INEQUALITIES

1. For $p > 1$ and $a_1, a_2, \ldots, a_n$ positive, show that

$$\sum_{k=1}^{n} \left(\frac{a_1 + a_2 + \cdots + a_k}{k} \right)^p < \left(\frac{p}{p-1} \right)^p \sum_{k=1}^{n} a_k^p.$$

2. If $a_n > 0$ for $n = 1, 2, \ldots,$ show that

$$\sum_{n=1}^{\infty} \sqrt[n]{a_1 a_2 \cdots a_n} \le e \sum_{n=1}^{\infty} a_n,$$

provided that $\sum_{n=1}^{\infty} a_n$ converges.

3. For $n = 1, 2, 3, \ldots$ let

$$x_n = \frac{1000^n}{n!}.$$

Find the largest term of the sequence.

4. Suppose that $a_1, a_2, \ldots, a_n$ with $n \ge 2$ are real numbers greater than -1, and all the numbers a_j have the same sign. Show that

$$(1 + a_1)(1 + a_2) \cdots (1 + a_n) > 1 + a_1 + a_2 + \cdots + a_n.$$

5. If $a_1, \ldots, a_{n+1}$ are positive real numbers with $a_1 = a_{n+1}$, show that

$$\sum_{i=1}^{n} \left(\frac{a_i}{a_{i+1}} \right)^n \ge \sum_{i=1}^{n} \frac{a_{i+1}}{a_i}.$$

6. Show that for any real numbers $a_1, a_2, \ldots, a_n$,

$$\left(\sum_{i=1}^{n} \frac{a_i}{i} \right)^2 \le \sum_{i=1}^{n} \sum_{j=1}^{n} \frac{a_i a_j}{i + j - 1}.$$

7. Let $y = f(x)$ be a continuous, strictly increasing function of x for $x \ge 0$, with $f(0) = 0$, and let f^{-1} denote the inverse function to f. If a and b are nonnegative constants, then show that

$$ab \le \int_0^a f(x)dx + \int_0^b f^{-1}(y)dy.$$

8. Let $a_1, a_2, \ldots, a_n$ be real numbers. Show that

$$\min_{i<j} (a_i - a_j)^2 \le M^2 \left(a_1^2 + \cdots + a_n^2 \right),$$

where

$$M^2 = \frac{12}{n(n^2 - 1)}.$$

9. Let f be a continuous function on the interval $[0,1]$ such that $0 < m \le f(x) \le M$ for all x in $[0,1]$. Show that
$$\left(\int_0^1 \frac{dx}{f(x)}\right)\left(\int_0^1 f(x)dx\right) \le \frac{(m+M)^2}{4mM}.$$

10. Consider any sequence $a_1, a_2, \ldots$ of real numbers. Show that
$$\sum_{n=1}^{\infty} a_n \le \frac{2}{\sqrt{3}} \sum_{n=1}^{\infty} \left(\frac{r_n}{n}\right)^{1/2}$$
where
$$r_n = \sum_{k=n}^{\infty} a_k^2.$$
(If the left-hand side of the inequality is ∞, then so is the right-hand side.)

11. Show that
$$\frac{1}{(n-1)!}\int_n^{\infty} w(t)e^{-t}dt < \frac{1}{(e-1)^n},$$
where t is real, n is a positive integer, and
$$w(t) = (t-1)(t-2)\cdots(t-n+1).$$

12. Let $(a_n)_{n=1}^{\infty}$ and $(b_n)_{n=1}^{\infty}$ be two sequences of positive numbers. Show that the following statements are equivalent:
   - There is a sequence $(c_n)_{n=1}^{\infty}$ of positive numbers such that $\sum_{n=1}^{\infty} \frac{a_n}{c_n}$ and $\sum_{n=1}^{\infty} \frac{c_n}{b_n}$ both converge.
   - $\sum_{n=1}^{\infty} \sqrt{\frac{a_n}{b_n}} < \infty$

13. Suppose that a, b, c are real numbers in the interval $[-1,1]$ such that $1 + 2abc \ge a^2 + b^2 + c^2$. Prove that $1 + 2(abc)^n \ge a^{2n} + b^{2n} + c^{2n}$ for all positive integers n.

14. Suppose $f : \mathbb{R} \to \mathbb{R}$ is a two times differentiable function satisfying $f(0) = 1, f'(0) = 0$ and for all $x \in [0,\infty)$, it satisfies
$$f''(x) - 5f'(x) + 6f(x) \ge 0$$
Prove that, for all $x \in [0,\infty)$,
$$f(x) \ge 3e^{2x} - 2e^{3x}$$

15. Let $f : [0,1] \to \mathbb{R}$ be a continuous function satisfying $xf(y) + yf(x) \le 1$ for every $x, y \in [0,1]$.
(a) Show that $\int_0^1 f(x)dx \le \frac{\pi}{4}$.
(b) Find such a function for which equality occurs.

16. For what pairs of positive real numbers (a,b) does the improper integral shown converge?
$$\int_b^{\infty}\left(\sqrt{\sqrt{x+a}-\sqrt{x}} - \sqrt{\sqrt{x}-\sqrt{x-b}}\right)\,\mathrm{d}x$$

17. Let A be a positive real number. What are the possible values of $\sum_{j=0}^{\infty} x_j^2$, given that $x_0, x_1, \cdots$ are positive numbers for which $\sum_{j=0}^{\infty} x_j = A$?

18. Let $f(x)$ be a continuous real-valued function defined on the interval $[0,1]$. Show that

$$\int_0^1 \int_0^1 |f(x) + f(y)| dx\, dy \geq \int_0^1 |f(x)| dx$$

19. For each continuous function $f : [0,1] \to \mathbb{R}$, let $I(f) = \int_0^1 x^2 f(x)\, dx$ and $J(f) = \int_0^1 x\,(f(x))^2\, dx$. Find the maximum value of $I(f) - J(f)$ over all such functions f.

20. Suppose that $f : [0,1] \to \mathbb{R}$ has a continuous derivative and that $\int_0^1 f(x)\, dx = 0$. Prove that for every $\alpha \in (0,1)$,

$$\left| \int_0^\alpha f(x)\, dx \right| \leq \frac{1}{8} \max_{0 \leq x \leq 1} |f'(x)|$$

21. For $m \geq 3$, a list of $\binom{m}{3}$ real numbers a_{ijk} $(1 \leq i < j < k \leq m)$ is said to be area definite for $\mathbb{R}^n$ if the inequality

$$\sum_{1 \leq i < j < k \leq m} a_{ijk} \cdot \text{Area}(\triangle A_i A_j A_k) \geq 0$$

holds for every choice of m points $A_1, \ldots, A_m$ in $\mathbb{R}^n$. For example, the list of four numbers $a_{123} = a_{124} = a_{134} = 1, a_{234} = -1$ is area definite for $\mathbb{R}^2$. Prove that if a list of $\binom{m}{3}$ numbers is area definite for $\mathbb{R}^2$, then it is area definite for $\mathbb{R}^3$.

22. Let $X_1, X_2, ..$ be independent random variables with the same distribution, and let $S_n = X_1 + X_2 + ... + X_n, n = 1, 2, ...$ For what real numbers c is the following statement true:

$$\mathbb{P}\left(\left| \frac{S_{2n}}{2n} - c \right| \leq \left| \frac{S_n}{n} - c \right| \right) \geq \frac{1}{2}.$$

23. Let $H_k = \sum_{i=1}^k \frac{1}{i}$. Prove that the function $f : \mathbb{R} \to \mathbb{R}$ defined by

$$f(x) = 1 + \sum_{n=1}^{\infty} \frac{x^n}{\prod_{k=1}^n H_k}$$

has no real zeros.

24. Let f be a continuous, nonnegative function on $[0,1]$. Show that

$$\int_0^1 f(x)^3 dx \geq 4 \left(\int_0^1 x f(x)^2 dx \right) \left(\int_0^1 x^2 f(x) dx \right)$$

25. Let $f : \mathbb{R} \to \mathbb{R}$ be an infinitely differentiable function satisfying $f(0) = 0$, $f(1) = 1$, and $f(x) \geq 0$ for all $x \in \mathbb{R}$. Show that there exist a positive integer n and a real number x such that $f^{(n)}(x) < 0$.

26. Let $f = (f_1, f_2)$ be a function from $\mathbb{R}^2$ to $\mathbb{R}^2$ with continuous partial derivatives $\frac{\partial f_i}{\partial x_j}$ that are positive everywhere. Suppose that

$$\frac{\partial f_1}{\partial x_1}\frac{\partial f_2}{\partial x_2} - \frac{1}{4}\left(\frac{\partial f_1}{\partial x_2} + \frac{\partial f_2}{\partial x_1}\right)^2 > 0$$

everywhere. Prove that f is one-to-one.

27. Determine the greatest possible value of $\sum_{i=1}^{10} \cos(3x_i)$ for real numbers $x_1, x_2, \ldots, x_{10}$ satisfying $\sum_{i=1}^{10} \cos(x_i) = 0$.

28. Let $X_0 = 1$ and $X_{n+1} = X_n + \lfloor X_n^{3/10} \rfloor$. Prove that $X_n = (7/10)^{10/7} n^{10/7} - 7n/8 + O(n^{999/1000})$.

29. Let $a_0 = 1$ and $a_{n+1} = a_n + e^{-a_n}$. Prove that $e^{a_n} - n - \ln(n)/2$ converges to a constant.