3} + \cdots + \frac{n+1}{n+2} - \frac{n}{n+1} = -\frac{1}{2} + \frac{n+1}{n+2}$$

Taking the limit of S_n as $n \to \infty$ then gives

$$\lim_{n\to\infty} S_n = \lim_{n\to\infty} \frac{n+1}{n+2} - \frac{1}{2} = \lim_{n\to\infty} \frac{1+1/n}{1+2/n} - \frac{1}{2} = 1 - \frac{1}{2} = \frac{1}{2}$$

Hence, the series converges.

(b) Let the series

$$\sum_{n=1}^{\infty} \frac{1-n}{2^{n+1}} = \sum_{n=1}^{\infty} \left(\frac{n+1}{2^{n+1}} - \frac{n}{2^n}\right)$$

be given. To show that this series converges we consider the partial sum

$$S_n = \frac{1}{2} - \frac{1}{2} + \frac{3}{8} - \frac{1}{2} + \frac{1}{4} - \frac{3}{8} + \cdots + \frac{n+1}{2^{n+1}} = -\frac{1}{2} + \frac{n+1}{2^{n+1}}$$

Taking the limit of S_n as $n \to \infty$ then gives

$$\lim_{n\to\infty} S_n = \lim_{n\to\infty} \frac{n+1}{2^{n+1}} - \frac{1}{2} = \lim_{n\to\infty} \frac{1}{(n+1)\,2^n} - \frac{1}{2} = 0 - \frac{1}{2} = -\frac{1}{2}$$

using *L'Hospital's rule*. Hence, the series converges.

10. Let $y = f(x)$ satisfy the following conditions:

(a) $f(x)$ is defined and continuous for $c \le x < \infty$

(b) $f(x)$ decreases as x increases and $\lim_{x\to\infty} f(x) = 0$

(c) $f(n) = a_n$

Let us suppose the improper integral $\int_c^\infty f(x)\,dx$ diverges. Assumptions (b) and (c) imply that $a_n > 0$ for n sufficiently large. Hence, by Theorem 7 of Section 6.5 the series $\sum a_n$ is either convergent or properly divergent. Let the integer m be chosen so that $m > c$. Then, since $f(x)$ is decreasing

$$\int_n^{n+1} f\left(x\right)\,dx \le f\left(n\right) = a_n \quad \text{for } n \ge m$$

Hence, $a_m + \cdots + a_{m+p} \ge \int_m^{m+p+1} f\left(x\right)\,dx$. However, since $\int_c^\infty f(x)\,dx$ diverges it follows that $\lim_{p\to\infty} \int_m^{m+p+1} f(x)\,dx$ diverges, which thus ultimately implies that the series $\sum_m^\infty a_n$ must be divergent as well.

11. Let an alternating series

$$a_1 - a_2 + a_3 - a_4 + \cdots = \sum_{n=1}^{\infty} \left(-1\right)^{n+1} a_n, \quad a_n > 0$$

be given along with the two conditions

(a) $a_{n+1} \le a_n$ for $n = 1, 2, \ldots$

(b) $\lim_{n\to\infty} a_n = 0$

What remains to be proven is that such a series converges given the aforementioned conditions. Let $S_n = a_1 - a_2 + a_3 - a_4 + \cdots \pm a_n$ denote the nth partial sum of an alternating series. Then $S_1 = a_1$, $S_2 = a_1 - a_2 < S_1$, $S_3 = S_2 + a_3 > S_2$, $S_3 = S_1 - (a_2 - a_3) < S_1$, so that $S_2 < S_3 < S_1$. As such, we may conclude that $S_1 > S_3 > S_5 > S_7 > \cdots > S_6 > S_4 > S_2$ or $S_n \le a_1$ and that each $S_n \ge 0$ for $n = 1, 2, \ldots$.

Next, let an $\epsilon > 0$ be given. By the Cauchy criterion our goal is to find an N so that whenever $m > n > N$ then

$$\left|S_m - S_n\right| = |a_{n+1} - a_{n+2} + \cdots \pm a_m| < \epsilon$$

Now since each partial sum is non-negative (i.e. $S_n \ge 0$) and acknowledging that all partial sums are $\le$ the first term a_1, but now applied to the alternating series starting at a_{n+1} instead of a_1 we can write

$$\left|S_m - S_n\right| \le a_{n+1} < \epsilon$$

Now because $\lim_{n\to\infty} a_n = 0$ we can find N such that $a_{n+1} < \epsilon$ whenever $n > N$. Hence,

$$m > n > N \implies \left|S_m - S_n\right| \le a_{n+1} < \epsilon$$

which thus satisfies our initial condition

$$\left|S_m - S_n\right| = |a_{n+1} - a_{n+2} + \cdots \pm a_m| < \epsilon$$

We may conclude that the sequence of partial sums S_n of our original alternating series subject to conditions (a) and (b) satisfies the Cauchy criterion and therefore, is convergent. Hence, the alternating series itself is convergent.

12. (a) Let the series

$$\sum_{n=1}^{\infty} a_n = \sum_{n=1}^{\infty} \frac{n+4}{2n^3 - 1}$$

be given. In order to determine convergence or divergence we first try the comparison test for convergence. To this end, note that $n + 4 \leq 5n$ and $2n^3 - 1 \geq n^3$ for $n = 1, 2, \ldots$. Hence,

$$|a_n| = \frac{n+4}{2n^3 - 1} \leq \frac{5n}{n^3} = \frac{5}{n^2} = b_n \quad \text{for } n = 1, 2, \ldots$$

As such, if we can prove that $\sum_{n=1}^{\infty} b_n$ converges, then $\sum_{n=1}^{\infty} a_n$ is absolutely convergent. Now let $y = f(x) = 5/x^2$, which satisfies the following conditions:

i. $f(x)$ is defined and continuous for $c \leq x < \infty$ for $c \neq 0$

ii. $f(x)$ decreases as x increases and $\lim_{x\to\infty} f(x) = 0$

iii. $f(n) = b_n$

Then by the integral test the series $\sum_{n=1}^{\infty} b_n$ converges or diverges according to whether the improper integral $\int_c^{\infty} f(x)\, dx$ converges or diverges. As such, we evaluate

$$\int_1^{\infty} \frac{5}{x^2}\, dx = \lim_{b\to\infty} \int_1^{b} \frac{5}{x^2}\, dx = \lim_{b\to\infty} -\frac{5}{x}\bigg|_1^b = 5 - \lim_{b\to\infty} \frac{5}{b} = 5 - \frac{5}{\infty} = 5$$

Hence, since the improper integral $\int_c^{\infty} f(x)\, dx$ converges, so do the series $\sum_{n=1}^{\infty} b_n$ and $\sum_{n=1}^{\infty} a_n$.

(b) Let the series

$$\sum_{n=1}^{\infty} a_n = \sum_{n=1}^{\infty} \frac{3n - 5}{n 2^n}$$

be given. Since $a_n \neq 0$ for $n = 1, 2, \ldots$ we can try the ratio test in order to determine convergence or divergence:

$$\begin{aligned}
\lim_{n\to\infty} \left|\frac{a_{n+1}}{a_n}\right| = L = \lim_{n\to\infty} \left|\frac{3(n+1) - 5}{(n+1)\, 2^{n+1}} \frac{n 2^n}{3n - 5}\right| &= \frac{1}{2} \lim_{n\to\infty} \left|\frac{3(n+1) - 5}{n+1} \frac{n}{3n - 5}\right| \\
&= \frac{1}{2} \lim_{n\to\infty} \left|\frac{3(1 + 1/n) - 5/n}{1 + 1/n} \frac{1}{3 - 5/n}\right| \\
&= \frac{1}{2} \frac{3 + 0 - 0}{1 + 0} \frac{1}{3 - 0} = \frac{1}{2}
\end{aligned}$$

Hence, since $L = 1/2 < 1$ the series $\sum_{n+1}^{\infty} a_n$ is absolutely convergent.

(c) Let the series

$$\sum_{n=1}^{\infty} a_n = \sum_{n=1}^{\infty} \frac{e^n}{n+1}$$

be given. Then

$$\lim_{n\to\infty} a_n = \lim_{n\to\infty} \frac{e^n}{n+1} = \lim_{n\to\infty} e^n = \infty$$

using *L'Hospital's rule*. Hence, it follows from the nth term test that the series $\sum_{n=1}^{\infty} a_n$ diverges.

(d) Let the series

$$\sum_{n=1}^{\infty} a_n = \sum_{n=1}^{\infty} \frac{n^2}{n!+1}$$

be given. Since

$$|a_n| = \frac{n^2}{n!+1} < \frac{n^2}{n!} = b_n \quad \text{for } n = 1, 2, \ldots$$

the comparison test for convergence tells us that if $\sum_{n=1}^{\infty} b_n$ converges, then $\sum_{n=1}^{\infty} a_n$ is absolutely convergent. Since $b_n \neq 0$ for $n = 1, 2, \ldots$ we can use the ratio test in order to determine if $\sum_{n=1}^{\infty} b_n$ converges:

$$\lim_{n\to\infty} \left| \frac{b_{n+1}}{b_n} \right| = L = \lim_{n\to\infty} \frac{(n+1)^2}{(n+1)!} \frac{n!}{n^2} = \lim_{n\to\infty} \frac{(n+1)^2}{n^2(n+1)} = \lim_{n\to\infty} \frac{n+1}{n^2} = \lim_{n\to\infty} \frac{1+1/n}{n}$$
$$= \frac{1+0}{\infty} = 0$$

Hence, since $L = 0 < 1$ we may conclude that $\sum_{n=1}^{\infty} b_n$ is absolutely convergent by the ratio test and thus, that $\sum_{n=1}^{\infty} a_n$ is absolutely convergent by the comparison test for convergence.

(e) Let the series

$$\sum_{n=1}^{\infty} a_n = \sum_{n=1}^{\infty} \frac{n!}{3 \cdot 5 \cdots (2n+3)}$$

be given. Since $a_n \neq 0$ for $n = 1, 2, \ldots$ we can use the ratio test to determine convergence:

$$\begin{aligned} \lim_{n\to\infty} \left| \frac{a_{n+1}}{a_n} \right| = L &= \lim_{n\to\infty} \frac{(n+1)!}{3 \cdot 5 \cdots [2(n+1)+3]} \frac{3 \cdot 5 \cdots (2n+3)}{n!} \\ &= \lim_{n\to\infty} \frac{n}{2(n+1)+3} \\ &= \lim_{n\to\infty} \frac{1}{2(1+1/n)+3/n} = \frac{1}{2(1+0)+0} = \frac{1}{2} \end{aligned}$$

Hence, since $L = 1/2 < 1$ we may conclude that $\sum_{n=1}^{\infty} a_n$ is absolutely convergent.

(f) Let the series

$$\sum_{n=1}^{\infty}(-1)^n a_n = \sum_{n=1}^{\infty}\frac{(-1)^n \ln n}{2n+3}$$

be given. This is an alternating series. Note that for $n = 1, 2, 3, 4$ its terms are actually increasing (i.e. $a_{n+1} > a_n$) in absolute value and $a_{n+1} \leq a_n$ only becomes true when $n = 5, 6, \ldots$. This is not a problem for the alternating series test to be valid however. Furthermore

$$\lim_{n\to\infty} a_n = \lim_{n\to\infty}\frac{\ln n}{2n+3} = \lim_{n\to\infty}\frac{1/n}{2} = \frac{0}{2} = 0$$

using *L'Hospital's rule*. Hence, the alternating series converges.

(g) Let the series

$$\sum_{n=2}^{\infty} a_n = \sum_{n=2}^{\infty}\frac{1+\ln^2 n}{n\ln^2 n}$$

be given. As such, let us define the function $y = f(x) = (1+\ln^2 x)/n\ln^2 x$. Then

$$\lim_{x\to\infty} f(x) = \lim_{x\to\infty}\frac{1+\ln^2 x}{x\ln^2 x} = \lim_{x\to\infty}\left(\frac{1}{x\ln^2 x}+\frac{1}{x}\right) = \frac{1}{\infty}+\frac{1}{\infty} = 0$$

Furthermore, $f(x)$ satisfies the following conditions:

i. $f(x)$ is defined and continuous for $c \leq x < \infty$

ii. $f(x)$ decreases as x increases for $x \geq 2$ and $\lim_{x\to\infty} f(x) = 0$

iii. $f(n) = a_n$

Hence, we can use the integral test to determine whether the series $\sum_{n=2}^{\infty} a_n$ converges or diverges:

$$\begin{aligned}
\int_2^{\infty}\frac{1+\ln^2 x}{x\ln^2 x}\,dx = \lim_{b\to\infty}\int_2^b \frac{1+\ln^2 x}{x\ln^2 x}\,dx &= \lim_{b\to\infty}\int_2^b\left(\frac{1}{x\ln^2 x}+\frac{1}{x}\right)dx \\
&= \lim_{b\to\infty}\int_2^b\frac{dx}{x\ln^2 x}+\lim_{b\to\infty}\int_2^b\frac{dx}{x} \\
&= \lim_{b\to\infty}\int_{\ln 2}^{\ln b}\frac{du}{u^2}+\lim_{b\to\infty}\ln|x|\Big|_2^b \\
&= \lim_{b\to\infty} -\frac{1}{u}\Big|_{\ln 2}^{\ln b}+\lim_{b\to\infty}(\ln b-\ln 2) \\
&= \lim_{b\to\infty}\left(-\frac{1}{\ln b}+\frac{1}{\ln 2}+\ln b-\ln 2\right) = \infty
\end{aligned}$$

In conclusion, since the improper integral $\int_c^{\infty} f(x)\,dx$ diverges, so will the series $\sum_{n=2}^{\infty} a_n$.

(h) Let the series

$$\sum_{n=1}^{\infty} a_n = \sum_{n=1}^{\infty} \frac{\cos n\pi}{n+2} \equiv \sum_{n=1}^{\infty} (-1)^n b_n = \sum_{n=1}^{\infty} \frac{(-1)^n}{n+2}$$

be given. $\sum_{n=1}^{\infty}(-1)^n b_n$ is an alternating series with terms that are decreasing in absolute value: $b_{n+1} < b_n$ for $n = 1, 2, \ldots$ and $\lim_{n\to\infty} b_n = 0$. Hence, by the alternating series test the series $\sum_{n=1}^{\infty}(-1)^n b_n$ converges and thus, so will the series $\sum_{n=1}^{\infty} a_n$.

(i) Let the series

$$\sum_{n=1}^{\infty} \frac{\ln n}{n + \ln n}$$

be given. Now since $a \geq 0$ and $n + \ln n < 2n$ for $n = 1, 2, \ldots$ we can define $b_n = \ln n/2n$ such that $a_n > b_n \geq 0$. Then by the comparison test for divergence if $\sum_{n=1}^{\infty} b_n$ diverges so will $\sum_{n=1}^{\infty} a_n$. To this end, let us define the function $y = f(x) = \ln x/2x$. Now since $\ln x < 2x$ for $1 \leq x < \infty$ and

$$\lim_{x\to\infty} f(x) = \lim_{x\to\infty} \frac{\ln x}{2x} = \lim_{x\to\infty} \frac{1/x}{2} = 0$$

using *L'Hospital's rule*, we find that

i. $f(x)$ is defined and continuous for $c \leq x < \infty$, where $c = 1$
ii. $f(x)$ decreases as x increases and $\lim_{x\to\infty} f(x) = 0$
iii. $f(n) = a_n$

Then the series $\sum_{n=1}^{\infty} b_n$ converges or diverges according to whether the improper integral $\int_c^{\infty} f(x)\,dx$ converges or diverges:

$$\int_1^{\infty} \frac{\ln x}{2x}\,dx = \frac{1}{2}\lim_{b\to\infty} \int_1^{b} \frac{\ln x}{x}\,dx = \frac{1}{2}\lim_{b\to\infty} \int_0^{\ln b} u\,du = \lim_{b\to\infty} \left.\frac{u^2}{4}\right|_0^{\ln b} = \lim_{b\to\infty} \frac{\ln^2 b}{4} = \infty$$

where we have used the substitution $u = \ln x$. Hence, by the integral test the series $\sum_{n=1}^{\infty} b_n$ diverges and so by the comparison test for divergence the series $\sum_{n=1}^{\infty} a_n$ diverges as well.

(j) Let the series

$$\sum_{n=1}^{\infty} a_n = \sum_{n=1}^{\infty} \left(\frac{n+1}{2n}\right)^n$$

be given. Then

$$\lim_{n\to\infty} \sqrt[n]{|a_n|} = R = \lim_{n\to\infty} \sqrt[n]{\left(\frac{n+1}{2n}\right)^n} = \lim_{n\to\infty} \frac{n+1}{2n} = \lim_{n\to\infty} \frac{1+1/n}{2} = \frac{1}{2}$$

Then by the root test, since $R = 1/2 < 1$ the series $\sum_{n=1}^{\infty} a_n$ is absolutely convergent.

13. Let $a_n > 0$ and $b_n > 0$ for $n = 1, 2, \ldots$ and let the sequence a_n/b_n have limit k, possibly infinite.

   (a) Suppose $0 < k < \infty$, i.e. $\lim_{n\to\infty} a_n/b_n = k$ is some positive number. Then for some $\epsilon > 0$ we know that there must exist a positive integer N such that for all $n > N$ it is true that

   $$\left|\frac{a_n}{b_n} - k\right| < \epsilon \iff (k-\epsilon)\, b_n < a_n < (k+\epsilon)\, b_n$$

   As $k > 0$ we can choose ϵ sufficiently small so that $k - \epsilon > 0$. Hence,

   $$b_n < \frac{a_n}{k-\epsilon}$$

   As such, by the comparison test for convergence, if $\sum a_n$ converges then so must $\sum b_n$. Similarly $a_n < (k+\epsilon)b_n$. Hence, if $\sum a_n$ diverges then by the comparison test for divergence so will $\sum b_n$. In conclusion, both series $\sum a_n$ and $\sum b_n$ either both converge or both diverge.

   (b) Suppose $k = 0$. Then for some $\epsilon > 0$ there must exist a positive integer N such that for all $n > N$ it is true that

   $$\frac{a_n}{b_n} < \epsilon \iff a_n < \epsilon b_n$$

   Hence, by the comparison test for convergence, if $\sum b_n$ converges then so must $\sum a_n$. Additionally, as long as $\sum a_n$ converges the inequality can still be satisfied if $\sum b_n$ diverges by choosing ϵ sufficiently small.

   (c) Suppose $k = \infty$. Then for some $\epsilon > 0$ we know that there must exist a positive integer N such that for all $n > N$ it is true that

   $$(k-\epsilon)\, b_n < a_n < (k+\epsilon)\, b_n$$

   From the first inequality we see that

   $$a_n > (k-\epsilon)\, b_n$$

   from which we may gather that $\sum a_n$ may diverge while $\sum b_n$ converges, since $k = \infty$. Similarly, since $a_n < (k+\epsilon)b_n$ then the comparison test for divergence tells us that divergence of $\sum a_n$ implies divergence of $\sum b_n$.

14. (a) Let the series

   $$\sum_{n=1}^{\infty} a_n = \sum_{n=1}^{\infty} \frac{2n+1}{3n^2+n+1}$$

   be given and let $b_n = 1/n$. Using Problem 13 we thus find

   $$\lim_{n\to\infty} \frac{a_n}{b_n} = \lim_{n\to\infty} \frac{2n^2+n}{3n^2+n+1} = \lim_{n\to\infty} \frac{2+1/n}{3+1/n+1/n^2} = \frac{2}{3}$$

and so the series $\sum a_n$ and $\sum b_n$ either both converge or both diverge. Since the series $\sum_{n=1}^{\infty} b_n = \sum_{n=1}^{\infty} 1/n$ diverges we conclude that the series $\sum_{n=1}^{\infty} a_n$ must diverge as well.

(b) Let the series

$$\sum_{n=1}^{\infty} a_n = \sum_{n=1}^{\infty} \frac{n^3 - 3n^2 + 5}{n^5 + n + 1}$$

be given and let $b_n = 1/n^2$. Hence,

$$\lim_{n\to\infty} \frac{a_n}{b_n} = \lim_{n\to\infty} \frac{n^5 - 3n^4 + 5n^2}{n^5 + n + 1} = \lim_{n\to\infty} \frac{1 - 3/n + 5/n^3}{1 + 1/n^4 + 1/n^5} = 1$$

and so the series $\sum a_n$ and $\sum b_n$ either both converge or both diverge. Since the series $\sum_{n=1}^{\infty} b_n = \sum_{n=1}^{\infty} 1/n^2$ converges we conclude that the series $\sum_{n=1}^{\infty} a_n$ must converge as well.

(c) Let the series

$$\sum_{n=1}^{\infty} a_n = \sum_{n=1}^{\infty} \sin \frac{1}{n}$$

be given and let $b_n = 1/n$. Hence,

$$\lim_{n\to\infty} \frac{a_n}{b_n} = \lim_{n\to\infty} \frac{\sin(1/n)}{1/n} = \lim_{n\to\infty} \frac{\cos(1/n)/n^2}{1/n^2} = \lim_{n\to\infty} \cos\frac{1}{n} = \cos\frac{1}{\infty} = 1$$

using *L'Hospital's rule* and so the series $\sum a_n$ and $\sum b_n$ either both converge or both diverge. Since the series $\sum_{n=1}^{\infty} b_n = \sum_{n=1}^{\infty} 1/n$ diverges we conclude that the series $\sum_{n=1}^{\infty} a_n$ must diverge as well.

(d) Let the series

$$\sum_{n=1}^{\infty} a_n = \sum_{n=1}^{\infty} \left(1 - \cos\frac{1}{n}\right)$$

be given and let $b_n = 1/n^2$. Hence,

$$\lim_{n\to\infty} \frac{a_n}{b_n} = \lim_{n\to\infty} \frac{1 - \cos(1/n)}{1/n^2} = \frac{1}{2} \lim_{n\to\infty} \frac{\sin(1/n)}{1/n} = \frac{1}{2}$$

using *L'Hospital's rule* and so the series $\sum a_n$ and $\sum b_n$ either both converge or both diverge. Since the series $\sum_{n=1}^{\infty} b_n = \sum_{n=1}^{\infty} 1/n^2$ converges we conclude that the series $\sum_{n=1}^{\infty} a_n$ must converge as well.

Section 6.9

1. (a) Let the sum $\sum_{n=1}^{\infty} 1/n^2$ be given and let us define the allowed error as $\epsilon = 1$. We know from the previous section that this series converges by the integral test of

Theorem 14. Hence, by Theorem 23 we find

$$|R_n| = \sum_{m=n+1}^{\infty} \frac{1}{m^2} < \int_n^{\infty} f(x)\ dx = \int_n^{\infty} \frac{dx}{x^2} = \frac{1}{n} = T_n$$

and so the condition $T_n \leq \epsilon$ then translates to the inequality $n \geq 1$, which is satisfied for $n = 1$. Hence, one term is sufficient to compute the sum with given allowed error $\epsilon = 1$ and so $S_1 = 1$.

(b) Let the sum $\sum_{n=1}^{\infty}(-1)^{n+1}/n^2$ be given and let us define the allowed error as $\epsilon = 1/10$. Now since this series converges by the alternating series test then by Theorem 26

$$|R_n| < a_{n+1} = T_n$$

Hence, we end up with the inequality $a_{n+1} \leq \epsilon$ or $1/(n+1)^2 \leq 1/10 \iff (n+1)^2 \geq 10$, which is satisfied for $n = 3$. Hence, three terms is sufficient to compute the sum with the given allowed error $\epsilon = 1/10$ and so $S_3 \approxeq 0.86$.

(c) Let the sum $\sum_{n=1}^{\infty} a_n = \sum_{n=1}^{\infty} n/(n^3+5)$ be given and let us define the allowed error as $\epsilon = 1/5$. It is true that $n^3 + 5 > n^3$ and so we can define $b_n = 1/n^2$ such that $|a_n| < b_n$ for $n \geq n_1 = 1$. Now since $\sum_{n=1}^{\infty} b_n = \sum_{n=1}^{\infty} 1/n^2$ converges then by Theorem 22 and Theorem 23 it follows that

$$|R_n| \leq \sum_{m=n+1}^{\infty} b_m = \sum_{m=n+1}^{\infty} \frac{1}{m^2} < \int_n^{\infty} f(x)\ dx = \int_n^{\infty} \frac{dx}{x^2} = \frac{1}{n} = T_n$$

Taking a hint from (a) we find $T_n \leq \epsilon \implies n \geq 5$. Hence, five terms are sufficient to compute the sum with the given allowed error $\epsilon = 1/5$ and so $S_5 \approxeq 0.51$.

(d) Let the sum $\sum n = 1^{\infty} 1/(n^2+1)$ be given and let us define the allowed error as $\epsilon = 1/2$. It is true that $n^2 + 1 > n^2$ and so we can define $b_n = 1/n^2$ such that $|a_n| < b_n$ for $n \geq n_1 = 1$. Now since $\sum_{n=1}^{\infty} b_n = \sum_{n=1}^{\infty} 1/n^2$ converges then by Theorem 22 and Theorem 23 it follows that

$$|R_n| \leq \sum_{m=n+1}^{\infty} b_m = \leq \sum_{m=n+1}^{\infty} b_m \frac{1}{m^2} < \int_n^{\infty} f(x)\ dx = \int_n^{\infty} \frac{dx}{x^2} = \frac{1}{n} = T_n$$

Taking a hint from (a) we find $T_n \leq \epsilon \implies n \geq 2$. Hence, two terms are sufficient to compute the sum with the given allowed error $\epsilon = 1/2$ and so $S_2 = 0.7$.

(e) Let the sum $\sum_{n=1}^{\infty} 1/n^n$ be given and let us define the allowed error as $\epsilon = 1/100$. Then

$$\sqrt[n]{|a_n|} = \frac{1}{n} \leq r < 1$$

for $n \geq 2$, so that the series $\sum a_n$ converges by the root test. Hence, by Theorem 25

$$|R_n| \leq \frac{r^{n+1}}{1-r} = T_n \implies \frac{1}{(n+1)^{n+1}} \cdot \frac{1}{1 - \dfrac{1}{n+1}} = \frac{1}{n\,(n+1)^n} \leq \epsilon$$

for $n \geq 2$. In other words, we are looking for the smallest integer $n \geq 2$ such that $n(n+1)^n \geq 100$, which is satisfied for $n = 3$. Hence, three terms are sufficient to compute the sum with the given allowed error $\epsilon = 1/100$ and so $S_3 \approxeq 1.287$.

(f) Let the sum $\sum_{n+1}^{\infty} 1/n!$ be given and let us define the allowed error as $\epsilon = 1/100$. Then

$$\left|\frac{a_{n+1}}{a_n}\right| = \frac{n!}{(n+1)!} = \frac{1}{n+1} \leq r < 1$$

for $n \geq 1$, so that the series $\sum a_n$ converges by the ratio test. Hence, by Theorem 24

$$|R_n| \leq \frac{|a_{n+1}|}{1-r} = T_n \implies \frac{1}{(n+1)!} \cdot \frac{1}{1 - \dfrac{1}{n+2}} = \frac{1}{(n+1)!}\left(1 + \frac{1}{n+1}\right) \leq \epsilon$$

for $n \geq 1$. In other words, we are looking for the smallest integer $n \geq 1$ such that $T_n \leq \epsilon$, which is satisfied for $n = 4$. Hence, four terms are sufficient to compute the sum with the given allowed error $\epsilon = 1/100$ and so $S_4 \approxeq 1.708$.

(g) Let the sum $\sum_{n+1}^{\infty}(-1)^{n+1}/(2n-1)!$ be given and let us define the allowed error as $\epsilon = 1/1000$. Since

$$\left|\frac{a_{n+1}}{a_n}\right| = \frac{(2n-1)!}{(2n+1)!} < 1 \qquad \lim_{n\to\infty} a_n = \lim_{n\to\infty} \frac{1}{(2n-1)!} = 0$$

the series $\sum a_n$ converges by the alternating series test. Hence, by Theorem 26

$$|R_n| < a_{n+1} = \frac{1}{(2n+1)!} = T_n \implies \frac{1}{(2n+1)!} \leq \epsilon$$

and so we are looking for the smallest integer such that $(2n+1)! \geq 1000$, which is satisfied for $n = 3$. Hence, three terms are sufficient to compute the sum with the given allowed error $\epsilon = 1/1000$ and so $S_3 \approxeq 0.8417$.

(h) Let the sum $\sum_{n+2}^{\infty}(-1)^n/(n \ln n)$ be given and let us define the allowed error as $\epsilon = 1/2$. Since

$$\left|\frac{a_{n+1}}{a_n}\right| = \frac{n \ln n}{(n+1)\ln(n+1)} < 1 \qquad \lim_{n\to\infty} a_n = \lim_{n\to\infty} \frac{1}{n \ln n} = 0$$

the series $\sum a_n$ converges by the alternating series test. Hence, by Theorem 26

$$|R_n| < a_{n+1} = \frac{1}{(n+1)\ln(n+1)} = T_n \implies \frac{1}{(n+1)\ln(n+1)} \leq \epsilon$$

and so we are looking for the smallest integer such that $(n+1)\ln(n+1) \geq 2$, which is satisfied for $n = 2$. Hence, one term is sufficient to compute the sum with the given allowed error $\epsilon = 1/2$ and so $S_1 \approxeq 0.72$.

(i) Let the sum $\sum_{n=2}^{\infty} 1/(n^3 \ln n)$ be given and let us define the allowed error as $\epsilon = 1/2$. It is true that $n^3 \ln n > n^2$ for $n \geq 2$ and so we can define $b_n = 1/n^2$ such that $|a_n| < b_n$ for $n \geq n_1 = 2$. Now since $\sum_{n=2}^{\infty} b_n = \sum_{n=2}^{\infty} 1/n^2$ converges then by Theorem 22 and Theorem 23 it follows that

$$|R_n| \leq \sum_{m=n+1}^{\infty} b_m = \sum_{m=n+1}^{\infty} \frac{1}{m^2} < \int_n^{\infty} f(x)\, dx = \int_n^{\infty} \frac{dx}{x^2} = \frac{1}{n} = T_n$$

Taking a hint from (a) we find $T_n \leq \epsilon \implies n \geq 2$. Hence, one term is sufficient to compute the sum with the given allowed error $\epsilon = 1/2$ and so $S_1 \approxeq 0.18$.

(j) Let the sum $\sum_{n=1}^{\infty} 2^n/(3^n + 1)$ be given and let us define the allowed error as $\epsilon = 1/10$. It is true that $3^n + 1 > 3^n$ for $n \geq 1$ and so we can define $b_n = 2^n/3^n$ such that $|a_n| < b_n$ for $n \geq n_1 = 1$. Now since $\sqrt[n]{|b_n|} = \sqrt[n]{2^n/3^n} = 2/3 \leq r < 1$ for $n \geq 1$ we may conclude that the series $\sum b_n$ converges by the root test. Hence, choosing $r = 2/3$ then by Theorem 25

$$|R_n| \leq \frac{r^{n+1}}{1-r} = \frac{2^{n+1}}{3^n} = T_n \implies \frac{2^{n+1}}{3^n} \leq \epsilon$$

and so we are looking for the smallest integer such that $3^n/2^{n+1} \geq 10$, which is satisfied for $n = 8$. Hence, eight terms are sufficient to compute the sum with the given allowed error $\epsilon = 1/10$ and so $S_8 \approxeq 1.697$.

2. Let $\sum a_n$ be the geometric series $1 + r + r^2 + \cdots = \sum_{n=0}^{\infty} r^n$. By Theorem 16 this series converges for $-1 < r < 1$. Hence, by Theorem 23

$$|R_n| = \sum_{m=n+1}^{\infty} r^m < \int_n^{\infty} r^x\, dx = T_n$$

Or

$$\begin{aligned} T_n = \int_n^{\infty} r^x\, dx = \lim_{b\to\infty} \int_n^b r^x\, dx = \lim_{b\to\infty} \int_n^b e^{x \ln r}\, dx &= \lim_{b\to\infty} \int_{n \ln r}^{b \ln r} \frac{e^u}{\ln r}\, du \\ &= \lim_{b\to\infty} \left. \frac{e^u}{\ln r} \right|_{n \ln r}^{b \ln r} \\ &= \lim_{b\to\infty} \frac{e^{b \ln r}}{\ln r} - \frac{e^{n \ln r}}{\ln r} \\ &= -\frac{e^{n \ln r}}{\ln r} = -\frac{r^n}{\ln r} \end{aligned}$$

assuming $0 < r < 1$.

(a) let the given allowed error $\epsilon = 1/100$. In order to determine how many terms are needed to compute the sum with error less than ϵ we require $T_n < \epsilon$. For $r = 1/2$ this results in

$$-\frac{1}{2^n \ln 2^{-1}} < \frac{1}{100} \iff n > \frac{\ln(100/\ln 2)}{\ln 2}$$

which is satisfied for $n = 8$. Hence, when $r = 1/2$, 8 terms are sufficient to compute the sum with error less than $\epsilon = 1/100$. For $r = 0.9 = 9/10$ we get

$$-\frac{1}{\ln(9/10)}\left(\frac{9}{10}\right)^n < \frac{1}{100} \iff n > \frac{\ln 100 - \ln(-\ln 9/10)}{\ln 10/9}$$

which is satisfied for $n = 66$. Hence, when $r = 0.9$, 66 terms are sufficient to compute the sum with error less than $\epsilon = 1/100$. For $r = 0.99 = 99/100$ we get

$$-\frac{1}{\ln(99/100)}\left(\frac{99}{100}\right)^n < \frac{1}{100} \iff n > \frac{\ln 100 - \ln(-\ln 99/100)}{\ln 100/99}$$

which is satisfied for $n = 916$. Hence, when $r = 0.99$, 916 terms are sufficient to compute the sum with error less than $\epsilon = 1/100$.

(b) The closed form formula (6.17) for a geometric series $1 + ar + ar^2 + \cdots$, with $a = 1$ and $-1 < r < 1$ is given by $S = 1/(1-r)$. Likewise, the closed form formula for the partial sum of the same geometric series is given by $S_n = (1-r^n)/(1-r)$. The remainder R_n after n terms thus can be defined as

$$|R_n| = |S_n - S| = \left|\frac{1-r^n}{1-r} - \frac{1}{1-r}\right| = \left|\frac{-r^n}{1-r}\right| < \epsilon \iff -\epsilon < -\frac{r^2}{1-r} < \epsilon$$

The inequality on the right hand side can be further manipulated to finally get

$$\begin{aligned} -\frac{r^n}{1-r} &< \epsilon \\ r^n &> -\epsilon(1-r) \\ \ln|r|^n &> \ln|-\epsilon(1-r)| \\ n &> \frac{\ln \epsilon(1-r)}{\ln|r|} \end{aligned}$$

where $-1 < r < 1$.

(c) When r approaches 1 from the left we note that

$$\lim_{r\to 1^-} \frac{\ln \epsilon(1-r)}{\ln|r|} = \lim_{r\to 1^-} \frac{\ln \epsilon(1-r)}{\ln r} = \lim_{r\to 1^-} \ln \epsilon(1-r) \cdot \lim_{r\to 1^-} \frac{1}{\ln r} = -\infty \cdot -\infty = \infty$$

Hence, it follows from (b) that $n \to \infty$ when $r \to 1^-$, or in other words; that the number of terms needed to compute the sum with error less than a fixed ϵ becomes infinite.

3. Let the series

$$1 - \frac{1}{2^p} + \frac{1}{3^p} - \cdots = \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{n^p} = \sum_{n=1}^{\infty} (-1)^{n+1} a_n$$

where $p > 0$ be given. As such, $S_n = a_1 - a_2 + a_3 - a_4 + \cdots \pm a_n$ and so $S_1 = a_1 = 1$, $S_2 = a_1 - a_2 = 1 - 2^{-p}$ so that $0 < S_2 < S_1$, $S_3 = S_1 - (a_2 - a_3) = 1 - 2^{-p} + 3^{-p}$ so that $0 < S_3 < S_1$ and $S_2 < S_3 < S_1$. Reasoning in this way, we conclude that

$$S_1 > S_3 > S_5 > S_7 > \cdots > S_6 > S_4 > S_2$$

Hence, the smallest partial sum is S_2, but we just established that $S_2 = 1 - 2^{-p} > 0$. Hence, it follows that the sum $S = \lim_{n\to\infty} S_n$ must be positive whenever $p > 0$.

Section 6.10

1. Let the following relations be given:

$$\sum_{n=1}^{\infty} \frac{1}{n^2} = \frac{\pi^2}{6} \qquad \sum_{n=1}^{\infty} \frac{1}{n^4} = \frac{\pi^4}{90} \qquad \sum_{n=1}^{\infty} \frac{1}{n^6} = \frac{\pi^6}{945}$$

Then by (6.15)

(a)

$$\sum_{n=1}^{\infty} \frac{6}{n^2} = 6\sum_{n=1}^{\infty} \frac{1}{n^2} = \pi^2$$

(b)

$$\sum_{n=1}^{\infty} \frac{n^2+1}{n^4} = \sum_{n=1}^{\infty} \frac{1}{n^2} + \sum_{n=1}^{\infty} \frac{1}{n^4} = \frac{\pi^2}{6} + \frac{\pi^4}{90} =$$

(c)

$$\sum_{n=1}^{\infty} \frac{2n^2-3}{n^4} = \sum_{n=1}^{\infty} \frac{2}{n^2} - \sum_{n=1}^{\infty} \frac{3}{n^4} = 2\sum_{n=1}^{\infty} \frac{1}{n^2} - 3\sum_{n=1}^{\infty} \frac{1}{n^4} = \frac{\pi^2}{3} - \frac{\pi^4}{30}$$

(d)

$$\begin{aligned}\sum_{n=1}^{\infty} \frac{9+3n^2+5n^4}{n^6} &= \sum_{n=1}^{\infty} \frac{9}{n^6} + \sum_{n=1}^{\infty} \frac{3}{n^4} + \sum_{n=1}^{\infty} \frac{5}{n^2} = 9\sum_{n=1}^{\infty} \frac{1}{n^6} + 3\sum_{n=1}^{\infty} \frac{1}{n^4} + 5\sum_{n=1}^{\infty} \frac{1}{n^2} \\ &= \frac{5\pi^2}{6} + \frac{\pi^4}{30} + \frac{\pi^6}{105}\end{aligned}$$

(e)

$$\sum_{n=3}^{\infty} \frac{n^4-1}{n^6} = \sum_{n=3}^{\infty} \frac{1}{n^2} - \sum_{n=3}^{\infty} \frac{1}{n^6} = \sum_{n=1}^{\infty} \frac{1}{n^2} - \frac{5}{4} - \sum_{n=1}^{\infty} \frac{1}{n^6} + \frac{65}{64} = \frac{\pi^2}{6} - \frac{\pi^6}{945} - \frac{15}{64}$$

(f)

$$\begin{aligned}
\sum_{n=2}^{\infty} \frac{n^2+1}{\left(n^2-1\right)^2} = \sum_{n=2}^{\infty} \left[\frac{1}{2\left(n+1\right)^2} + \frac{1}{2\left(n-1\right)^2}\right] &= \sum_{n=2}^{\infty} \frac{1}{2\left(n+1\right)^2} + \sum_{n=2}^{\infty} \frac{1}{2\left(n-1\right)^2} \\
&= \frac{1}{2}\sum_{n=2}^{\infty} \frac{1}{\left(n+1\right)^2} + \frac{1}{2}\sum_{n=2}^{\infty} \frac{1}{\left(n-1\right)^2} \\
&= \frac{1}{2}\sum_{n=2}^{\infty} \frac{1}{n^2} - \frac{1}{8} + \frac{1}{2}\sum_{n=2}^{\infty} \frac{1}{n^2} + \frac{1}{2} \\
&= \frac{1}{2}\sum_{n=1}^{\infty} \frac{1}{n^2} - \frac{1}{8} - \frac{1}{2} + \frac{1}{2}\sum_{n=1}^{\infty} \frac{1}{n^2} + \frac{1}{2} - \frac{1}{2} \\
&= \sum_{n=1}^{\infty} \frac{1}{n^2} - \frac{5}{8} = \frac{\pi^2}{6} - \frac{5}{8}
\end{aligned}$$

2. (a)

$$\sum_{n=1}^{\infty} \frac{1}{n^3} = \sum_{n=1}^{\infty} \frac{1}{n^3} + 1 - 1 = \sum_{n=2}^{\infty} \frac{1}{n^3} + 1 = \sum_{n=2}^{\infty} \frac{1}{\left(n-1\right)^3}$$

(b)

$$\begin{aligned}
\sum_{n=1}^{\infty} \left[f\left(n+1\right) - f\left(n\right)\right] &= \sum_{n=1}^{\infty} f\left(n+1\right) - \sum_{n=1}^{\infty} f\left(n\right) \\
&= \sum_{n=1}^{\infty} f\left(n\right) + \lim_{n\to\infty} f\left(n\right) - f\left(1\right) - \sum_{n=1}^{\infty} f\left(n\right) \\
&= \lim_{n\to\infty} f\left(n\right) - f\left(1\right)
\end{aligned}$$

if the limit exists.

(c)

$$\begin{aligned}
\sum_{n=2}^{\infty} \left[f\left(n+1\right) - f\left(n-1\right)\right] &= \sum_{n=2}^{\infty} f\left(n+1\right) - \sum_{n=2}^{\infty} f\left(n-1\right) \\
&= \sum_{n=1}^{\infty} f\left(n+1\right) + \lim_{n\to\infty} f\left(n+1\right) - f\left(2\right) - \sum_{n=1}^{\infty} f\left(n\right) \\
&= \sum_{n=1}^{\infty} f\left(n\right) - f\left(1\right) + \lim_{n\to\infty} f\left(n\right) + \lim_{n\to\infty} f\left(n+1\right) - f\left(2\right) \\
&\quad - \sum_{n=1}^{\infty} f\left(n\right) \\
&= \lim_{n\to\infty} \left[f\left(n\right) + f\left(n+1\right)\right] - f\left(1\right) - f\left(2\right)
\end{aligned}$$

if the limit exists.

3. (a) Let $f(n) = 1/n^2$. Then using 2(b)

$$\begin{aligned}
\sum_{n=1}^{\infty} \left[f\left(n+1\right) - f\left(n\right) \right] &= \lim_{n\to\infty} f\left(n\right) - f\left(1\right) \\
\sum_{n=1}^{\infty} \left[\frac{1}{\left(n+1\right)^2} - \frac{1}{n^2} \right] &= \lim_{n\to\infty} \frac{1}{n^2} - 1 \\
\sum_{n=1}^{\infty} -\frac{2n+1}{n^2\left(n+1\right)^2} &= 0 - 1 \\
\sum_{n=1}^{\infty} \frac{2n+1}{n^2\left(n+1\right)^2} &= 1
\end{aligned}$$

(b) Let $f(n) = 1/n$. Then using 2(b)

$$\begin{aligned}
\sum_{n=1}^{\infty} \left[f\left(n+1\right) - f\left(n\right) \right] &= \lim_{n\to\infty} f\left(n\right) - f\left(1\right) \\
\sum_{n=1}^{\infty} \left[\frac{1}{n+1} - \frac{1}{n} \right] &= \lim_{n\to\infty} \frac{1}{n} - 1 \\
\sum_{n=1}^{\infty} -\frac{1}{n\left(n+1\right)} &= 0 - 1 \\
\sum_{n=1}^{\infty} \frac{1}{n\left(n+1\right)} &= 1
\end{aligned}$$

(c) Let $f(n) = 1/n$. Then using 2(c)

$$\begin{aligned}
\sum_{n=2}^{\infty} \left[f\left(n+1\right) - f\left(n-1\right) \right] &= \lim_{n\to\infty} \left[f\left(n\right) + f\left(n+1\right) \right] - f\left(1\right) - f\left(2\right) \\
\sum_{n=2}^{\infty} \left[\frac{1}{n+1} - \frac{1}{n-1} \right] &= \lim_{n\to\infty} \left(\frac{1}{n} + \frac{1}{n+1} \right) - 1 - \frac{1}{2} \\
\sum_{n=2}^{\infty} -\frac{2}{n^2-1} &= 0 + 0 - 1 - \frac{1}{2} \\
-2\sum_{n=2}^{\infty} \frac{1}{n^2-1} &= -\frac{3}{2} \\
\sum_{n=2}^{\infty} \frac{1}{n^2-1} &= \frac{3}{4}
\end{aligned}$$

(d) Let $f(n) = 1/n^2$. Then using 2(c)

$$\begin{aligned}
\sum_{n=2}^{\infty} \left[f(n+1) - f(n-1)\right] &= \lim_{n\to\infty} \left[f(n) + f(n+1)\right] - f(1) - f(2) \\
\sum_{n=2}^{\infty} \left[\frac{1}{(n+1)^2} - \frac{1}{(n-1)^2}\right] &= \lim_{n\to\infty} \left[\frac{1}{n^2} + \frac{1}{(n+1)^2}\right] - 1 - \frac{1}{4} \\
\sum_{n=2}^{\infty} -\frac{4n}{(n^2-1)^2} &= 0 + 0 - 1 - \frac{1}{4} \\
\sum_{n=2}^{\infty} \frac{4n}{(n^2-1)^2} &= \frac{5}{4}
\end{aligned}$$

4. Let the relation

$$\frac{1}{1-r} = 1 + r + \cdots + r^n + \cdots = \sum_{n=0}^{\infty} r^n \qquad -1 < r < 1$$

be given.

(a) Using the *Cauchy product* as illustrated in Fig. 6.6 we can thus write

$$\begin{aligned}
\frac{1}{(1-r)^2} &= \frac{1}{1-r} \cdot \frac{1}{1-r} \\
&= (1 + r + \cdots + r^n + \cdots) \cdot (1 + r + \cdots + r^n + \cdots) \\
&= 1 + (1 \cdot r + r \cdot 1) + \left(1 \cdot r^2 + r \cdot r + r^2 \cdot 1\right) + \cdots \\
&\quad + \left(1 \cdot r^n + r \cdot r^{n-1} + \cdots + r^n \cdot 1\right) + \cdots \\
&= 1 + 2r + 3r^2 + \cdots + (n+1)\, r^n + \cdots
\end{aligned}$$

(b) Firstly, we will derive the formula for a sum of an arithmetic sequence $a_m = a_1 + (m-1)d$, where d denotes the common difference between successive terms. We will start by expressing the arithmetic series in two different ways:

$$\begin{aligned}
S_m &= a_1 + (a_1 + d) + (a_1 + 2d) + \cdots + \left[a_1 + (m-2)\, d\right] + \left[a_1 + (m-1)\, d\right] \\
S_m &= \left[a_m - (m-1)\, d\right] + \left[a_m - (m-2)\, d\right] + \cdots + (a_m - 2d) + (a_m - d) + a_m
\end{aligned}$$

Adding both equations, we find that all terms involving d cancel and so we are left with

$$2S_m = m\,(a_1 + a_m) \iff S_m = \frac{m\,(a_1 + a_m)}{2}$$

Now, again using the *Cauchy product*

$$
\begin{aligned}
\frac{1}{(1-r)^3} &= \frac{1}{(1-r)^2}\cdot\frac{1}{1-r}\\
&= \left[1+2r+3r^2+\cdots+(n+1)\,r^n+\cdots\right]\cdot\left(1+r+\cdots+r^n+\cdots\right)\\
&= 1+(1\cdot r+2r\cdot 1)+\cdots+\left[1\cdot r^n+2r\cdot r^{n-1}+\cdots+(n+1)\cdot r^n\right]+\cdots\\
&= 1+3r+\cdots+\left[1+2+\cdots+(n+1)\right]r^n+\cdots\\
&= 1+3r+\cdots+\frac{(n+2)\,(n+1)}{2}r^n+\cdots
\end{aligned}
$$

where we have used the fact that the arithmetic sequence $1+2+\cdots+(n+1)$ can be written as $(n+2)(n+1)/2$ using the derived formula above.

5. We want to prove that

$$
(1-r)^{-k} = 1+kr+\frac{k\,(k+1)}{1\cdot 2}r^2+\cdots+\frac{k\,(k+1)\cdots(k+n-1)}{1\cdot 2\cdots n}r^n+\cdots
$$

for $-1<r<1$, $k=1,2,\ldots$. Using the solutions to 4(a) and 4(b) we can confirm the above equation is true for $k=1,2,3$. It remains to be proven that the equation is true for $k=1,2,\ldots$. In order to simplify the discussion we will write the coefficients appearing in the equation above as binomial coefficients and also make use of *Pascal's identity*:

$$
\binom{k}{n} = \frac{k!}{n!\,(k-n)!} \qquad\qquad \binom{k}{n} = \binom{k-1}{n-1}+\binom{k-1}{n}
$$

Next, we assume the equation is true for some positive integer $k\geq 2$ and consider the expansion

$$
\begin{aligned}
(1-r)^{-k-1} &= (1-r)^{-1}\left[1+kr+\frac{k\,(k+1)}{1\cdot 2}r^2+\cdots+\frac{k\,(k+1)\cdots(k+n-1)}{1\cdot 2\cdots n}r^n+\cdots\right]\\
&= (1-r)^{-1}\left[1+\binom{k}{1}r+\binom{k+1}{2}r^2+\cdots+\binom{k+n-1}{n}r^n+\cdots\right]\\
&= \left(1+r+r^2+\cdots+r^n\right)\left[1+\binom{k}{1}r+\binom{k+1}{2}r^2+\cdots+\binom{k+n-1}{n}r^n+\cdots\right]\\
&= 1+\left[1+\binom{k}{1}\right]r+\left[1+\binom{k}{1}+\binom{k+1}{2}\right]r^2+\cdots\\
&\quad+\left[1+\binom{k}{1}+\binom{k+1}{2}+\cdots+\binom{k+n-2}{n-1}+\binom{k+n-1}{n}\right]r^n+\cdots\\
&= 1+\binom{k+1}{1}r+\binom{k+2}{2}r^2+\cdots+\binom{k+n}{n}r^n+\cdots\\
&= 1+(k+1)\,r+\frac{(k+1)\,(k+2)}{1\cdot 2}r^2+\cdots+\frac{(k+1)\,(k+2)\cdots(k+n)}{1\cdot 2\cdots n}r^n+\cdots
\end{aligned}
$$

Hence, the equation is true for $k+1$ and so by induction the equation must be true for any positive integer $k \geq 1$.

6. Let $\sin x$ and $\cos x$ be represented for all x by the absolutely convergent series

$$\sin x = x - \frac{x^3}{3!} + \frac{x^5}{5!} - \cdots + (-1)^{n+1}\,\frac{x^{2n-1}}{(2n-1)!} + \cdots = \sum_{n=1}^{\infty} a_n$$
$$\cos x = 1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \cdots + (-1)^{n}\,\frac{x^{2n}}{(2n)!} + \cdots = \sum_{n=0}^{\infty} b_n$$

Then by (6.24) it follows that

$$\begin{aligned}
\sin x \cos x &= \sum_{n=0}^{\infty} a_n \cdot \sum_{n=0}^{\infty} b_n \\
&= \left[x - \frac{x^3}{3!} + \frac{x^5}{5!} - \cdots + (-1)^n\,\frac{x^{2n+1}}{(2n+1)!} + \cdots\right] \\
&\quad \times \left[1 - \frac{x^2}{2!} + \frac{x^4}{4!} - \cdots + (-1)^n\,\frac{x^{2n}}{(2n)!} + \cdots\right] \\
&= x - \frac{2x^3}{3} + \frac{2x^5}{15} - \cdots + x^{2n+1} \sum_{k=0}^{m} \frac{(-1)^k\,(-1)^{m-k}}{(2k+1)!\,(2m-2k)!} + \cdots
\end{aligned}$$

and

$$\frac{1}{2}\sin 2x = x - \frac{2^2 x^3}{3!} + \frac{2^4 x^5}{5!} - \cdots + (-1)^n\,\frac{2^{2n} x^{2n+1}}{(2n+1)!} + \cdots$$

Hence, we need to prove that

$$\sum_{k=0}^{m} \frac{1}{(2m+1)!\,(2m-2k)!} = \frac{2^{2m}}{(2k+1)!} \iff \sum_{k=0}^{m} \frac{(2m+1)!}{(2k+1)!\,(2m-2k)!} = 2^{2m}$$

To this end (making use of *Pascal's identity*)

$$\begin{aligned}
\sum_{k=0}^{m} \frac{(2m+1)!}{(2k+1)!\,(2m-2k)!} &= \sum_{k=0}^{m} \binom{2m+1}{2k+1} \\
&= \sum_{k=0}^{m} \left[\binom{2m}{2k} + \binom{2m}{2k+1}\right] \\
&= \sum_{k=0}^{m} \left[\frac{(2m)!}{(2k)!\,(2m-2k)!} + \frac{(2m)!}{(2k+1)!\,(2m-2k-1)!}\right] \\
&= \sum_{k=0}^{2m} \frac{(2m)!}{k!\,(2m-k)!} \\
&= \sum_{k=0}^{2m} \binom{2m}{k}
\end{aligned}$$

Now from the definition of the binomial formula

$$(x+y)^n = \sum_{k=0}^{n} \binom{n}{k} x^{n-k} y^k$$

it then finally follows that

$$\sum_{k=0}^{2m} \binom{2m}{k} = (1+1)^{2m} = 2^{2m}$$

which thus completes the proof.

7. Let the sequence a_n be close to the sequence b_n and let $\sum_{n=1}^{\infty} b_n$ be known. We can write $\sum_{n=1}^{\infty} a_n = \sum_{n=1}^{\infty} b_n - \sum_{n=1}^{\infty}(b_n - a_n)$.

   (a) Let $\sum_{n=1}^{\infty} a_n = \sum_{n=1}^{\infty}(2^n+1)^{-1}$ and let us choose $\sum_{n=1}^{\infty} b_n = \sum_{n=1}^{\infty} 2^{-n} = 1$. Hence,

$$\begin{aligned}\sum_{n=1}^{\infty} a_n &= \sum_{n=1}^{\infty} b_n - \sum_{n=1}^{\infty} (b_n - a_n)\\ \sum_{n=1}^{\infty} (2^n+1)^{-1} &= \sum_{n=1}^{\infty} 2^{-n} - \sum_{n=1}^{\infty} (4^n+2^n)^{-1}\\ &= 1 - \sum_{n=1}^{\infty} (4^n+2^n)^{-1}\end{aligned}$$

   As such, we find that for $n \geq 7$ the expression $\sum_{n=1}^{\infty} a_n = 1 - \sum_{n=1}^{\infty}(4^n+2^n)^{-1} \approxeq 0.7645$, whereas we require $n \geq 15$ for $\sum_{n=1}^{\infty} a_n = \sum_{n=1}^{\infty}(2^n+1)^{-1} \approxeq 0.7645$.

   (b) Let $\sum_{n=1}^{\infty} a_n = \sum_{n=1}^{\infty}(2^n+9^{-1})^{-1}$ and let us choose $\sum_{n=1}^{\infty} b_n = \sum_{n=1}^{\infty} 2^{-n} = 1$. Hence,

$$\begin{aligned}\sum_{n=1}^{\infty} a_n &= \sum_{n=1}^{\infty} b_n - \sum_{n=1}^{\infty} (b_n - a_n)\\ \sum_{n=1}^{\infty} \left(2^n+9^{-1}\right)^{-1} &= \sum_{n=1}^{\infty} 2^{-n} - \sum_{n=1}^{\infty} (4^n 9+2^n)^{-1}\\ &= 1 - \sum_{n=1}^{\infty} (4^n 9+2^n)^{-1}\end{aligned}$$

   As such, we find that for $n \geq 6$ the expression $\sum_{n=1}^{\infty} a_n = 1 - \sum_{n=1}^{\infty}(4^n 9+2^n)^{-1} \approxeq 0.9646$, whereas we require $n \geq 14$ for $\sum_{n=1}^{\infty} a_n = \sum_{n=1}^{\infty}(2^n+9^{-1})^{-1} \approxeq 0.9646$.

(c) Let $\sum_{n=1}^{\infty} a_n = \sum_{n=1}^{\infty} (n^2+1)^{-1}$ and let us choose $\sum_{n=1}^{\infty} b_n = \sum_{n=1}^{\infty} n^{-2} = \pi^2/6$. Hence,

$$\sum_{n=1}^{\infty} a_n = \sum_{n=1}^{\infty} b_n - \sum_{n=1}^{\infty} (b_n - a_n)$$

$$\begin{aligned}\sum_{n=1}^{\infty} \left(n^2+1\right)^{-1} &= \sum_{n=1}^{\infty} n^{-2} - \sum_{n=1}^{\infty} \left(n^4+n^2\right)^{-1} \\ &= \frac{\pi^2}{6} - \sum_{n=1}^{\infty} \left(n^4+n^2\right)^{-1}\end{aligned}$$

For $n \geq 16$ we then find $\sum_{n=1}^{\infty} a_n = (\pi^2/6) - \sum_{n=1}^{\infty} (n^4+n^2)^{-1} \approxeq 1.0767$. Next, we use $b_n = n^{-4}$. Then

$$\begin{aligned}\sum_{n=1}^{\infty} a_n &= \frac{\pi^2}{6} - \sum_{n=1}^{\infty} \left(n^4+n^2\right)^{-1} \\ &= \frac{\pi^2}{6} - \sum_{n=1}^{\infty} n^{-4} + \sum_{n=1}^{\infty} \left(n^6+n^4\right)^{-1} \\ &= \frac{\pi^2}{6} - \frac{\pi^4}{90} + \sum_{n=1}^{\infty} \left(n^6+n^4\right)^{-1}\end{aligned}$$

For $n \geq 6$ we then find $\sum_{n=1}^{\infty} a_n = (\pi^2/6) - (\pi^4/90) + \sum_{n=1}^{\infty} (n^6+n^4)^{-1} \approxeq 1.0767$. Lastly, we use $b_n = n^{-6}$. Then

$$\begin{aligned}\sum_{n=1}^{\infty} a_n &= \frac{\pi^2}{6} - \frac{\pi^4}{90} + \sum_{n=1}^{\infty} \left(n^6+n^4\right)^{-1} \\ &= \frac{\pi^2}{6} - \frac{\pi^4}{90} + \sum_{n=1}^{\infty} n^{-6} - \sum_{n=1}^{\infty} \left(n^8+n^6\right)^{-1} \\ &= \frac{\pi^2}{6} - \frac{\pi^4}{90} + \frac{\pi^6}{945} - \sum_{n=1}^{\infty} \left(n^8+n^6\right)^{-1}\end{aligned}$$

For $n \geq 3$ we then find $\sum_{n=1}^{\infty} a_n = (\pi^2/6) - (\pi^4/90) + (\pi^6/945) - \sum_{n=1}^{\infty} (n^8+n^6)^{-1} \approxeq 1.0767$.

Section 6.13

1. (a) Let the series $\sum_{n=1}^{\infty} x^n/(2n^2-n)$ be given. By the ratio test we find

$$\begin{aligned}\lim_{n\to\infty} \left|\frac{a_{n+1}}{a_n}\right| = \lim_{n\to\infty} \left|\frac{x^{n+1}}{2\left(n+1\right)^2 - (n+1)} \frac{2n^2-n}{x^n}\right| &= |x| \lim_{n\to\infty} \frac{2n^2-n}{2n^2+3n+1} \\ &= |x| \lim_{n\to\infty} \frac{2-1/n}{2+3/n+1/n^2} = |x|\end{aligned}$$

Hence, by the ratio test the series converges when $\lim_{n\to\infty} |a_{n+1}/a_n| = L = |x| < 1$ or $-1 < x < 1$. To test for convergence when $x = \pm 1$ we employ the integral test:

$$\begin{aligned}\int_1^\infty \frac{(\pm 1)}{2y^2 - y}\,dy = (\pm 1)\lim_{b\to\infty}\int_1^b \left(\frac{2}{2y-1} - \frac{1}{y}\right) dy &= (\pm 1)\lim_{b\to\infty}\left(\int_1^{2b-1}\frac{du}{u} - \int_1^b \frac{dy}{y}\right)\\ &= (\pm 1)\lim_{b\to\infty}\left(\ln|2b-1| - \ln|b|\right)\\ &= (\pm 1)\lim_{b\to\infty}\ln\frac{2b-1}{b}\\ &= (\pm 1)\lim_{b\to\infty}\ln\left(2 - \frac{1}{b}\right) = (\pm 1)\ln 2\end{aligned}$$

Since the improper integral $\int_c^\infty f(y)\,dy$ converges, so will the series $\sum_{n=1}^\infty (\pm 1)/(2n^2 - n)$. Hence, the series $\sum_{n=1}^\infty x^n/(2n^2 - n)$ converges for $-1 \le x \le 1$.

(b) Let the series $\sum_{n=1}^\infty nx^n/2^n$ be given. By the ratio test we find

$$\lim_{n\to\infty}\left|\frac{a_{n+1}}{a_n}\right| = \lim_{n\to\infty}\left|\frac{(n+1)\,x^{n+1}}{2^{n+1}}\,\frac{2^n}{nx^n}\right| = \frac{|x|}{2}\lim_{n\to\infty}\frac{n+1}{n} = \frac{|x|}{2}\lim_{n\to\infty}\left(1+\frac{1}{n}\right) = \frac{|x|}{2}$$

Hence, by the ratio test the series converges when $\lim_{n\to\infty}|a_{n+1}/a_n| = L = |x|/2 < 1$ or $-2 < x < 2$.

(c) Let the series $\sum_{n=1}^\infty 1/nx^{2n}$ be given. By the ratio test we find

$$\lim_{n\to\infty}\left|\frac{a_{n+1}}{a_n}\right| = \lim_{n\to\infty}\left|\frac{nx^{2n}}{(n+1)\,x^{2(n+1)}}\right| = \frac{1}{x^2}\lim_{n\to\infty}\frac{n}{n+1} = \frac{1}{x^2}\lim_{n\to\infty}\frac{1}{1+1/n} = \frac{1}{x^2}$$

Hence, by the ratio test the series converges when $\lim_{n\to\infty}|a_{n+1}/a_n| = L = 1/x^2 < 1$ or $|x| > 1 \iff x > 1,\ x < -1$.

(d) Let the series $\sum_{n=0}^\infty 1/2^{nx}$ be given. By the ratio test we find

$$\lim_{n\to\infty}\left|\frac{a_{n+1}}{a_n}\right| = \lim_{n\to\infty}\left|\frac{2^{nx}}{2^{(n+1)x}}\right| = \frac{1}{|2^x|}$$

Hence, by the ratio test the series converges when $\lim_{n\to\infty}|a_{n+1}/a_n| = L = 1/2^x < 1$ or $2^x > 2^0 \implies x > 0$.

(e) Let the series $\sum_{n=1}^\infty x^n/(1-x)^n$ be given. By the ratio test we find

$$\lim_{n\to\infty}\left|\frac{a_{n+1}}{a_n}\right| = \lim_{n\to\infty}\left|\frac{x^{n+1}}{(1-x)^{n+1}}\,\frac{(1-x)^n}{x^n}\right| = \left|\frac{x}{1-x}\right|$$

Hence, by the ratio test the series converges when $\lim_{n\to\infty}|a_{n+1}/a_n| = L = |x/(1-x)| < 1$ or $x - 1 < x < 1 - x \implies x < 1/2$.

(f) Let the series $\sum_{n=1}^{\infty} 2^n \sin^n x/n^2$ be given. By the ratio test we find

$$\lim_{n\to\infty}\left|\frac{a_{n+1}}{a_n}\right| = \lim_{n\to\infty}\left|\frac{2^{n+1}\sin^{n+1}x}{(n+1)^2}\frac{n^2}{2^n\sin^n x}\right| = 2|\sin x|\lim_{n\to\infty}\frac{n^2}{n^2+2n+1}$$
$$= 2|\sin x|\lim_{n\to\infty}\frac{1}{1+2/n+1/n^2} = 2|\sin x|$$

Hence, by the ratio test the series converges when $\lim_{n\to\infty}|a_{n+1}/a_n| = L = 2|\sin x| < 1$ or $-1/2 < \sin x < 1/2 \iff \sin^{-1}(-1/2) < x < \sin^{-1}(1/2)$, which is satisfied when $(-\pi/6)+n\pi < x < (\pi/6)+n\pi$ for $n = 0, \pm1, \pm2, \ldots$.

(g) Let the series $\sum_{n=1}^{\infty}(x-1)^n/n^2$ be given. By the ratio test we find

$$\lim_{n\to\infty}\left|\frac{a_{n+1}}{a_n}\right| = \lim_{n\to\infty}\left|\frac{(x-1)^{n+1}}{(n+1)^2}\frac{n^2}{(x-1)^n}\right| = |x-1|\lim_{n\to\infty}\frac{n^2}{n^2+2n+1}$$
$$= |x-1|\lim_{n\to\infty}\frac{1}{1+2/n+1/n^2} = |x-1|$$

Hence, by the ratio test the series converges when $\lim_{n\to\infty}|a_{n+1}/a_n| = L = |x-1| < 1$ or $-1 < x-1 < 1 \iff 0 < x < 2$. For $x = 0$ and $x = 2$ the series converges by comparison with the harmonic series of order 2:

$$\left|\frac{(\pm1)^n}{n^2}\right| \le \frac{1}{n^2}$$

Hence, the series converges for $0 \le x \le 2$.

(h) Let the series $\sum_{n=1}^{\infty} 1/x^n \ln(n+1)$ be given. By the ratio test we find

$$\lim_{n\to\infty}\left|\frac{a_{n+1}}{a_n}\right| = \lim_{n\to\infty}\left|\frac{x^n\ln(n+1)}{x^{n+1}\ln(n+2)}\right| = \frac{1}{|x|}\lim_{n\to\infty}\frac{\ln(n+1)}{\ln(n+2)} = \frac{1}{|x|}\lim_{n\to\infty}\frac{1/(n+1)}{1/(n+2)}$$
$$= \frac{1}{|x|}\lim_{n\to\infty}\frac{1+2/n}{1+1/n} = \frac{1}{|x|}$$

Hence, by the ratio test the series converges when $\lim_{n\to\infty}|a_{n+1}/a_n| = L = 1/|x| < 1$ or $|x| > 1 \iff x > 1,\ x \le -1$.

(i) Let the series $\sum_{n=1}^{\infty}(x-2)^{3n}/n!$ be given. By the ratio test we find

$$\lim_{n\to\infty}\left|\frac{a_{n+1}}{a_n}\right| = \lim_{n\to\infty}\left|\frac{(x-2)^{3(n+1)}}{(n+1)!}\frac{n!}{(x-2)^{3n}}\right| = |(x-2)^3|\lim_{n\to\infty}\frac{1}{n+1} = 0$$

Hence, the series converges for all x.

(j) Let the series $\sum_{n=2}^{\infty} x^n/\ln^n n$ be given. By the ratio test we find

$$\lim_{n\to\infty}\left|\frac{a_{n+1}}{a_n}\right| = \lim_{n\to\infty}\left|\frac{x^{n+1}}{\ln^{n+1}n}\frac{\ln^n n}{x^n}\right| = |x|\lim_{n\to\infty}\frac{1}{\ln n} = 0$$

Hence, the series converges for all x.

2. (a) Let the series $\sum_{n=1}^{\infty} x^n/n^3$, where $-1 \leq x \leq 1$ be given. The ratio test gives

$$\lim_{n\to\infty} \left|\frac{a_{n+1}}{a_n}\right| = \lim_{n\to\infty} \left|\frac{x^{n+1}}{(n+1)^3} \frac{n^3}{x^n}\right| = |x| \lim_{n\to\infty} \frac{n^3}{n^3+3n^2+3n+1}$$
$$= |x| \lim_{n\to\infty} \frac{1}{1+3/n+3/n^2+1/n^3} = |x|$$

Hence, the series converges for $|x| < 1 \iff -1 < x < 1$. For $x = \pm 1$ the series converges by comparison with the harmonic series of order 2:

$$\left|\frac{(\pm 1)^n}{n^3}\right| \leq \frac{1}{n^3} \leq \frac{1}{n^2}$$

Hence, the series converges for $-1 \leq x \leq 1$. The convergence is uniform for this range, since the comparison

$$\left|\frac{x^n}{n^3}\right| \leq \frac{1}{n^2} = M_n$$

holds for all x of the range and the series $\sum M_n = \sum_{n=1}^{\infty} 1/n^2$ converges.

(b) Let the series $\sum_{n=1}^{\infty} \tanh^n x/n!$, where x is any real number be given. This series converges uniformly for all x, since

$$\left|\frac{\tanh^n x}{n!}\right| \leq \frac{1}{n!} = M_n$$

holds for all x of the range and the series $\sum M_n = \sum_{n=1}^{\infty} 1/n!$ converges.

(c) Let the series $\sum_{n=1}^{\infty} \sin nx/(n^2+1)$, where x is any real number be given. This series converges uniformly for all x, since

$$\left|\frac{\sin nx}{n^2+1}\right| \leq \frac{1}{n^2+1} < \frac{1}{n^2} = M_n$$

holds for all x of the range and the series $\sum M_n = \sum_{n=1}^{\infty} 1/n^2$ converges.

(d) Let the series $\sum_{n=1}^{\infty} e^{nx}/2^n$, where $x \leq \ln(3/2)$ be given. The ratio test gives

$$\lim_{n\to\infty} \left|\frac{a_{n+1}}{a_n}\right| = \lim_{n\to\infty} \frac{e^{(n+1)x}}{2^{n+1}} \frac{2^n}{e^{nx}} = \lim_{n\to\infty} \frac{e^x}{2} = \frac{e^x}{2}$$

Hence, the series converges for $e^x/2 < 1 \iff x < \ln 2$. Because $\ln 3/2 < \ln 2$ the series converges uniformly, since

$$\frac{e^{nx}}{2^n} \leq \frac{e^{n \ln 3/2}}{2^n} = \frac{3^n}{4^n} = M_n$$

holds for all $x < \ln 3/2$ and the series $\sum M_n = \sum_{n=1}^{\infty} (3/4)^n$ converges according to the ratio test:

$$\lim_{n\to\infty} \left|\frac{a_{n+1}}{a_n}\right| = \lim_{n\to\infty} \frac{3^{n+1}}{4^{n+1}} \frac{4^n}{3^n} = \frac{3}{4} = L < 1$$

(e) Let the series $\sum_{n=0}^{\infty} x^n/n! = \sum_{n=1}^{\infty} x^n/n! + 1$, where $-1 \leq x \leq 1$ be given. The ratio test gives

$$\lim_{n\to\infty} \left| \frac{a_{n+1}}{a_n} \right| = \lim_{n\to\infty} \left| \frac{x^{n+1}}{(n+1)!} \frac{n!}{x^n} \right| = \lim_{n\to\infty} \frac{|x|}{n+1}$$

Hence, the series $\sum_{n=1}^{\infty} x^n/n!$ converges for $|x| < 1 \iff -1 < x < 1$. For $x = \pm 1$ the series converges by comparison with:

$$\left| \frac{(\pm 1)^n}{n!} \right| \leq \frac{1}{n!}$$

Hence, the series converges for $-1 \leq x \leq 1$. The convergence is uniform for this range, since the comparison

$$\left| \frac{x^n}{n!} \right| \leq \frac{1}{n!} = M_n$$

holds for all x of the range and the series $\sum M_n = \sum_{n=1}^{\infty} 1/n!$ converges.

(f) Let the series $\sum_{n=1}^{\infty} nx^n$, where $-1/2 \leq x \leq 1/2$ be given. The ratio test gives

$$\lim_{n\to\infty} \left| \frac{a_{n+1}}{a_n} \right| = \lim_{n\to\infty} \left| \frac{(n+1)\, x^{n+1}}{nx^n} \right| = |x| \lim_{n\to\infty} \left(1 + \frac{1}{n} \right) = |x|$$

Hence, the series converges for $|x| < 1 \iff -1 < x < 1$. This series converges uniformly for $-1/2 \leq x \leq 1/2$, since

$$|nx^n| \leq \frac{n}{2^n} = M_n$$

for all x of the range and the series $\sum M_n = \sum_{n=1}^{\infty} n/2^n$ converges according to the ratio test:

$$\lim_{n\to\infty} \left| \frac{a_{n+1}}{a_n} \right| = \lim_{n\to\infty} \frac{n+1}{2^{n+1}} \frac{2^n}{n} = \frac{1}{2} \lim_{n\to\infty} \left(1 + \frac{1}{n} \right) = \frac{1}{2} = L < 1$$

(g) Let the series $\sum_{n=1}^{\infty} nx^n$, where $-0.9 \leq x \leq 0.9$ be given. From (f) it follows that the series converges for $|x| < 1 \iff -1 < x < 1$. The series converges uniformly for $-0.9 \leq x \leq 0.9$, since

$$|nx^n| \leq n \left(\frac{9}{10} \right)^n = M_n$$

for all x of the range and the series $\sum M_n = \sum_{n=1}^{\infty} n(9/10)^n$ converges according to the ratio test:

$$\lim_{n\to\infty} \left| \frac{a_{n+1}}{a_n} \right| = \lim_{n\to\infty} \frac{n+1}{n} \left(\frac{9}{10} \right)^{n+1} \left(\frac{10}{9} \right)^n = \frac{9}{10} \lim_{n\to\infty} \left(1 + \frac{1}{n} \right) = 0.9 = L < 1$$

(h) Let the series $\sum_{n=1}^{\infty} nx^n$, where $-a \le x \le a$, $a < 1$ be given. From (f) it follows that the series converges for $|x| < 1 \iff -1 < x < 1$. The series converges uniformly for $-a \le x \le a$, since

$$|nx^n| \le na^n = M_n < n^n$$

and the series $\sum M_n = \sum_{n=1}^{\infty} na^n$ converges according to the ratio test:

$$\lim_{n\to\infty} \left|\frac{a_{n+1}}{a_n}\right| = \lim_{n\to\infty} \frac{(n+1)\, a^{n+1}}{na^n} = a \lim_{n\to\infty} \left(1 + \frac{1}{n}\right) = a = L < 1$$

3. Let $\sum_{n=1}^{\infty} u_n(x)$ be uniformly convergent for the interval $a \le x \le b$. In other words, some convergent series of constants $\sum_{n=1}^{\infty} M_n$ exists such that

$$|u_n\,(x)\,| \le M_n \quad a \le x \le b$$

Note that each constant M_n is the *same* for all $x \in [a, b]$. Hence, it must be the same for any smaller interval contained in $a \le x \le b$, since this smaller interval is just some subset E_1 that is part of the set E of values of x that represents the interval $a \le x \le b$. As such, the series must be uniformly convergent in each smaller interval contained in $a \le x \le b$ as well.

4. Let $\sum_{n=1}^{\infty} v_n(x)$ be uniformly convergent for a set E of values of x. Hence, some convergent series of constants $\sum_{n=1}^{\infty} M_n$ exists such that

$$|v_n(x)| \le M_n \quad \text{for all } x \text{ in } E$$

Furthermore, let $|u_n(x)| \le v_n(x)$ for $x \in E$. In other words, for each fixed x, each term of the series $\sum_{n=1}^{\infty} |u_n(x)|$ is less than or equal to the nth term $v_n(x)$ of the uniformly convergent series $\sum_{n=1}^{\infty} v_n(x)$. Hence, by the comparison test (Section 6.6, Theorem 12) the series $\sum_{n=1}^{\infty} u_n(x)$ is absolutely convergent for $x \in E$ and since

$$|u_n\,(x)\,| \le |v_n\,(x)\,| \le M_n \quad \text{for all } x \text{ in } E$$

it follows that $\sum_{n=1}^{\infty} u_n(x)$ is uniformly convergent for $x \in E$.

5. Let $0 < u_n(x) < 1/n$ (which implies that $\lim_{n\to\infty} u_n(x) = 0$) and $u_{n+1}(x) \le u_n(x)$ for $a \le x \le b$. Hence, by the alternating series test (Section 6.6, Theorem 18) the series $\sum_{n=1}^{\infty}(-1)^n u_n(x)$ converges. Furthermore, $|u_n(x)| < 1/n = M_n$ for all x of the range considered and hence, the alternating series converges uniformly for $a \le x \le b$.

6. Let a convergent series $\sum_{n=1}^{\infty} M_n$ of constants $M_n > 0$ be given. Hence, for some $\epsilon > 0$ and N can be found such that $|M_{n+1}+M_{n+2}+\cdots+M_m| \le \epsilon$ for $m > n > N$ (Section 6.5, Theorem 9). Next, let a sequence $f_n(x)$ be given such that $|f_{n+1}(x)-f_n(x)| \le M_n$ for all $x \in E$. Since $M_{n+1} \le \epsilon$ for $n > N$ it is true (after relabelling) that $|f_{n+1}(x)-f_n(x)| \le \epsilon$. In other words, there exists some $n > N$ such that the difference between $f_{n+1}(x)$ and $f_n(x)$ is not greater than $\epsilon > 0$ (which can be chosen arbitrarily small) for each $x \in E$. Hence, the sequence $f_n(x)$ is uniformly convergent for all $x \in E$.

7. (a) Let the sequence $(n+x)/x$, where $0 \le x \le 1$ be given. This sequence converges uniformly for the range of x given, since

$$|f_{n+1}(x) - f_n(x)| = \left|\frac{n+1+x}{n+1} - \frac{n+x}{n}\right| = \left|\frac{-x}{n(n+1)}\right| \le \frac{1}{n^2} = M_n$$

and the series of constants $\sum_{n=1}^{\infty} M_n = \sum_{n=1}^{\infty} 1/n^2$ converges.

(b) Let the sequence $x^n/n!$, where $-1 \le x \le 1$ be given. This sequence converges uniformly for the range of x given, since

$$|f_{n+1}(x) - f_n(x)| = \left|\frac{x^{n+1}}{(n+1)!} - \frac{x^n}{n!}\right| = \frac{|x^n|}{n!}\left|\frac{x}{n+1} - 1\right| \le \frac{3}{2}\frac{1}{n!} = M_n$$

and the series of constants $\sum_{n=1}^{\infty} M_n = \sum_{n=1}^{\infty} 1/n!$ converges. The constant $3/2$ is justified by noting that

$$\max\left|\frac{x}{n+1} - 1\right| = \max(a)$$

in the interval $-1 \le x \le 1$ occurs when $x = -1$, $n = 1$. Furthermore, as $n \to \infty$ we see that $a \to 1$.

(c) Let the sequence $f_n(x) = \ln(1+nx)/n$, where $1 \le x \le 2$ be given. Firstly, we note that

$$\lim_{n\to\infty} f_n(x) = \lim_{n\to\infty} \frac{\ln(1+nx)}{n} = \lim_{n\to\infty} \frac{x}{1+nx} = 0$$

and since $f_n(x) > 0$ for $1 \le x \le 2$ this implies $f_{n+1}(x) < f_n(x)$. As such

$$\frac{\ln(1+nx)}{n+1} < \frac{\ln[1+(n+1)x]}{n+1} < \frac{\ln(1+nx)}{n}$$

or equivalently

$$\frac{\ln(1+nx)}{n+1} - \frac{\ln(1+nx)}{n} < \frac{\ln[1+(n+1)x]}{n+1} - \frac{\ln(1+nx)}{n} < 0$$

And so we learn that

$$\left|\frac{\ln(1+nx)}{n+1} - \frac{\ln(1+nx)}{n}\right| > \left|\frac{\ln[1+(n+1)x]}{n+1} - \frac{\ln(1+nx)}{n}\right|$$

Hence, for $1 \le x \le 2$ we find

$$\begin{aligned}
|f_{n+1}(x) - f_n(x)| = \left|\frac{\ln[1+(n+1)x]}{n+1} - \frac{\ln(1+nx)}{n}\right| &< \ln(1+nx)\left|\frac{1}{n+1} - \frac{1}{n}\right| \\
&= \frac{\ln(1+nx)}{n(n+1)} \\
&< \frac{\ln(1+nx)}{n^2} \\
&\le \frac{\ln(1+2n)}{n^2} = M_n
\end{aligned}$$

It remains to be shown that the series of constants $\sum_{n=1}^{\infty} M_n$ converges. To this end we employ the *integral test*:

$$\begin{aligned}
\int_1^{\infty} \frac{\ln(1+2x)}{x^2}\,dx &= \lim_{b\to\infty} \int_1^b \frac{\ln(1+2x)}{x^2}\,dx \\
&= \lim_{b\to\infty} -\frac{\ln(1+2x)}{x}\bigg|_1^b + \lim_{b\to\infty} \int_1^b \frac{2}{x(1+2x)}\,dx \\
&= \ln 3 - \lim_{b\to\infty} \frac{\ln(1+2b)}{b} + 2\lim_{b\to\infty} \int_1^b \left(\frac{1}{x} - \frac{2}{1+2x}\right) dx \\
&= \ln 3 + 2\lim_{b\to\infty} \left[\ln|x| - \ln|1+2x|\right]_1^b \\
&= 3\ln 3 + 2\lim_{b\to\infty} \left[\ln b - \ln(1+2b)\right] \\
&= 3\ln 3 + 2\lim_{b\to\infty} \ln \frac{b}{1+2b} = 3\ln 3 + 2\ln\left(\lim_{b\to\infty} \frac{b}{1+2b}\right) \\
&= 3\ln 3 - 2\ln 2
\end{aligned}$$

Since this integral converges and all the conditions of the integral test are satisfied, we may conclude that $\sum_{n=1}^{\infty} M_n = \sum_{n=1}^{\infty} \ln(1+2n)/n^2$ converges. Hence, the original sequence $f_n(x) = \ln(1+nx)/n$ converges uniformly for $1 \le x \le 2$.

(d) Let the sequence $f_n(x) = n/e^{nx^2}$, where $1/2 \le x \le 1$ be given. Firstly, we note that

$$\lim_{n\to\infty} f_n(x) = \lim_{n\to\infty} \frac{n}{e^{nx^2}} = \lim_{n\to\infty} \frac{1}{x^2 e^{nx^2}} = 0$$

and since $f_n(x) > 0$ for $1/2 \le x \le 1$ this implies $f_{n+1}(x) < f_n(x)$. However, if we plot $f_n(x)$ for various values of n (keeping x fixed) we see that $f_{n+1} < f_n(x)$ only is true for $n \ge 4$. As stated at the start of Section 6.6, the convergence or divergence of a series is unaffected if a finite number of terms of the series are discarded. Hence, in testing for convergence of $\sum M_n$ we can simply ignore the first four terms and aim to prove $\sum_{n=4}^{\infty} M_n$ does converge for a certain M_n yet to be determined. Continuing with our sequence, we conclude (for $n \ge 4$)

$$\frac{n}{e^{(n+1)x^2}} < \frac{n+1}{e^{(n+1)x^2}} < \frac{n}{e^{nx^2}}$$

or equivalently

$$\frac{n}{e^{(n+1)x^2}} - \frac{n}{e^{nx^2}} < \frac{n+1}{e^{(n+1)x^2}} - \frac{n}{e^{nx^2}} < 0$$

And so we learn that

$$\left|\frac{n}{e^{(n+1)x^2}} - \frac{n}{e^{nx^2}}\right| > \left|\frac{n+1}{e^{(n+1)x^2}} - \frac{n}{e^{nx^2}}\right|$$

Hence, for $1/2 \leq x \leq 1$, $n \geq 4$ we find

$$\begin{aligned}
|f_{n+1}(x) - f_n(x)| = \left|\frac{n+1}{e^{(n+1)x^2}} - \frac{n}{e^{nx^2}}\right| &< \frac{n}{e^{nx^2}}\left|\frac{1}{e^{x^2}} - 1\right| \\
&= \frac{n}{e^{nx^2}}\left(1 - \frac{1}{e^{x^2}}\right) \\
&\leq \max_{1/2 \leq x \leq 1}\left[\frac{n}{e^{nx^2}}\left(1 - \frac{1}{e^{x^2}}\right)\right] \\
&= \frac{n}{e^{n/4}}\left(1 - \frac{1}{e^{1/4}}\right) = M_n
\end{aligned}$$

It remains to be shown that the series of constants $\sum_{n=4}^{\infty} M_n$ converges. To this end we employ the *integral test*:

$$\begin{aligned}
\int_4^{\infty} \frac{x}{e^{x/4}}\,dx = \lim_{b\to\infty}\int_4^b \frac{x}{e^{x/4}}\,dx &= \lim_{b\to\infty}\int_4^b xe^{-x/4}\,dx \\
&= \lim_{b\to\infty} -4xe^{-x/4}|_4^b + \lim_{b\to\infty}\int_4^b 4e^{-x/4}\,dx \\
&= \lim_{b\to\infty}\left[-4xe^{-x/4} - 16e^{-x/4}\right]_4^b \\
&= \lim_{b\to\infty}\left(-4be^{-b/4} - 16e^{-b/4}\right) + 32e^{-1} = \frac{32}{e}
\end{aligned}$$

Since this integral converges and all the conditions of the integral test are satisfied, we may conclude that $\sum_{n=4}^{\infty} M_n = \sum_{n=4}^{\infty} ne^{-n/4}(1 - e^{-1/4})$ converges. Hence, the original sequence $f_n(x) = n/e^{nx^2}$ converges uniformly for $1/2 \leq x \leq 1$.

Section 6.16

1. (a)