PUTNAM TRAINING
EASY PUTNAM PROBLEMS

(Last updated: September 29, 2017)

REMARK. This is a list of exercises on Easy Putnam Problems — Miguel A. Lerma

EXERCISES

1. 2016-A1. Find the smallest positive integer \( j \) such that for every polynomial \( p(x) \) with integer coefficients and for every \( k \), the integer

\[
p^{(j)}(k) = \frac{d^j}{dx^j} p(x) \bigg|_{x=k}
\]

(the \( j \)-th derivative of \( p(x) \) at \( k \)) is divisible by 2016.

2. 2016-B1. Let \( x_0, x_1, x_2, \ldots \) be the sequence such that \( x_0 = 1 \) and for \( n \geq 0 \),

\[
x_{n+1} = \ln (e^{x_n} - x_n)
\]

(as usual, the function \( \ln \) is the natural logarithm). Show that the infinite series

\[
x_0 + x_1 + x_2 + \cdots
\]

converges and find its sum.

3. 2016-B3. Suppose that \( S \) is a finite set of points in the plane such that the area of triangle \( \triangle ABC \) is at most 1 whenever \( A, B, \) and \( C \) are in \( S \). Show that there exists a triangle of area 4 such that (together with its interior) covers the set \( S \).

4. 2015-A1. Let \( A \) and \( B \) be points on the same branch of the hyperbola \( xy = 1 \). Suppose that \( P \) is a point lying between \( A \) and \( B \) on this hyperbola, such that the area of the triangle \( \triangle APB \) is as large as possible. Show that the region bounded by the hyperbola and the chord \( AP \) has the same area as the region bounded by the hyperbola and the chord \( PB \).

5. 2015-B1. Let \( f \) be a three times differentiable function (defined on \( \mathbb{R} \) and real-valued) such that \( f \) has at least five distinct real zeros. Prove that \( f + 6f' + 12f'' + 8f''' \) has at least two distinct real zeros.

Let $T$ be the set of all triples $(a, b, c)$ of positive integers for which there exist triangles with side lengths $a, b, c$. Express

$$\sum_{(a,b,c) \in T} \frac{2^a}{3^b 5^c}$$

as a rational number in lowest terms.

7. 2014-A1. Prove that every nonzero coefficient of the Taylor series of

$$(1 - x + x^2)e^x$$

about $x = 0$ is a rational number whose numerator (in lowest terms) is either 1 or a prime number.

8. 2014-B1. A base 10 over-expansion of a positive integer $N$ is an expression of the form

$$N = d_k 10^k + d_{k-1} 10^{k-1} + \cdots + d_0 10^0$$

with $d_k \neq 0$ and $d_i \in \{0, 1, 2, \ldots, 10\}$ for all $i$. For instance, the integer $N = 10$ has two base 10 over-expansions: $10 = 10 \cdot 10^1 + 0 \cdot 10^0$. Which positive integers have a unique base 10 over-expansion?

9. 2013-A1. Recall that a regular icosahedron is a convex polyhedron having 12 vertices and 20 faces; the faces are congruent equilateral triangles. On each face of a regular icosahedron is written a nonnegative integer such that the sum of all 20 integers is 39. Show that there are two faces that share a vertex and have the same integer written on them.

10. 2013-B1. For positive integers $n$, let the numbers $c(n)$ be determined by the rules

$$c(1) = 1, \quad c(2n) = c(n), \quad c(2n + 1) = (-1)^n c(n).$$

Find the value of

$$\sum_{n=1}^{2013} c(n)c(n+2).$$

11. 2012-A1. Let $d_1, d_2, \ldots, d_{12}$ be real numbers in the interval $(1, 12)$. Show that there exist distinct indices $i, j, k$ such that $d_i, d_j, d_k$ are the side lengths of an acute triangle.

12. 2012-B1. Let $S$ be the class of functions from $[0, \infty)$ to $[0, \infty)$ that satisfies:

(i) The functions $f_1(x) = e^x - 1$ and $f_2(x) = \ln (x + 1)$ are in $S$.
(ii) If $f(x)$ and $g(s)$ are in $S$, then functions $f(x) + g(x)$ and $f(g(x))$ are in $S$;
(iii) If $f(x)$ and $g(x)$ are in $S$ and $f(x) \geq g(x)$ for all $x \geq 0$, then the function $f(x) - g(x)$ is in $S$.

Prove that if $f(x)$ and $g(x)$ are in $S$, then the function $f(x)g(x)$ is also in $S$.

13. 2011-B1. Let $h$ and $k$ be positive integers. Prove that for every $\varepsilon > 0$, there are positive integers $m$ and $n$ such that

$$\varepsilon < |h\sqrt{m} - k\sqrt{n}| < 2\varepsilon.$$
14. **2010-A1.** Given a positive integer \( n \), what is the largest \( k \) such that the numbers \( 1, 2, \ldots, n \) can be put into \( k \) boxes so that the sum of the numbers in each box is the same? [When \( n = 8 \), the example \( \{1, 2, 3, 6\}, \{4, 8\}, \{5, 7\} \) shows that the largest \( k \) is at least 3.]

15. **2010-B1.** Is there an infinite sequence of real numbers \( a_1, a_2, a_3, \ldots \) such that
\[
a_1^m + a_2^m + a_3^m + \cdots = m
\]
for every positive integer \( m \)?

16. **2010-B2.** Given that \( A \), \( B \), and \( C \) are noncollinear points in the plane with integer coordinates such that the distances \( AB, AC, \) and \( BC \) are integers, what is the smallest possible value of \( AB \)?

17. **2009-A1.** Let \( f \) be a real-valued function on the plane such that for every square \( ABCD \) in the plane, \( f(A) + f(B) + f(C) + f(D) = 0 \). Does it follow that \( f(P) = 0 \) for all points \( P \) in the plane?

18. **2009-B1.** Show that every positive rational number can be written as a quotient of products of factorials of (not necessarily distinct) primes. For example,
\[
\frac{10}{9} = \frac{2! \cdot 5!}{3! \cdot 3! \cdot 3!}
\]

19. **2008-A1.** Let \( f : \mathbb{R}^2 \rightarrow \mathbb{R} \) be a function such that \( f(x, y) + f(y, z) + f(z, x) = 0 \) for all real numbers \( x, y, \) and \( z \). Prove that there exists a function \( g : \mathbb{R} \rightarrow \mathbb{R} \) such that \( f(x, y) = g(x) - g(y) \) for all real numbers \( x \) and \( y \).

20. **2008-A2.** Alan and Barbara play a game in which they take turns filling entries of an initially empty \( 2008 \times 2008 \) array. Alan plays first. At each turn, a player chooses a real number and places it in a vacant entry. The game ends when all the entries are filled. Alan wins if the determinant of the resulting matrix is nonzero; Barbara wins if it is zero. Which player has a winning strategy?

21. **2008-B1.** What is the maximum number of rational points that can lie on a circle in \( \mathbb{R}^2 \) whose center is not a rational point? (A rational point is a point both of whose coordinates are rational numbers.)

22. **2007-A1.** Find all values of \( \alpha \) for which the curves \( y = \alpha x^2 + \alpha x + \frac{1}{24} \) and \( x = \alpha y^2 + \alpha y + \frac{1}{24} \) are tangent to each other.

23. **2007-B1.** Let \( f \) be a polynomial with positive integer coefficients. Prove that if \( n \) is a positive integer, then \( f(n) \) divides \( f(f(n) + 1) \) if and only if \( n = 1 \). [Note: one must assume \( f \) is nonconstant.]
24. **2006-A1.** Find the volume of the region of points \((x, y, z)\) such that

\[
(x^2 + y^2 + z^2 + 8)^2 \leq 36(x^2 + y^2).
\]

25. **2006-B2.** Prove that, for every set \(X = \{x_1, x_2, \ldots, x_n\}\) of \(n\) real numbers, there exists a non-empty subset \(S\) of \(X\) and an integer \(m\) such that

\[
\left| m + \sum_{s \in S} s \right| \leq \frac{1}{n+1}.
\]

26. **2005-A1.** Show that every positive integer is a sum of one or more numbers of the form \(2^r3^s\), where \(r\) and \(s\) are nonnegative integers and no summand divides another. (For example, 23 = 9 + 8 + 6.)

27. **2005-B1.** Find a nonzero polynomial \(P(x, y)\) such that \(P([a], [2a]) = 0\) for all real numbers \(a\). (Note: \([\nu]\) is the greatest integer less than or equal to \(\nu\).)

28. **2004-A1.** Basketball star Shanille O’Keal’s team statistician keeps track of the number, \(S(N)\), of successful free throws she has made in her first \(N\) attempts of the season. Early in the season, \(S(N)\) was less than 80% of \(N\), but by the end of the season, \(S(N)\) was more than 80% of \(N\). Was there necessarily a moment in between when \(S(N)\) was exactly 80% of \(N\)?

29. **2004-B2.** Let \(m\) and \(n\) be positive integers. Show that

\[
\frac{(m+n)!}{(m+n)^{m+n}} < \frac{m! n!}{m^m n^n}.
\]

30. **2003-A1.** Let \(n\) be a fixed positive integer. How many ways are there to write \(n\) as a sum of positive integers, \(n = a_1 + a_2 + \cdots + a_k\), with \(k\) an arbitrary positive integer and \(a_1 \leq a_2 \leq \cdots \leq a_k \leq a_1 + 1\)? For example, with \(n = 4\) there are four ways: 4, 2+2, 1+1+2, 1+1+1+1.

31. **2002-A1.** Let \(k\) be a fixed positive integer. The \(n\)-th derivative of \(\frac{1}{x^k-1}\) has the form \(\frac{P_n(x)}{(x^k-1)^{n+1}}\) where \(P_n(x)\) is a polynomial. Find \(P_n(1)\).

32. **2002-A2.** Given any five points on a sphere, show that some four of them must lie on a closed hemisphere.

33. **2001-A1.** Consider a set \(S\) and a binary operation \(*\), i.e., for each \(a, b \in S\), \(a * b \in S\). Assume \((a * b) * a = b\) for all \(a, b \in S\). Prove that \(a * (b * a) = b\) for all \(a, b \in S\).

34. **2000-A2.** Prove that there exist infinitely many integers \(n\) such that \(n, n+1, n+2\) are each the sum of the squares of two integers. [Example: 0 = 0^2 + 0^2, 1 = 0^2 + 1^2, 2 = 1^2 + 1^2.]
35. **1999-A1.** Find polynomials $f(x)$, $g(x)$, and $h(x)$, if they exist, such that for all $x$,

$$|f(x)| - |g(x)| + h(x) = \begin{cases} 
-1 & \text{if } x < -1 \\
3x + 2 & \text{if } -1 \leq x \leq 0 \\
-2x + 2 & \text{if } x > 0. 
\end{cases}$$

36. **1998-A1.** A right circular cone has base of radius 1 and height 3. A cube is inscribed in the cone so that one face of the cube is contained in the base of the cone. What is the side-length of the cube?

37. **1997-A5.** Let $N_n$ denote the number of ordered $n$-tuples of positive integers $(a_1, a_2, \ldots, a_n)$ such that $1/a_1 + 1/a_2 + \ldots + 1/a_n = 1$. Determine whether $N_{10}$ is even or odd.

38. **1988-B1.** A composite (positive integer) is a product $ab$ with $a$ and $b$ not necessarily distinct integers in $\{2, 3, 4, \ldots\}$. Show that every composite is expressible as $xy + xz + yz + 1$, with $x, y, z$ positive integers.
HINTS

1. When is the coefficient of \( \frac{d^j}{dx^j} x^n \) divisible by 2016?

2. Show that the sum telescopes and the n-th term tends to zero.

3. Consider three points A, B, and C such that triangle \( \Delta ABC \) has the largest area.

4. Find the area of the triangle, maximize it, and compute the area between the cords and the hyperbola.

5. The given expression is the third derivative of a function with the same zeros as \( f \).

6. Rewrite the sum and add the resulting geometric sums.

7. The coefficient can be computed and simplified explicitly.

8. —

9. If the numbers of the faces having a common vertex have different numbers, what can we say about their sum?

10. Telescoping.

11. Three numbers \( 0 < a \leq b \leq c \) are the side lengths of an acute triangle precisely if \( a^2 + b^2 > c^2 \).

12. \( e^{u+v} = e^u e^v \).

13. There is some rational number between \( \frac{3e}{hk} \) and \( \frac{4e}{hk} \).

14. For \( k \) to be as large as possible the “boxes” must be “small”.

15. One approach is to use the Cauchy-Schwartz inequality for some appropriately chosen values of \( k \). Another approach is to look at how the LHS grows with \( m \) depending on the values of the \( a_k \).

16. By looking at Pythagorean triples we get a reasonable conjecture about what the smallest possible value of \( AB \) could be. Then use \( |AC - BC| \leq AB \), with equality if and only if \( A, B, C \) are collinear.

17. Find relations among the values of the function at nine points forming a 2 by 2 square grid.

18. Induction.

19. Try successively \( (x, y, z) = (0, 0, 0), (x, y, z) = (x, 0, 0), (x, y, z) = (x, y, 0) \).

20. Try either getting two equal rows, or all rows summing zero.
21. How can we find the center of a circle if we are given some points on that circle?

22. Considered different cases depending on how each curve intersects the line \( y = x \).

23. Consider \( f(f(n) + 1) \mod f(n) \).

24. Change to cylindrical coordinates.


26. Induction. The base case is \( 1 = 2^0 3^0 \). The induction step depends on the parity of \( n \). If \( n \) is even, divide by 2. If it is odd, subtract a suitable power of 3.

27. Note that \([2a] = 2[a] \) or \([2a] = 2[a] + 1 \) depending on whether the fractional part of \( a \) is in \([0, 0.5) \) or \([0.5, 1) \).

28. Assume that \( S(N) \) jumps abruptly from less than \( 4/5 \) to more that \( 4/5 \) at some point and find a contradiction.

29. Rewrite the inequality \( \frac{(m+n)!}{m!n!} m^m n^n < (m+n)^{m+n} \).

30. If \( 0 < k \leq n \), is there any such sum with exactly \( k \) terms? How many?

31. Differentiate \( P_n(x)/(x^k - 1)^{n+1} \) and get a relation between \( P_n(1) \) and \( P_{n+1}(1) \).

32. Draw a great circle through two of the points.

33. Replace \( a \) by \( b * a \).

34. Show that the equation \( x^2 - y^2 = z^2 + 1 \) has infinitely many integer solutions. Set \( n = y^2 + z^2 \).

35. Try with first degree polynomials. Some of those polynomials must change sign precisely at \( x = -1 \) and \( x = 0 \). Recall that \( |u| = \pm u \) depending on whether \( u \geq 0 \) or \( u < 0 \).

36. Consider the plane containing both the axis of the cone and two opposite vertices of the cube’s bottom face.

37. Discard solutions coming in pairs, such as the ones for which \( a_1 \neq a_2 \); so we may assume \( a_1 = a_2 \).

38. —
Solutions

1. The answer is $j = 8$.
   We have $\frac{d}{dx}x^j = j!$, so $j!$ must be a multiple of $2016 = 2^5 \cdot 3^2 \cdot 7$. Since $2^5$ does not divide $7!$ we have $j \geq 8$.
   Next, for any polynomial $p(x) = \sum_{i=0}^{n} a_i x^i$, we have
   \[
   \frac{d^8}{dx^8}p(x) \bigg|_{x=k} = \sum_{i=8}^{n} n(n-1)(n-2)(n-3)(n-4)(n-5)(n-6)(n-7) a_i k^{i-8}.
   \]

   So, all we need to prove is that $n(n-1) \cdots (n-7)$ a multiple of $2^5$, $3^2$, and $7$.
   In fact, one of any seven consecutive integers is a multiple of 7, so
   \[n(n-1)(n-2)(n-3)(n-4)(n-5)(n-6)\] must be a multiple of 7.
   One of every three consecutive integers is a multiple of 3, so
   \[n(n-1)(n-2)\] and \[(n-3)(n-4)(n-5)\] are multiples of 3, which implies
   \[n(n-1)(n-2)(n-3)(n-4)(n-5)\] is a multiple of $3^2$.
   Finally, given eight consecutive integers, four of them will be multiples of 2, two will
   be multiples of 4, and one is a multiple of 8, hence
   \[n(n-1)(n-2)(n-3)(n-4)(n-5)(n-6)(n-7)\] is a multiple of $2^4 \cdot 2^2 \cdot 2 = 2^7$, which is in fact more than needed.

2. First we prove that $x_n$ has a limit as $n \to \infty$. The recurrence can be written $e^{x_{n+1}} = e^{x_n} - x_n$. For $x > 0$ we have $e^x > 1 + x$, hence by induction we get $0 < x_{n+1} < x_n \leq 1$, so the sequence is decreasing and bounded. By the Monotonous Convergence Theorem that implies that $x_n$ has in fact a limit.
   Next we prove that the limit is zero. In fact, let $x = \lim_{n \to \infty} x_n$. Then $x = \ln(e^x - x)$, $e^x = e^x - x$, hence $x = 0$.
   Finally we will prove that the sum is $e - 1$. From the recursive definition of $x_n$ we have $x_n = e^{x_n} - e^{x_{n+1}}$, hence
   \[
   x_0 + x_1 + x_2 + \cdots + x_N = (e^{x_0} - e^{x_1}) + (e^{x_1} - e^{x_2}) + \cdots + (e^{x_N} - e^{x_{N+1}})
   = e^{x_0} - e^{x_{N+1}} \xrightarrow[N \to \infty]{} e^1 - e^0 = e - 1.
   \]

3. See figure 1
   Pick three points $A$, $B$, $C$ in $S$ such that the triangle $\Delta ABC$ has maximum area.
   Draw lines $A'B'$, $B'C'$, $C'A'$ parallel to $AB$, $BC$, $CA$ respectively. For any point $P$
   above line $B'C'$, the triangle $\Delta PBC$ will have larger area than $\Delta ABC$ because it has
   the same base but more height than $\Delta ABC$, hence all points of $S$ must below line
   $B'C'$. A similar argument leads to the conclusion that all points of $S$ must be on the
   triangle $\Delta A'B'C'$. Also note that triangles $\Delta ABC$ and $\Delta CB'A$ are each half of the
   parallelogram $ABCB'$, so they are equal. For the same reason $\Delta BAC'$ and $\Delta A'CB$
   are also equal to $\Delta ABC$. Since the area of $\Delta ABC$ is at most 1, then the area of
   $\Delta A'B'C'$ is at most 4, and this completes the proof.
4. If \( A = (x_1, \frac{1}{x_1}) \), \( B = (x_2, \frac{1}{x_2}) \), \( P = (x, \frac{1}{x}) \), the area of the triangle \( APB \) is

\[
T(x) = \begin{vmatrix} 1 & 1 & 1 \\ x_1 & x_2 & x \\ \frac{1}{x_1} & \frac{1}{x_2} & \frac{1}{x} \end{vmatrix}.
\]

Its derivative respect to \( x \) is

\[
T'(x) = \frac{x_2 - x_1}{x_1 x_2} - (x_2 - x_1) \frac{1}{x^2}.
\]

Solving \( T'(x) = 0 \) we get a maximum at \( x_0 = \sqrt{x_1 x_2} \).
Alternatively we could also find \( P \) as the point where the tangent to the hyperbola is parallel to \( AB \). The slope of the hyperbola at \( (x, \frac{1}{x}) \) is \(-1/x^2\), hence

\[
-\frac{1}{x^2} = \frac{1}{x_2} - \frac{1}{x_1} \Rightarrow x_0 = \sqrt{x_1 x_2}.
\]

Next, the line going through \((x_1, \frac{1}{x_1})\) and \((x_0, \frac{1}{x_0})\) is

\[
\frac{x - x_1}{x_0 - x_1} = \frac{y - \frac{1}{x_1}}{\frac{1}{x_0} - \frac{1}{x_1}} \Rightarrow y = \frac{1}{x_1} + \frac{x_1 - x}{x_0 x_1}.
\]

The area of the region bounded by the hyperbola and the chord \( AP \) is

\[
R_A = \int_{x_1}^{x_0} \left( \frac{1}{x_1} + \frac{x_1 - x}{x_0 x_1} - \frac{1}{x} \right) dx = \frac{x_2 - x_1}{2 \sqrt{x_1 x_2}} - \log \sqrt{\frac{x_2}{x_1}}.
\]

If we swap \( x_1 \) and \( x_2 \) in the computations above and integrate between \( x_0 \) and \( x_2 \) we get the area of the region bounded by the hyperbola and the chord \( PB \):

\[
R_B = \int_{x_0}^{x_2} \left( \frac{1}{x_2} + \frac{x_2 - x}{x_0 x_2} - \frac{1}{x} \right) dx = \frac{x_2 - x_1}{2 \sqrt{x_1 x_2}} - \log \sqrt{\frac{x_2}{x_1}}.
\]

That shows that \( R_A = R_B \), QED.
5. The given expression multiplied by \( e^{x/2} \) is the third derivative of \( g(x) = 8e^{x/2}f(x) \), which has the same zeros as \( f(x) \). We know (from Rolle’s theorem) that between two distinct real zeros of a function there is a zero of its derivative, hence \( g'' \) must have at least \( 5 - 3 = 2 \) distinct real zeros, and the same is true for the given expression.

6. In order to form a triangle, \( a, b, c \) must verify \( a + b > c, b + c > a, \) and \( c + a > b \). Hence the following numbers (Ravi substitution) \( x = a + b - c, y = b + c - a, \) and \( z = c + a - b \) must be all positive, and all have the same parity, hence they can be written as \( (x, y, z) = (2u, 2v, 2w) \), or \( (x, y, z) = (2u - 1, 2v - 1, 2w - 1) \) with \( u, v, w \geq 1 \). Also we have \( a = \frac{x + z}{2}, b = \frac{x + y}{2}, c = \frac{y + z}{2} \). Hence

\[
\sum_{(a, b, c) \in T} \frac{2^a}{3!5^c} = \sum_{u, v, w \geq 1} \frac{2^{u+w}}{3^u5^v5^w} + \sum_{u, v, w \geq 1} \frac{2^{u+w-1}}{3^{u+1}5^{v+w-1}}
\]

\[
= \sum_{u, v, w \geq 1} \frac{2^{u+w}}{3^u5^v5^w} \left( 1 + \frac{2-1}{3-5-1} \right)
\]

\[
= \sum_{u=1}^{\infty} \sum_{v=1}^{\infty} \frac{2^u}{3^u} \sum_{w=1}^{\infty} \frac{1}{5^v5^w}
\]

\[
= \frac{17}{2} \cdot \frac{2}{3} \cdot \frac{1}{15} \cdot \frac{2}{5}
\]

\[
= \frac{17}{21}.
\]

7. The coefficient of \( x^n \) in the Taylor series of \( (1 - x + x^2)e^x \) for \( n = 0, 1, 2 \) is \( 1, 0, \frac{1}{2} \), respectively. For \( n \geq 3 \), the coefficient of \( x^n \) is

\[
\frac{1}{n!} - \frac{1}{(n-1)!} + \frac{1}{(n-2)!} = \frac{1 - n + n(n-1)}{n!}
\]

\[
= \frac{n - 1}{n(n-2)!}.
\]

If \( n - 1 \) is prime, then since \( n - 1 \) is relatively prime to \( n \) and to \( (n-2)! \), the lowest-terms numerator is \( n - 1 \), which is prime. If \( n - 1 = ab \) is composite, then if \( a \neq b \), both \( a \) and \( b \) appear separately in \( (n-2)! \), and so the lowest-terms numerator is 1.

If \( n - 1 = a^2 \), then either \( a = 2 \), in which case the coefficient is \( \frac{1}{30} = \frac{2}{15} \); or \( a > 2 \), in which case \( n - 1 = a^2 > 2a \), whence both \( a \) and \( 2a \) appear in \( (n-2)! \), and so \( n - 1 = a^2 \) divides \( (n-2)! \) and the lowest-terms numerator is 1.

8. These are the integers with no 0’s in their usual base 10 expansion. If the usual base 10 expansion of \( N \) is \( d_k10^k + \cdots + d_010^0 \) and one of the digits is 0, then there exists an \( i \leq k - 1 \) such that \( d_i = 0 \) and \( d_{i+1} > 0 \); then we can replace \( d_{i+1}10^{i+1} + (0)10^i \) by \( (d_{i+1} - 1)10^{i+1} + (10)10^i \) to obtain a second base 10 over-expansion.

We claim conversely that if \( N \) has no 0’s in its usual base 10 expansion, then this standard form is the unique base 10 over-expansion for \( N \). This holds by induction on
the number of digits of $N$: if $1 \leq N \leq 9$, then the result is clear. Otherwise, any base 10 over-expansion $N = d_k 10^k + \cdots + d_1 10 + d_0 10^0$ must have $d_0 \equiv N \pmod{10}$, which uniquely determines $d_0$ since $N$ is not a multiple of 10; then $(N - d_0)/10$ inherits the base 10 over-expansion $d_k 10^{k-1} + \cdots + d_1 10^0$, which must be unique by the induction hypothesis.

9. If the numbers on the faces having a common vertex $v$ have different numbers $a_0 < a_1 < a_2 < a_3 < a_4$, then $a_k \geq k$ for $k = 0, 1, 2, 3, 4$, and $S_v = a_0 + a_1 + a_2 + a_3 + a_4 \geq 0 + 1 + 2 + 3 + 4 = 10$. Adding over the 12 vertices we get $\sum_v S_v \geq 12 \cdot 10 = 120$. In that sum each number occurs three times, one per each vertex of the face, so the sum of the numbers written on the faces of the icosahedron will be greater than or equal to $120/3 = 40$, contradicting the hypothesis that it is 39.

10. We have:
\[
c(2n)c(2n + 2) + c(2n + 1)c(2n + 3) = c(n)c(n + 1) + (-1)^n c(n)(-1)^{n+1}c(n + 1)
\]
\[
= c(n)c(n + 1) - c(n)c(n + 1) = 0,
\]
so each term in an even position cancels with the next term, and the sum telescopes:
\[
\sum_{n=1}^{2013} c(n)c(n + 2) = \underbrace{c(1)c(3)}_{-1} + \sum_{n=2}^{2013} c(n)c(n + 2) = -1.
\]

11. Assume without loss of generality that $1 < d_1 \leq d_2 \leq \cdots \leq d_{12} < 12$.
Note that three numbers $0 < a \leq b \leq c$ are the side lengths of an acute triangle precisely if $a^2 + b^2 > c^2$, so if not such three indices exist we would have $d_i^2 + d_{i+1}^2 \leq d_{i+2}^2$ for $i = 1, \ldots, 10$. Consequently $1 < d_1, d_2, d_3 \geq d_1^2 + d_2^2 > 2$, $d_4 \geq d_2^2 + d_3^2 > 3$, and analogously $d_5^2 > 5, d_6^2 > 8, d_7^2 > 13, d_8^2 > 21, d_9^2 > 34, d_{10}^2 > 55, d_{11}^2 > 89, d_{12}^2 > 144$, but this last inequality implies $d_{12} > 12$, which is a contradiction.

12. Assume $f(x)$ and $g(x)$ are in $S$. Then by (ii) the following function is in $S$:
\[
f_2(f(x)) + f_2(g(x)) = \ln(f(x) + 1) + \ln(g(x) + 1)
\]
\[
= \ln((f(x) + 1)(g(x) + 1))
\]
\[
= \ln(f(x)g(x) + f(x) + g(x) + 1).
\]
Next, by (i) the following function is in $S$:
\[
f_1(\ln(f(x)g(x) + f(x) + g(x) + 1)) = e^{\ln(f(x)g(x) + f(x) + g(x) + 1)} - 1
\]
\[
= f(x)g(x) + f(x) + g(x).
\]
Finally we can apply (iii), subtract $f(x)$, then $g(x)$, and we get that the following function is in $S$:
\[
(f(x)g(x) + f(x) + g(x)) - f(x) - g(x) = f(x)g(x),
\]
where the use of (iii) is justified because the final difference $f(x)g(x)$ is non-negative.
13. Since the rational numbers are dense in the reals, we can find positive integers \( a, b \) such that
\[
\frac{3\varepsilon}{hk} < \frac{b}{a} < \frac{4\varepsilon}{hk}.
\]
By choosing \( a \) and \( b \) large enough we can also ensure that \( 3a^2 > b \). We then have
\[
\frac{\varepsilon}{hk} < \frac{b}{3a} < \frac{b}{\sqrt{a^2 + b + a}} = \sqrt{a^2 + b - a}
\]
and
\[
\sqrt{a^2 + b - a} = \frac{b}{\sqrt{a^2 + b + a}} \leq \frac{b}{2a} < 2 \frac{\varepsilon}{hk}.
\]
We may then take \( m = k^2(a^2 + b), n = h^2a^2 \).

14. The largest such \( k \) is \( \lfloor \frac{n+1}{2} \rfloor = \lceil \frac{n}{2} \rceil \). For \( n \) even, this value is achieved by the partition
\[
\{1, n\}, \{2, n-1\}, \ldots;
\]
for \( n \) odd, it is achieved by the partition
\[
\{n\}, \{1, n-1\}, \{2, n-2\}, \ldots.
\]
One way to see that this is optimal is to note that the common sum can never be less than \( n \), since \( n \) itself belongs to one of the boxes. This implies that \( k \leq (1 + \cdots + n)/n = (n + 1)/2 \). Another argument is that if \( k > (n + 1)/2 \), then there would have to be two boxes with one number each (by the pigeonhole principle), but such boxes could not have the same sum.

15. - First solution: No such sequence exists. If it did, then the Cauchy-Schwartz inequality would imply
\[
8 = (a_1^2 + a_2^2 + \cdots)(a_1^4 + a_2^4 + \cdots) \\
\geq (a_1^3 + a_2^3 + \cdots)^2 = 9,
\]
contradiction.  
- Second solution: Suppose that such a sequence exists. If \( a_k^2 \in [0, 1] \) for all \( k \), then \( a_1^4 \leq a_2^4 \) for all \( k \), and so
\[
4 = a_1^4 + a_2^4 + \cdots \leq a_1^2 + a_2^2 + \cdots = 2,
\]
contradiction. There thus exists a positive integer \( k \) for which \( a_k^2 > 1 \). However, in this case, for \( m \) large, \( a_k^{2m} > 2m \) and so \( a_1^{2m} + a_2^{2m} + \cdots \neq 2m \).

16. The smallest distance is 3, achieved by \( A = (0, 0), B = (3, 0), C = (0, 4) \). To check this, it suffices to check that \( AB \) cannot equal 1 or 2. (It cannot equal 0 because if two of the points were to coincide, the three points would be collinear.) The triangle inequality implies that \( |AC - BC| \leq AB \), with equality if and only if \( A, B, C \) are collinear. If \( AB = 1 \), we may assume without loss of generality that \( A = (0, 0), B = (1, 0) \). To avoid collinearity, we must have \( AC = BC \), but this forces \( C = (1/2, y) \) for some \( y \in \mathbb{R} \), a contradiction.
If $AB = 2$, then we may assume without loss of generality that $A = (0, 0), B = (2, 0)$. The triangle inequality implies $|AC - BC| \in \{0, 1\}$. Also, for $C = (x, y), AC^2 = x^2 + y^2$ and $BC^2 = (2 - x)^2 + y^2$ have the same parity; it follows that $AC = BC$. Hence $c = (1, y)$ for some $y \in \mathbb{R}$, so $y^2$ and $y^2 + 1 = BC^2$ are consecutive perfect squares. This can only happen for $y = 0$, but then $A, B, C$ are collinear, a contradiction again.

17. Yes, it does follow. Let $P$ be any point in the plane. Let $ABCD$ be any square with center $P$. Let $E, F, G, H$ be the midpoints of the segments $AB, BC, CD, DA$, respectively. The function $f$ must satisfy the equations

$$
0 = f(A) + f(B) + f(C) + f(D)
$$
$$
0 = f(E) + f(F) + f(G) + f(H)
$$
$$
0 = f(A) + f(E) + f(P) + f(H)
$$
$$
0 = f(B) + f(F) + f(P) + f(E)
$$
$$
0 = f(C) + f(G) + f(P) + f(F)
$$
$$
0 = f(D) + f(H) + f(P) + f(G).
$$

If we add the last four equations, then subtract the first equation and twice the second equation, we obtain $0 = 4f(P)$, whence $f(P) = 0$.

18. Every positive rational number can be uniquely written in lowest terms as $a/b$ for $a, b$ positive integers. We prove the statement in the problem by induction on the largest prime dividing either $a$ or $b$ (where this is considered to be $1$ if $a = b = 1$). For the base case, we can write $1/1 = 2!/2!$. For a general $a/b$, let $p$ be the largest prime dividing either $a$ or $b$. Assume $p$ divides $a$ (the other case, with $p$ dividing $b$, is analogous). Then $a/b = p^ka'/b$ for some $k > 0$ and positive integers $a', b$ whose largest prime factors are strictly less than $p$. Writing $p = p!/p - 1)$ we have $a/b = (p!)k\frac{a'}{(p - 1)^k b}$, and all prime factors of $a'$ and $(p - 1)^k b$ are strictly less than $p$. By the induction hypothesis, $\frac{a'}{(p - 1)^k b}$ can be written as a quotient of products of prime factorials, and so $a/b = (p!)k\frac{a'}{(p - 1)^k b}$ can as well. This completes the induction.

19. The function $g(x) = f(x, 0)$ works. Substituting $(x, y, z) = (0, 0, 0)$ into the given functional equation yields $f(0, 0) = 0$, whence substituting $(x, y, z) = (x, 0, 0)$ yields $f(x, 0) + f(0, x) = 0$. Finally, substituting $(x, y, z) = (x, y, 0)$ yields $f(x, y) = -f(y, 0) - f(0, x) = g(x) - g(y)$.

20. **First solution:** Pair each entry of the first row with the entry directly below it in the second row. If Alan ever writes a number in one of the first two rows, Barbara writes the same number in the other entry in the pair. If Alan writes a number anywhere other than the first two rows, Barbara does likewise. At the end, the resulting matrix will have two identical rows, so its determinant will be zero.

**Second solution:** Whenever Alan writes a number $x$ in an entry in some row, Barbara writes $-x$ in some other entry in the same row. At the end, the resulting matrix will have all rows summing to zero, so it cannot have full rank.
21. There are at most two such points. For example, the points $(0,0)$ and $(1,0)$ lie on a circle with center $(1/2, x)$ for any real number $x$, not necessarily rational. On the other hand, with three points $A$, $B$, $C$, we could find the center of the circle as the intersection of the perpendicular bisectors of the segments $AB$ and $BC$. If $A$, $B$, and $C$ are rational, the middle points of $AB$ and $BC$ will be rational, the bisectors will be rational lines (representable by equations with rational coefficients), and their intersection will be rational.

22. The only such points are $2/3, 3/2, (13 \pm \sqrt{601})/12$. In fact, let $C_1$ and $C_2$ be the curves $y = \alpha x^2 + \alpha x + \frac{1}{24}$ and $x = \alpha y^2 + \alpha y + \frac{1}{24}$, respectively, and let $L$ be the line $y = x$. We consider three cases. If $C_1$ is tangent to $L$, then the point of tangency $(x,x)$ satisfies

$$2\alpha x + \alpha = 1, \quad x = \alpha x^2 + \alpha x + \frac{1}{24};$$

by symmetry, $C_2$ is tangent to $L$ there, so $C_1$ and $C_2$ are tangent. Writing $\alpha = 1/(2x+1)$ in the first equation and substituting into the second, we must have

$$x = \frac{x^2 + x + 1}{2x+1} + \frac{1}{24},$$

which simplifies to $0 = 24x^2 - 2x - 1 = (6x + 1)(4x - 1)$, or $x \in \{1/4, -1/6\}$. This yields $\alpha = 1/(2x + 1) \in \{2/3, 3/2\}$. If $C_1$ does not intersect $L$, then $C_1$ and $C_2$ are separated by $L$ and so cannot be tangent. If $C_1$ intersects $L$ in two distinct points $P_1, P_2$, then it is not tangent to $L$ at either point. Suppose at one of these points, say $P_1$, the tangent to $C_1$ is perpendicular to $L$; then by symmetry, the same will be true of $C_2$, so $C_1$ and $C_2$ will be tangent at $P_1$. In this case, the point $P_1 = (x,x)$ satisfies

$$2\alpha x + \alpha = -1, \quad x = \alpha x^2 + \alpha x + \frac{1}{24};$$

writing $\alpha = -1/(2x+1)$ in the first equation and substituting into the second, we have

$$x = \frac{x^2 + x + 1}{2x+1} + \frac{1}{24},$$

or $x = (-23 \pm \sqrt{601})/72$. This yields $\alpha = -1/(2x + 1) = (13 \pm \sqrt{601})/12$. If instead the tangents to $C_1$ at $P_1, P_2$ are not perpendicular to $L$, then we claim there cannot be any point where $C_1$ and $C_2$ are tangent. Indeed, if we count intersections of $C_1$ and $C_2$ (by using $C_1$ to substitute for $y$ in $C_2$, then solving for $y$), we get at most four solutions counting multiplicity. Two of these are $P_1$ and $P_2$, and any point of tangency counts for two more. However, off of $L$, any point of tangency would have a mirror image which is also a point of tangency, and there cannot be six solutions. Hence we have now found all possible $\alpha$. 
23. The problem fails if $f$ is allowed to be constant, e.g., take $f(n) = 1$. We thus assume that $f$ is nonconstant. Write $f(n) = \sum_{i=0}^{d} a_i n^i$ with $a_i > 0$. Then

$$f(f(n) + 1) = \sum_{i=0}^{d} a_i (f(n) + 1)^i,$$

$$\equiv f(1) \pmod{f(n)}.$$ 

If $n = 1$, then this implies that $f(f(n) + 1)$ is divisible by $f(n)$. Otherwise, $0 < f(1) < f(n)$ since $f$ is nonconstant and has positive coefficients, so $f(f(n) + 1)$ cannot be divisible by $f(n)$.

24. We change to cylindrical coordinates, i.e., we put $r = \sqrt{x^2 + y^2}$. Then the given inequality is equivalent to

$$r^2 + z^2 + 8 \leq 6r,$$

or

$$(r - 3)^2 + z^2 \leq 1.$$ 

This defines a solid of revolution (a solid torus); the area being rotated is the disc $(x - 3)^2 + z^2 \leq 1$ in the $xz$-plane. By Pappus’s theorem, the volume of this equals the area of this disc, which is $\pi$, times the distance through which the center of mass is being rotated, which is $(2\pi)3$. That is, the total volume is $6\pi^2$.

25. Let $\{x\} = x - \lfloor x \rfloor$ denote the fractional part of $x$. For $i = 0, \ldots, n$, put $s_i = x_1 + \cdots + x_i$ (so that $s_0 = 0$). Sort the numbers $\{s_0\}, \ldots, \{s_n\}$ into ascending order, and call the result $t_0, \ldots, t_n$. Since $0 = t_0 \leq \cdots \leq t_n < 1$, the differences

$$t_1 - t_0, \ldots, t_n - t_{n-1}, 1 - t_n$$

are nonnegative and add up to 1. Hence (as in the pigeonhole principle) one of these differences is no more than $1/(n+1)$; if it is anything other than $1 - t_n$, it equals $\pm(\{s_i\} - \{s_j\})$ for some $0 \leq i < j \leq n$. Put $S = \{x_{i+1}, \ldots, x_j\}$ and $m = \lfloor s_i \rfloor - \lfloor s_j \rfloor$; then

$$\left| m + \sum_{s \in S} s \right| = |m + s_j - s_i|$$

$$= |\{s_j\} - \{s_i\}|$$

$$\leq \frac{1}{n+1},$$

as desired. In case $1 - t_n \leq 1/(n+1)$, we take $S = \{x_1, \ldots, x_n\}$ and $m = -\lfloor s_n \rfloor$, and again obtain the desired conclusion.

26. We proceed by induction, with base case $1 = 2^03^0$. Suppose all integers less than $n - 1$ can be represented. If $n$ is even, then we can take a representation of $n/2$ and multiply each term by 2 to obtain a representation of $n$. If $n$ is odd, put $m = \lfloor \log_3 n \rfloor$, 

so that $3^m \leq n < 3^{m+1}$. If $3^m = n$, we are done. Otherwise, choose a representation $(n - 3^m)/2 = s_1 + \cdots + s_k$ in the desired form. Then
\[ n = 3^m + 2s_1 + \cdots + 2s_k, \]
and clearly none of the $2s_i$ divide each other or $3^m$. Moreover, since $2s_i \leq n - 3^m < 3^{m+1} - 3^m$, we have $s_i < 3^m$, so $3^m$ cannot divide $2s_i$ either. Thus $n$ has a representation of the desired form in all cases, completing the induction.

27. Take $P(x, y) = (y - 2x)(y - 2x - 1)$. To see that this works, first note that if $m = \lfloor a \rfloor$, then $2m$ is an integer less than or equal to $2a$, so $2m \leq \lfloor 2a \rfloor$. On the other hand, $m+1$ is an integer strictly greater than $a$, so $2m+2$ is an integer strictly greater than $2a$, so $\lfloor 2a \rfloor \leq 2m + 1$.

28. Yes. Suppose otherwise. Then there would be an $N$ such that $S(N) < 80\%$ and $S(N + 1) > 80\%$; that is, O’Keal’s free throw percentage is under 80\% at some point, and after one subsequent free throw (necessarily made), her percentage is over 80\%. If she makes $m$ of her first $N$ free throws, then $m/N < 4/5$ and $(m + 1)/(N + 1) > 4/5$. This means that $5m < 4N < 5m + 1$, which is impossible since then $4N$ is an integer between the consecutive integers $5m$ and $5m + 1$.

29. We have
\[ (m + n)^{m+n} > \binom{m+n}{m} m^m n^n \]
because the binomial expansion of $(m+n)^{m+n}$ includes the term on the right as well as some others. Rearranging this inequality yields the claim.

30. There are $n$ such sums. More precisely, there is exactly one such sum with $k$ terms for each of $k = 1, \ldots, n$ (and clearly no others). To see this, note that if $n = a_1 + a_2 + \cdots + a_k$ with $a_1 \leq a_2 \leq \cdots \leq a_k \leq a_1 + 1$, then
\[
ka_1 = a_1 + a_1 + \cdots + a_1 \\
\leq n \leq a_1 + (a_1 + 1) + \cdots + (a_1 + 1) \\
= ka_1 + k - 1.
\]
However, there is a unique integer $a_1$ satisfying these inequalities, namely $a_1 = \lfloor n/k \rfloor$. Moreover, once $a_1$ is fixed, there are $k$ different possibilities for the sum $a_1 + a_2 + \cdots + a_k$: if $i$ is the last integer such that $a_i = a_1$, then the sum equals $ka_1 + (i - 1)$. The possible values of $i$ are $1, \ldots, k$, and exactly one of these sums comes out equal to $n$, proving our claim.

31. By differentiating $P_n(x)/(x^k - 1)^{n+1}$, we find that
\[
P_{n+1}(x) = (x^k - 1)P_n'(x) - (n + 1)kx^{k-1}P_n(x).
\]
Substituting $x = 1$ yields $P_{n+1}(1) = -(n + 1)kP_n(1)$. Since $P_0(1) = 1$, an easy induction gives $P_n(1) = (-k)^n n!$ for all $n \geq 0$. 
Note: one can also argue by expanding in Taylor series around 1. Namely, we have
\[
\frac{1}{x^k - 1} = \frac{1}{k(x-1) + \cdots} = \frac{1}{k} (x-1)^{-1} + \cdots,
\]
so
\[
\frac{d^n}{dx^n} \frac{1}{x^k - 1} = \frac{(-1)^n n!}{k(x-1)^{-n-1}}
\]
and
\[
P_n(x) = (x^k - 1)^{n+1} \frac{d^n}{dx^n} \frac{1}{x^k - 1} \\
= (k(x-1) + \cdots)^{n+1} \\
\left( \frac{(-1)^n n!}{k} (x-1)^{-n-1} + \cdots \right) \\
= (-k)^n n! + \cdots.
\]

32. Draw a great circle through two of the points. There are two closed hemispheres with this great circle as boundary, and each of the other three points lies in one of them. By the pigeonhole principle, two of those three points lie in the same hemisphere, and that hemisphere thus contains four of the five given points.

33. The hypothesis implies \(((b*a)*b)*(b*a) = b\) for all \(a, b \in S\) (by replacing \(a\) by \(b*a\)), and hence \(a*(b*a) = b\) for all \(a, b \in S\) (using \((b*a)*b = a\)).

34. - First solution: Let \(a\) be an even integer such that \(a^2 + 1\) is not prime. (For example, choose \(a \equiv 2 \pmod{5}\), so that \(a^2 + 1\) is divisible by 5.) Then we can write \(a^2 + 1\) as a difference of squares \(x^2 - b^2\), by factoring \(a^2 + 1\) as \(rs\) with \(r \geq s > 1\), and setting \(x = (r+s)/2\), \(b = (r-s)/2\). Finally, put \(n = x^2 - 1\), so that \(n = a^2 + b^2\), \(n+1 = x^2 + 0\), \(n+2 = x^2 + 1\).

- Second solution: It is well-known that the equation \(x^2 - 2y^2 = 1\) has infinitely many solutions (the so-called “Pell” equation). Thus setting \(n = 2y^2\) (so that \(n = y^2 + y^2\), \(n+1 = x^2 + 0^2\), \(n+2 = x^2 + 1^2\)) yields infinitely many \(n\) with the desired property.

- Third solution: As in the first solution, it suffices to exhibit \(x\) such that \(x^2 - 1\) is the sum of two squares. We will take \(x = 3^{2^n}\), and show that \(x^2 - 1\) is the sum of two squares by induction on \(n\): if \(3^{2^n} - 1 = a^2 + b^2\), then
\[
(3^{2^{n+1}} - 1) = (3^{2^n} - 1)(3^{2^n} + 1) \\
= (3^{2^{n-1}} a + b)^2 + (a - 3^{2^{n-1}} b)^2.
\]

35. Note that if \(r(x)\) and \(s(x)\) are any two functions, then
\[
\max(r, s) = (r + s + |r - s|)/2.
\]
Therefore, if \( F(x) \) is the given function, we have
\[
F(x) = \max\{-3x - 3, 0\} - \max\{5x, 0\} + 3x + 2
= (-3x - 3 + |3x - 3|)/2 \\
- (5x + |5x|)/2 + 3x + 2
= |(3x - 3)/2| - |5x/2| - x + \frac{1}{2},
\]
so we may set \( f(x) = (3x - 3)/2, g(x) = 5x/2, \) and \( h(x) = -x + \frac{1}{2}. \)

36. Consider the plane containing both the axis of the cone and two opposite vertices of the cube’s bottom face. The cross section of the cone and the cube in this plane consists of a rectangle of sides \( s \) and \( s\sqrt{2} \) inscribed in an isosceles triangle of base 2 and height 3, where \( s \) is the side-length of the cube. (The \( s\sqrt{2} \) side of the rectangle lies on the base of the triangle.) Similar triangles yield \( s/3 = (1 - s\sqrt{2}/2)/1, \) or \( s = (9\sqrt{2} - 6)/7. \)

37. We may discard any solutions for which \( a_1 \neq a_2, \) since those come in pairs; so assume \( a_1 = a_2. \) Similarly, we may assume that \( a_3 = a_4, a_5 = a_6, a_7 = a_8, a_9 = a_{10}. \) Thus we get the equation
\[
2/a_1 + 2/a_3 + 2/a_5 + 2/a_7 + 2/a_9 = 1.
\]
Again, we may assume \( a_1 = a_3 \) and \( a_5 = a_7, \) so we get \( 4/a_1 + 4/a_5 + 2/a_9 = 1; \) and \( a_1 = a_5, \) so \( 8/a_1 + 2/a_9 = 1. \) This implies that \( (a_1 - 8)(a_9 - 2) = 16, \) which by counting has 5 solutions. Thus \( N_{10} \) is odd.

38. Let \( x = a - 1, y = b - 1, z = 1. \) Then:
\[
xy + xz + yz + 1 = (a - 1)(b - 1) + (a - 1) + (b - 1) \cdot 1 + 1
= ab - a - b + 1 + a - 1 + b - 1 + 1
= ab.
\]