Second Semester of the school year 2023 - 2024. Last update on

School year 2023 - 2024

Nghia Doan

July 10, 2024

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Introduction

Welcome to the second semester of the school year 2023 - 2024!

For the second semester of the 2023-2024 school year, the club plans to organize the program as follows:

- Objective 1: maintain current levels of O, A, I, IC, Pre-algebra.
- Objective 2: strong emphasis on working under pressure.
- Objective 3: solving very challenging problems.

A. Biweekly activity

- On Friday, students will receive 10 problems to solve in that week.
- Detailed solutions must be submitted no later than the following Monday.
- On the following Saturday/Sunday, students receive exam questions already available in the common online folder. The test consists of 10 exercises that are almost identical to the 10 exercises received last week, with some minor changes in the test conditions. Students only need to submit the answer (an integer) for each problem. After 30 minutes, students only need to fill in 10 answers and a file is available in their personal folder.
- If the official solutions of the previous week are available, students must study them and make sure that they master the solutions in order to know how to reuse them, especially when working under duress.
- The submissions, both solutions on Friday and answers on Saturday, are graded, each contributes 50% to the final mark of the problem.

For example:

- *Friday, January 19: Students receive assignments of Session 1*
- *Friday, January 26: Students submit detailed solutions for assignments of Session 1*
- *Saturday, January 27: Students receive the exam of Session 1 (similar problems as received on Friday, January 19), take the exam for 30 minutes, and submit their answers.*
- *Monday, January 29: Students receive the official solutions of Session 1 for both the assignment and the exam Problem. They should study them carefully.*
- *Friday, February 2: Students receive markings of both solutions (submitted on Friday) and answers (submitted on Saturday)*
- *Friday, February 2: Students receive assignments of Session 2*

Note that: students who read and do well on the exercises during the week will have the opportunity to do the exercises correctly during the Purple Comet Competition (with an estimated duration of 3 minutes per exercise).

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Below is an example of a problem in a weekly assignment. You will need to submit a solution, similar like the one below.

Example (Problem 1 - Weekly)

(*5 points*) Find the number of integers n for which $\sqrt{\dfrac{(2020-n)^2}{2020-n^2}}$ is a real number.

Solution. The square root is a real number if the expression under the square root sign is non-negative.

$$\frac{(2020-n)^2}{2020-n^2} \geq 0.$$

There are two cases.

Case 1:

$$\frac{(2020-n)^2}{2020-n^2} = 0 \Rightarrow n = 2020.$$

Case 1:

$$\frac{(2020-n)^2}{2020-n^2} > 0 \Rightarrow 2020-n^2 > 0 \Rightarrow |n| < \sqrt{2020} < 45^2 = 2025 \Rightarrow -44 \leq n \leq 44.$$

There are $1 + 2 \cdot 44 = 89$ such integers between -44 and 44.

Hence, in total there are $1 + 89 = \boxed{90}$ such numbers. □

Then on the exam day, you get a variation of the problem. The correct answer of this problem is $\boxed{92.}$ *Below is the official* **generic solution** *that you don't have to submit.*

Example (Problem 1 - Exam)

(*5 points*) Find the number of integers n for which $\sqrt{\dfrac{(2048-n)^2}{2048-n^2}}$ is a real number.

Solution. Let $m > 1$ is a positive integer.

$$\sqrt{\frac{(m-n)^2}{m-n^2}} \text{ is real number } \Rightarrow \frac{(m-n)^2}{m-n^2} \geq 0.$$

We have two cases:

$$\begin{cases} \dfrac{(m-n)^2}{m-n^2} = 0 \Rightarrow n = m. \\ \dfrac{(m-n)^2}{m-n^2} > 0 \Rightarrow m - n^2 > 0 \Rightarrow |n| < \sqrt{m}. \end{cases} \Rightarrow n \in \{m, -\lfloor\sqrt{m}\rfloor, \ldots, -1, 0, 1, \ldots, \lfloor\sqrt{m}\rfloor\}.$$

There are $2 + 2\lfloor\sqrt{m}\rfloor$ such numbers. For $m = 2048$, there are $2(1 + \lfloor\sqrt{2048}\rfloor) = \boxed{92.}$ □

If you have successfully solved the problem in time then you will have an advantage at the exam. If you solve the problem in a generic way, the exam will be a breeze.

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Solution based on coding can accepted only if

- The code is written in C, C++, Python, MatLab, or Java. No other languages are allowed.
- The code should not use any non-standard libraries.
- The code should compile without extra settings, should result in no compilation errors, or runtime errors.
- Execution time should not exceed 10 minutes.
- Submission must contain both source code, input (if any) and output (printout).

Failure to comply to any of the requirements will lead to rejection of the solution.

B. Semester open competition: Every months for each level there will be 4 problems to solve. Students must submit solutions before given deadlines (will be stated clearly in the text).

C. Purple Comet competition: This year's Purple Comet exam schedule is as follow:

- April 6: middle-school (MS) teams - grade 8 (US, CA), grade 9 (FR, UK, VN) and younger
- April 7: high-school teams - grade 9 (US, CA), grade 10 (FR, UK, VN) and above

Each team has 6 members. Students will be selected based on their weekly activity before April.

- MS team: 60 minutes, 20 problems, middle school math, a team is divided into two groups:
  - M1 - the first ten lessons (1-10): corresponds to level I;
  - M2 - the last ten lessons (11-20): corresponds to level A.
- HS team: 90 minutes, 30 problems, high school math, a team is divided into three groups:
  - H1 - first ten lessons (1-10): corresponds to level I;
  - H2 - the middle ten lessons (11-20): corresponds to level A;
  - H3 - last ten lessons (20-30): corresponds to level O.

Have a great year!

Your teacher,

Nghia Doan

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Part I

2024

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Chapter 1

Session 1: Jan 19 - Jan 27

1.1 Middle School - Assignment

Middle school students: grade 8 (US, CA), grade 9 (FR, UK, VN) and younger.

- **Submission deadline: Friday, January 26**
- **Test: Saturday, January 27**
- **Official solutions: Monday, January 29**
- **Intermediate (I) level: Problems 1-10**
- **Advanced (A) level: Problems 5-14**

If you submit solution based on coding, please make sure that your submission is compliant. Read the introduction chapter for more information.

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Problem 1.1.1 (Problem 1)**.** (*5 points*) Alex launches his boat into a river and heads upstream at a constant speed. At the same time at a point 8 miles upstream from Alex, Alice launches her boat and heads downstream at a constant speed. Both boats move at 6 miles per hour in still water, but the river is flowing downstream at $2\frac{3}{10}$ miles per hour. Alex and Alice will meet at a point that is $\frac{m}{n}$ miles from Alex's starting point, where m and n are relatively prime positive integers. Find $m+n$.

Solution. Relative to the moving water, Alex and Alice are moving at 6 miles per hour, so they are approaching each other at 12 miles per hour. Thus, they meet after $\dfrac{8}{12} = \dfrac{2}{3}$ hours has travel $\dfrac{8}{2} = 4$ relative to the moving water. But the water is moving Alex downstream at r miles per hour, so Alex and Alice meet after Alex has traveled:

$$\frac{m}{n} = 4 - \frac{2}{3}\left(2\frac{3}{10}\right) = \frac{37}{15}.$$

Hence, $m+n = 37+15 = \boxed{52}$. □

Problem 1.1.2 (Problem 2)**.** (*5 points*) Find a positive integer n such that there is a polygon with n sides where each of its interior angles measures $177°$.

Solution. The sum of the measures of the interior angles in a polygon with n sides is $(n-2)180$ in degree.

$$177n = (n-2)180 \Rightarrow n(180-177) = 360 \Rightarrow n = \frac{360}{3} = \boxed{120.}$$

□

Problem 1.1.3 (Problem 3)**.** (*5 points*) Patrick started walking at a constant rate along a straight road from school to the park. One hour after Patrick left, Tanya started running along the same road from school to the park. One hour after Tanya left, Jose started bicycling along the same road from school to the park. Tanya ran at a constant rate of 2 miles per hour faster than Patrick walked, Jose bicycled at a constant rate of 7 miles per hour faster than Tanya ran, and all three arrived at the park at the same time. The distance from the school to the park is $\frac{m}{n}$ miles, where m and n are relatively prime positive integers. Find $m+n$.

Solution. Let t be the time it took Patrick to walk from school to the park in hours and let s be the speed that Patrick walked in miles per hour. Then the distance from the school to the park can be measured in different ways:

$$st = (s+2)(t-1) = (s+9)(t-2) \Rightarrow st = st - s + 2t - 2 = st - 2s + 9t - 18$$

$$-s + 2t - 2 = -2s + 9t - 18 = 0 \Rightarrow \begin{cases} s = 2t-2 \\ 2s = 9t - 18 \end{cases} \Rightarrow s = \frac{18}{5}, t = \frac{14}{5} \Rightarrow st = \frac{252}{25}$$

Therefore $\frac{m}{n} = \frac{252}{25}$, so $m+n = 252+25 = \boxed{277.}$ □

Problem 1.1.4 (Problem 4)**.** (*5 points*) Find the number of positive integers less than or equal to 2020 that are relatively prime to 588.

Solution. A number is relatively prime to $588 = 2^2 \cdot 3 \cdot 7^2$ if and only if it is not divisible by $2, 3$, or 7. Now, we count the number of positive integers less than or equal to 2020 that are divisible by $2, 3$, or 7, then find the total of those who is not divisible by $2, 3$, or 7 by complementary counting.

There are $\frac{2020}{2} = 1010$ positive integers that are divisible by 2.

There are $\left\lfloor \frac{2020}{3} \right\rfloor = 673$ positive integers that are divisible by 3.

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There are $\left\lfloor \frac{2020}{7} \right\rfloor = 288$ positive integers that are divisible by 7.

There are $\left\lfloor \frac{2020}{2\cdot 3} \right\rfloor = 336$ positive integers that are divisible by $6 = 2 \cdot 3$.

There are $\left\lfloor \frac{2020}{2\cdot 7} \right\rfloor = 144$ positive integers that are divisible by $14 = 2 \cdot 7$.

There are $\left\lfloor \frac{2020}{3\cdot 7} \right\rfloor = 96$ positive integers that are divisible by $21 = 3 \cdot 7$.

There are $\left\lfloor \frac{2020}{2\cdot 3\cdot 7} \right\rfloor = 48$ positive integers that are divisible by $42 = 2 \cdot 3 \cdot 7$.

By the Inclusion-Exclusion principle, there are $(1010 + 673 + 288) - (336 + 144 + 96) + 48 = 1443$ positive integers less than or equal to 2020 that are divisible by 2, 3, or 7. Hence, there are $2020 - 1443 = \boxed{577}$ positive integers less than or equal to 2020 that are relatively prime to 588. □

Problem 1.1.5 (Problem 5)**.** (*5 points*) Given that a, b, and c are distinct positive integers such that $a \cdot b \cdot c = 2020$, the minimum possible positive value of $\frac{1}{a} - \frac{1}{b} - \frac{1}{c}$ is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. Note that $2020 = 2^2 \cdot 5 \cdot 101$, thus we can assume that c is a multiple of 101, otherwise the expression $\frac{1}{a} - \frac{1}{b} - \frac{1}{c}$ cannot be positive. Furthermore,

$$\frac{1}{a} - \frac{1}{b} = \frac{b-a}{ab}$$

In order for $\frac{1}{a} - \frac{1}{b}$ be as small as possible we make $b - a$ as small as possible and ab as large as possible.

Note that c is a multiple of 101 so $ab \leq 20$ thus its largest value is 20. In addition $1 \leq b - a$, so the smallest possible value for $b - a$ is 1. Both cases happen when $b = 5, a = 4, c = 101$.

Hence

$$\frac{m}{n} = \frac{1}{4} - \frac{1}{5} - \frac{1}{101} = \frac{81}{2020} \Rightarrow m + n = \boxed{2101.}$$

□

Problem 1.1.6 (Problem 6)**.** (*5 points*) Mary mixes 2 gallons of a solution that is 40 percent alcohol with 3 gallons of a solution that is 60 percent alcohol. Sandra mixes 4 gallons of a solution that is 30 percent alcohol with $\frac{m}{n}$ gallons of a solution that is 80 percent alcohol, where m and n are relatively prime positive integers. Mary and Sandra end up with solutions that are the same percent alcohol. Find $m + n$.

Solution. Let $x = \frac{m}{n}$, then the fraction of each mixture that is alcohol is

$$\frac{0.4(2) + 0.6(3)}{5} = \frac{0.3(4) + 0.8x}{4 + x} \Rightarrow 0.52 = \frac{0.8x + 1.2}{x + 4} \Rightarrow x = \frac{22}{7} \Rightarrow m + n = \boxed{29.}$$

□

Problem 1.1.7 (Problem 7)**.** (*5 points*) Let a and b be positive integers such that $(a^3 - a^2 + 1)(b^3 - b^2 + 2) = 2020$. Find $10a + b$.

Solution. Case 1: $b = 1$, then $a^3 - a^2 + 1 = 1010 \Rightarrow a^2(a - 1) = 1009$, impossible since 1009 is prime.

Case 2: $b = 2$, then $b^3 - b^2 + 2 = 6 \nmid 2020$.

Case 3: $b = 3$, then $b^3 - b^2 + 2 = 20 \Rightarrow a^2(a - 1) = 100 \Rightarrow a = 5$.

Case 4: $b = 4$, then $b^3 - b^2 + 2 = 50 \nmid 2020$.

Case 5: $b \geq 5$, then $b^3 - b^2 = b^2(b - 1) + 2 \geq 25 \cdot 4 + 2 = 102$.

If $a \geq 4$ then $a^3 - a^2 + 1 = a^2(a - 1) + 1 \geq 16 \cdot 3 + 1 = 49$, thus $1 \leq a \leq 3$. It is easy to test that there is no such positive integer value for a.

Thus $a = 5, b = 3 \Rightarrow 10a + b = \boxed{53.}$ □

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Problem 1.1.8 (Problem 8)**.** (*5 points*) Find the number of three-digit palindromes that are divisible by 3. Recall that a palindrome is a number that reads the same forward and backward like 727 or 905509.

Solution. Let aba be the three-digit palindromes that are divisible by 3. Since $3 \mid 2a + b$, thus we can choose b based on the remainder of a when divided by 3.

Case 1: $a \in \{3, 6, 9\}$, then $b = 0, 3, 6, 9$.

Case 2: $a \in \{1, 4, 7\}$, then $b = 1, 4, 7$.

Case 3: $a \in \{2, 5, 8\}$, then $b = 2, 5, 8$.

Thus the number of three-digit palindromes that are divisible by 3 is $3 \cdot 4 + 3 \cdot 3 + 3 \cdot 3 = \boxed{30.}$ □

Problem 1.1.9 (Problem 9)**.** (*5 points*) Six different small books and three different large books sit on a shelf. Three children may each take either two small books or one large book. Find the number of ways the three children can select their books.

Solution. Consider the number of children who take large books.

Case 1: No child take a large book. Each child can select two small books in $\binom{6}{2} \cdot \binom{4}{2} \cdot \binom{2}{2} = 90$ ways.

Case 2: One child takes one large book. There are 3 ways to select a child who takes a large book, and there are 3 ways for that child to select which large book. Two child can select two small books in $\binom{6}{2} \cdot \binom{4}{2} = 90$ ways. In total there are $3 \cdot 3 \cdot 90 = 810$ ways.

Case 3: Two children takes two large books. There are 3 ways to select a child who takes two small books, and there are $\binom{6}{2} = 15$ ways for that child to select which two small books. There are $\binom{3}{1} \cdot \binom{2}{1} = 6$ ways for the other two children to select two large books. In total there are $3 \cdot 15 \cdot 6 = 270$ ways.

Case 4: There are $\binom{3}{1} \cdot \binom{2}{1} \cdot \binom{1}{1} = 6$ ways for each of the children to select one large book.

Thus the number ways is $90 + 810 + 270 + 6 = \boxed{1176.}$ □

Problem 1.1.10 (Problem 10)**.** (*5 points*) Daniel had a string that formed the perimeter of a square with area 98. Daniel cut the string into two pieces. With one piece he formed the perimeter of a rectangle whose width and length are in the ratio $2 : 3$. With the other piece he formed the perimeter of a rectangle whose width and length are in the ratio $3 : 8$. The two rectangles that Daniel formed have the same area, and each of those areas is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. Let s be the side length of the square then $s^2 = 98$, so $s = 7\sqrt{2}$. So the length of the string is $28\sqrt{2}$. Let the two rectangles made by Daniel be $2x \times 3x$ and $3y \times 8y$, then

$$2x \cdot 3x = 3y \cdot 8y \Rightarrow x^2 = 4y^2 \Rightarrow x = 2y.$$

The total perimeter of the two rectangles is $10x + 22y = 21x = 28\sqrt{2}$, so

$$x = \frac{4\sqrt{2}}{3}, \text{ and the area is } 6\left(\frac{4\sqrt{2}}{3}\right)^2 = \frac{64}{3}.$$

Hence, $m + n = 64 + 3 = \boxed{67.}$ □

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Problem 1.1.11 (Problem 11)**.** (*5 points*) Find the number of permutations of the letters ABCDE where the letters A and B are not adjacent and the letters C and D are not adjacent. For example, count the permutations ACBDE and DEBCA but not ABCED or EDCBA.

Solution. There are $5! = 120$ permutations of the letters ABCDE.

The number of permutations where A is adjacent to B can be counted considering the permutations of XCDE, where X represents AB or BA. There are $4! = 24$ permutations of XCDE and 2 possibilities for X. Thus, there are $24 \cdot 2 = 48$ permutations where A is adjacent to B.

Similarly there are 48 permutations where C is adjacent to D.

The number of permutations where A is adjacent to B and C is adjacent to D can be counted considering the permutations of XYE, where X represents AB or BA, Y represents CD or DC. There are $3! = 6$ permutations of XYE, 2 possibilities for X, 2 possibilities for Y. Thus, there are $6 \cdot 2 \cdot 2 = 24$ permutations where A is adjacent to B and C is adjacent to D.

Therefore there are $48 + 48 - 24 = 72$ permutations where A is adjacent to B or C is adjacent to D.

Hence, the number of permutations of the letters ABCDE where the letters A and B are not adjacent and the letters C and D are not adjacent is $120 - 72 = \boxed{48.}$ □

Problem 1.1.12 (Problem 12)**.** (*5 points*) Construct a geometric figure in a sequence of steps. In step 1, begin with a 4×4 square.

In step 2, attach a 1×1 square onto the each side of the original square so that the new squares are on the outside of the original square, have a side along the side of the original square, and the midpoints of the sides of the original square and the attached square coincide.

In step 3, attach a $\frac{1}{4} \times \frac{1}{4}$ square onto the centers of each of the 3 exposed sides of each of the 4 squares attached in step 2. For each positive integer n, in step $n+1$, attach squares whose sides are $\frac{1}{4}$ as long as the sides of the squares attached in step n placing them at the centers of the 3 exposed sides of the squares attached in step n. The diagram shows the figure after step 4.

If this is continued for all positive integers n, the area covered by all the squares attached in all the steps is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. The square in the first step has an area of $4 \cdot 4 = 16$. There are 4 squares added in the second step, each with area $1 \cdot 1 = 1$ for a total of 4. After this, there are 3 times as many squares added in each step, and each square has area $\frac{1}{4} \cdot \frac{1}{4} = \frac{1}{16}$ as large as the areas of the squares added in the previous step.

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Thus, each step adds $\dfrac{3}{16}$ the area that was added in the previous step. The total area of all the squares added in every step is:

$$16+4+4\cdot\frac{3}{16}+4\cdot\left(\frac{3}{16}\right)^2+\cdots=16+4\left(1+\left(\frac{3}{16}\right)+\left(\frac{3}{16}\right)^2+\cdots\right)=16+4\frac{1}{1-\left(\frac{3}{16}\right)}=16+\frac{64}{13}=\frac{272}{13}.$$

Hence, $m+n=272+13=\boxed{285.}$ □

Problem 1.1.13 (Problem 13)**.** (*5 points*) Wendy randomly chooses a positive integer less than or equal to 2020. The probability that the digits in Wendy's number add up to 10 is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m+n$.

Solution. There are 2020 equally likely choices.

Case 1: For the number of choices less than 1000. Selecting a number less than 1000 whose digits add up to 10 is the same as to place 10 stones into three piles. We use the sticks-and-stones method with 10 stones and 2 sticks. The number of ways to place 10 stones into three order piles is given by $\binom{10+2}{2}=66$. This number count the 3 cases when all ten stones end up in the same pile, which means some digit can be equal 10. Therefore the number of possible cases is $66-3=63$.

Case 2: For the number of choices at least 1000 and less than 2000. Similarly there are $\binom{9+2}{2}=55$.

Case 3: For the number of choices at least 2000. There are two such numbers: 2008 and 2017.

Therefore there are $63+55+2=120$ such numbers. The required probability is $\frac{120}{2020}=\frac{6}{101}$.

Hence, $m+n=6+101=\boxed{107.}$ □

Problem 1.1.14 (Problem 14)**.** (*5 points*) Right $\triangle ABC$ has side lengths 6, 8, and 10. Find the positive integer n such that the area of the region inside the circumcircle but outside the incircle of $\triangle ABC$ is $n\pi$.

Solution. The hypotenuse of the right $\triangle ABC$ is a diameter of the circumcircle, so the area of the circle is $\pi\left(\frac{10}{2}\right)^2=25\pi$. The area of the right $\triangle ABC$ is $\frac{1}{2}(6\cdot 8)=24$, its semi-perimeter is $\frac{1}{2}(6+8+10)=12$, its inradius is $\dfrac{24}{12}=2$. Thus, the area of the incircle is 4π. The area of the region inside the circumcircle but outside the incircle of $\triangle ABC$ is $25\pi-4\pi=21\pi$. Hence $n=\boxed{21.}$ □

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1.2 Middle School - Test

You have **30 minutes** to complete the test. You have to **submit only the answers**. No solution is required.

Note that you have to **follow the instructions by the COs** *for submitting the answers.*

- **Intermediate (I) level: Problems 1-10**
- **Advanced (A) level: Problems 5-14**

If you submit solution based on coding, please make sure that your submission is compliant. Read the introduction chapter for more information.

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Problem 1.2.1 (Problem 1)**.** (*5 points*) Alex launches his boat into a river and heads upstream at a constant speed. At the same time at a point 10 miles upstream from Alex, Alice launches her boat and heads downstream at a constant speed. Both boats move at 6 miles per hour in still water, but the river is flowing downstream at 3 miles per hour. Alex and Alice will meet at a point that is $\frac{m}{n}$ miles from Alex's starting point, where m and n are relatively prime positive integers. Find $m+n$.

Solution. Relative to the moving water, Alex and Alice are moving at 6 miles per hour, so they are approaching each other at 12 miles per hour. Thus, they meet after $\dfrac{10}{12} = \dfrac{5}{6}$ hours has travel $\dfrac{10}{2} = 5$ relative to the moving water. But the water is moving Alex downstream at r miles per hour, so Alex and Alice meet after Alex has traveled:

$$\frac{m}{n} = 5 - \frac{5}{6}(3) = \frac{5}{2}.$$

Hence, $m+n = 5+2 = \boxed{7}$. □

Problem 1.2.2 (Problem 2)**.** (*5 points*) Find a positive integer n such that there is a polygon with n sides where each of its interior angles measures $165°$.

Solution. The sum of the measures of the interior angles in a polygon with n sides is $(n-2)180$ in degree.

$$165n = (n-2)180 \Rightarrow n(180-165) = 360 \Rightarrow n = \frac{360}{15} = \boxed{24.}$$

□

Problem 1.2.3 (Problem 3)**.** (*5 points*) Patrick started walking at a constant rate along a straight road from school to the park. Two hour after Patrick left, Tanya started running along the same road from school to the park. One hour after Tanya left, Jose started bicycling along the same road from school to the park. Tanya ran at a constant rate of 1 miles per hour faster than Patrick walked, Jose bicycled at a constant rate of 6 miles per hour faster than Tanya ran, and all three arrived at the park at the same time. The distance from the school to the park is $\frac{m}{n}$ miles, where m and n are relatively prime positive integers. Find $m+n$.

Solution. Let t be the time it took Patrick to walk from school to the park in hours and let s be the speed that Patrick walked in miles per hour. Then the distance from the school to the park can be measured in different ways:

$$st = (s+1)(t-2) = (s+7)(t-3) \Rightarrow st = st - 2s + t - 2 = st - 3s + 7t - 21$$

$$-2s + t - 2 = -3s + 7t - 21 = 0 \Rightarrow \begin{cases} t = 2s+2 \\ 7t = 3s+21 \end{cases} \Rightarrow s = \frac{7}{11}, t = \frac{36}{11} \Rightarrow st = \frac{252}{121}$$

Therefore $\frac{m}{n} = \frac{252}{121}$, so $m+n = 252+121 = \boxed{373.}$ □

Problem 1.2.4 (Problem 4)**.** (*5 points*) Find the number of positive **even** integers less than or equal to 2024 that are relatively prime to 15.

Solution. A number is relatively prime to $15 = 3 \cdot 5$ if and only if it is not divisible by 3 or 5.

There are $\frac{2024}{2} = 1011$ positive integers that are divisible by 2.

Now we find the number of positive **even** integers that are divisible by 3 or 5

There are $\left\lfloor \frac{2024}{2\cdot 3} \right\rfloor = 337$ positive integers that are divisible by $6 = 2 \cdot 3$.

There are $\left\lfloor \frac{2024}{2\cdot 5} \right\rfloor = 202$ positive integers that are divisible by $10 = 2 \cdot 5$.

There are $\left\lfloor \frac{2024}{2\cdot 3\cdot 5} \right\rfloor = 67$ positive integers that are divisible by $30 = 2 \cdot 3 \cdot 5$.

By the Inclusion-Exclusion principle, there are $1012 - (337+202) + 67 = \boxed{540}$ positive even integers less than or equal to 2024 that are relatively prime to 15. □

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Problem 1.2.5 (Problem 5)**.** (*5 points*) Given that a, b, and c are distinct positive integers such that $a \cdot b \cdot c = 1236$, the minimum possible positive value of $\frac{1}{a} - \frac{1}{b} - \frac{1}{c}$ is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. Note that $1236 = 2^2 \cdot 3 \cdot 103$, thus we can assume that c is a multiple of 103, otherwise the expression $\frac{1}{a} - \frac{1}{b} - \frac{1}{c}$ cannot be positive. Furthermore,

$$\frac{1}{a} - \frac{1}{b} = \frac{b-a}{ab}$$

In order for $\frac{1}{a} - \frac{1}{b}$ be as small as possible we make $b - a$ as small as possible and ab as large as possible.

Note that c is a multiple of 103 so $ab \leq 12$ thus its largest value is 12. In addition $1 \leq b - a$, so the smallest possible value for $b - a$ is 1. Both cases happen when $b = 4, a = 3, c = 101$.

Hence

$$\frac{m}{n} = \frac{1}{3} - \frac{1}{4} - \frac{1}{103} = \frac{91}{1236} \Rightarrow m + n = \boxed{1327.}$$

□

Problem 1.2.6 (Problem 6)**.** (*5 points*) Mary mixes 2 gallons of a solution that is 30 percent alcohol with 3 gallons of a solution that is 70 percent alcohol. Sandra mixes 4 gallons of a solution that is 20 percent alcohol with $\frac{m}{n}$ gallons of a solution that is 90 percent alcohol, where m and n are relatively prime positive integers. Mary and Sandra end up with solutions that are the same percent alcohol. Find $m + n$.

Solution. Let $x = \frac{m}{n}$, then the fraction of each mixture that is alcohol is

$$\frac{0.3(2) + 0.7(3)}{5} = \frac{0.2(4) + 0.9x}{4 + x} \Rightarrow 0.54 = \frac{0.9x + 0.8}{x + 4} \Rightarrow x = \frac{34}{9} \Rightarrow m + n = \boxed{43.}$$

□

Problem 1.2.7 (Problem 7)**.** (*5 points*) Let a and b be positive integers such that $(a^3 - a^2 + 1)(b^3 - b^2 + 2) = 1938$. Find $10a + b$.

Solution. Case 1: $b = 1$, then $a^3 - a^2 + 1 = 969 \Rightarrow a^2(a - 1) = 968 = 2^3 \cdot 11^2$. No solution.

Case 2: $b = 2$, then $b^3 - b^2 + 2 = 6 \Rightarrow a^2(a - 1) = 322 = 2 \cdot 6 \cdot 23$. No solution.

Case 3: $b = 3$, then $b^3 - b^2 + 2 = 20 \nmid 1938$.

Case 4: $b = 4$, then $b^3 - b^2 + 2 = 50 \nmid 1938$.

Case 5: $b = 5$, then $b^3 - b^2 + 2 = 102 \Rightarrow a^2(a - 1) = 18 \Rightarrow a = 3$.

Case 6: $b \geq 6$, then $b^3 - b^2 + 2 = b^2(b - 1) + 3 \geq 36 \cdot 5 + 2 = 182$. Thus $a^3 - a^2 + 1 =\leq \frac{1938}{182} < 11$, thus $a \leq 2$. It is easy to test that there is no such positive integer value for a.

Thus $a = 3, b = 5 \Rightarrow 10a + b = \boxed{35.}$ □

Problem 1.2.8 (Problem 8)**.** (*5 points*) Find the number of *four-digit* palindromes that are divisible by 3. Recall that a palindrome is a number that reads the same forward and backward like 727 or 905509.

Solution. Let $abba$ be the four-digit palindromes that are divisible by 3. Since $3 \mid 2a + 2b$, so $3 \mid a + b$ thus we can choose b based on the remainder of a when divided by 3.

Case 1: $a \in \{3, 6, 9\}$, then $b = 0, 3, 6, 9$.

Case 2: $a \in \{1, 4, 7\}$, then $b = 2, 5, 8$.

Case 3: $a \in \{2, 5, 8\}$, then $b = 1, 4, 7$.

Thus the number of four-digit palindromes that are divisible by 3 is $3 \cdot 4 + 3 \cdot 3 + 3 \cdot 3 = \boxed{30.}$ □

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Problem 1.2.9 (Problem 9)**.** (*5 points*) Four different small books and four different large books sit on a shelf. Three children may each take either two small books or one large book. Find the number of ways the three children can select their books.

Solution. Consider the number of children who take large books. Since there are only four different small books, there should be at least one child who takes a large book.

Case 1: One child takes one large book. There are 3 ways to select a child who takes a large book, and there are 4 ways for that child to select which large book. Two child can select two small books in $\binom{4}{2} \cdot \binom{2}{2} = 6$ ways. In total there are $3 \cdot 4 \cdot 6 = 72$ ways.

Case 3: Two children takes two large books. There are 3 ways to select a child who takes two small books, and there are $\binom{4}{2} = 6$ ways for that child to select which two small books. There are $\binom{4}{1} \cdot \binom{3}{1} = 12$ ways for the other two children to select two large books. In total there are $3 \cdot 6 \cdot 12 = 216$ ways.

Case 3: There are $\binom{4}{1} \cdot \binom{3}{1} \cdot \binom{2}{1} = 24$ ways for each of the children to select one large book.

Thus the number ways is $72 + 216 + 24 = \boxed{312.}$ □

Problem 1.2.10 (Problem 10)**.** (*5 points*) Daniel had a string that formed the perimeter of a square. Daniel cut the string into two pieces. With one piece he formed the perimeter of a rectangle whose width and length are in the ratio $2 : 3$. With the other piece he formed the perimeter of a rectangle whose width and length are in the ratio $3 : 8$. The two rectangles that Daniel formed have the same area, and the measure of each of those areas is 2.

The length of the string is $m\sqrt{n}$, where m and n are positive integers, and n is not divisible by any perfect square larger than 1. Find $m + n$.

Solution. Let s be the side length of the original square, the length of the string is $4s$.

Let the two rectangles made by Daniel be $2x \times 3x$ and $3y \times 8y$, then

$$2x \cdot 3x = 3y \cdot 8y \Rightarrow x^2 = 4y^2 \Rightarrow x = 2y.$$

The total perimeter of the two rectangles is $10x + 22y = 21x = 4s$. Thus , and the area is $6 \cdot \left(\frac{4s}{21}\right)^2$. Since

$$x = \frac{4s}{21}, \text{ and the area is } 6\left(\frac{4s}{21}\right)^2 = \frac{32s^2}{147} = 2 \Rightarrow s = \frac{7\sqrt{3}}{4} \Rightarrow 4s = 7\sqrt{3}.$$

Hence, $m + n = 7 + 3 = \boxed{10.}$ □

Problem 1.2.11 (Problem 11)**.** (*5 points*) Find the number of permutations of the letters ABCDEF where the letters A and B are not adjacent, the letters C and D are not adjacent, and the letters E and F are not adjacent. For example, count the permutations FACBDE and DEBCAF but not ABCDEF or EDCBAF.

Solution. There are $6! = 720$ permutations of the letters ABCDEF.

The number of permutations where A is adjacent to B can be counted considering the permutations of XCDEF, where X represents AB or BA. There are $5! = 120$ permutations of XCDEF and 2 possibilities for X. Thus, there are $120 \cdot 2 = 240$ permutations where A is adjacent to B.

Similarly there are 240 permutations where C is adjacent to D, 240 permutations where E is adjacent to F.

The number of permutations where A is adjacent to B and C is adjacent to D can be counted considering the permutations of XYEF, where X represents AB or BA, Y represents CD or DC. There are $4! = 24$ permutations of XYEF, 2 possibilities for X, 2 possibilities for Y. Thus, there are $24 \cdot 2 \cdot 2 = 96$ permutations where A is adjacent to B and C is adjacent to D.

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Similarly there are 96 permutations where A is adjacent to B and E is adjacent to F. and 240 permutations where C is adjacent to D and E is adjacent to F.

Finally, the number of permutations where A is adjacent to B, C is adjacent to D, and E is adjacent to F can be counted considering the permutations of XYZ, where X represents AB or BA, Y represents CD or DC, Z represents EF. There are $3! = 6$ permutations of XYZ, 2 possibilities for X, 2 possibilities for Y, and 2 possibilities for Z. Thus, there are $6 \cdot 2 \cdot 2 \cdot 2 = 48$ permutations where A is adjacent to B, C is adjacent to D, and E is adjacent to F

Therefore there are $(240 + 240 + 240) - (96 + 96 + 96) + 48 = 480$ permutations where A is adjacent to B, C is adjacent to D, or E is adjacent to F.

Hence, the number of permutations of the letters ABCDE where the letters A and B are not adjacent, the letters C and D are not adjacent, and the letters E and F are not adjacent is $720 - 480 = \boxed{240.}$ □

Problem 1.2.12 (Problem 12)**.** (*5 points*) Construct a geometric figure in a sequence of steps. In step 1, begin with a 4×4 square.

In step 2, attach a 1×1 square onto the each side of the original square so that the new squares are on the outside of the original square, have a side along the side of the original square, and the midpoints of the sides of the original square and the attached square coincide.

In step 3, attach a $\frac{1}{4} \times \frac{1}{4}$ square onto the centers of each of the 3 exposed sides of each of the 4 squares attached in step 2. For each positive integer n, in step $n + 1$, attach squares whose sides are $\frac{1}{4}$ as long as the sides of the squares attached in step n placing them at the centers of the 3 exposed sides of the squares attached in step n. The diagram shows the figure after step 4.

If this is continued for all positive integers n, let $\frac{m}{n}$, where m and n are relatively prime positive integers, be the area covered by all the squares attached in all the **odd** steps: step 1, step 3, step 5, etc. Find $m + n$.

Solution. The square in the first step has an area of $4 \cdot 4 = 16$. There are 4 squares added in the second step, each with area $1 \cdot 1 = 1$ for a total of 4. After this, there are 3 times as many squares added in each step, and each square has area $\frac{1}{4} \cdot \frac{1}{4} = \frac{1}{16}$ as large as the areas of the squares added in the previous step.

Thus, each step adds $\frac{3}{16}$ the area that was added in the previous step. The areas of all the squares added are:

$$16,\ 4,\ 4 \cdot \frac{3}{16},\ 4 \cdot \left(\frac{3}{16}\right)^2,\ \ldots$$

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Now, the total area of all the squares added in every **odd** step is:

$$16 + 4 \cdot \frac{3}{16} + 4 \cdot \left(\frac{3}{16}\right)^3 + 4 \cdot \left(\frac{3}{16}\right)^5 + \cdots = 16 + 4 \cdot \frac{3}{16}\left(1 + \left(\frac{3}{16}\right)^2 + \left(\frac{3}{16}\right)^3 + \cdots\right)$$
$$= 16 + 4\frac{1}{1 - \left(\frac{3}{16}\right)^2} = \frac{4976}{247}$$

Hence, $m + n = 4976 + 247 = \boxed{5223.}$ □

Problem 1.2.13 (Problem 13)**.** (*5 points*) Wendy randomly chooses a positive integer less than or equal to 2024. The probability that the digits in Wendy's number add up to 8 is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. There are 2024 equally likely choices.

Case 1: For the number of choices less than 1000. Selecting a number less than 1000 whose digits add up to 8 is the same as to place 8 stones into three piles. We use the sticks-and-stones method with 8 stones and 2 sticks. The number of ways to place 8 stones into three order piles is given by $\binom{8+2}{2} = 45$.

Case 2: For the number of choices at least 1000 and less than 2000. Similarly there are $\binom{7+2}{2} = 36$.

Case 3: For the number of choices at least 2000. There are three such numbers: 2006, 2015, 2024.

Therefore there are $45 + 36 + 3 = 84$ such numbers. The required probability is $\frac{84}{2024} = \frac{21}{506}$.

Hence, $m + n = 21 + 506 = \boxed{527.}$ □

Problem 1.2.14 (Problem 14)**.** (*5 points*) Right $\triangle ABC$ has integer side lengths a, b, and c, where $\angle BAC = 90°$. Let r be the radius of the incircle, R be the radius of the circumcircle, then the ratio $\frac{r+R}{a+b}$ is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. The hypotenuse of the right $\triangle ABC$ is the diameter of the circle, thus $R = \frac{1}{2}c = \frac{1}{2}\sqrt{a^2 + b^2}$.

The area of the right $\triangle ABC$ is $\frac{1}{2}(a \cdot b)$, its semi-perimeter is $\frac{1}{2}(a + b + c)$, therefore its inradius is

$$r = \frac{ab}{a + b + c} = \frac{ab}{a + b + \sqrt{a^2 + b^2}}$$
$$r + R = \frac{ab}{a + b + \sqrt{a^2 + b^2}} + \frac{1}{2}\sqrt{a^2 + b^2} = \frac{2ab + (a + b)\sqrt{a^2 + b^2} + a^2 + b^2}{2(a + b + \sqrt{a^2 + b^2})}$$
$$= \frac{(a + b)^2 + (a + b)\sqrt{a^2 + b^2}}{2(a + b + \sqrt{a^2 + b^2})} = \frac{(a + b)(a + b + \sqrt{a^2 + b^2})}{2(a + b + \sqrt{a^2 + b^2})} = \frac{a + b}{2}$$
$$\Rightarrow \frac{r + R}{a + b} = \frac{1}{2} \Rightarrow m + n = 1 + 2 = \boxed{3.}$$

□

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1.3 High School - Assignment

High school students: grade 9 (US, CA), grade 10 (FR, UK, VN) and above.

- **Submission deadline: Friday, January 26**
- **Test: Saturday, January 27**
- **Official solutions: Monday, January 29**
- **Intermediate (I) level: Problems 1-10**
- **Advanced (A) level: Problems 4-13**
- **Olympiad (O) level: Problems 10-19**

If you submit solution based on coding, please make sure that your submission is compliant. Read the introduction chapter for more information.

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Problem 1.3.1 (Problem 1)**.** (*5 points*) There is a complex number K such that the quadratic polynomial $7x^2 + Kx + 12 - 5i$ has exactly one root, where $i = \sqrt{-1}$. Find $|K|^2$.

Note that for a complex number $x = a + bi$, $|x|$ denotes the absolute value of x and $|x| = \sqrt{a^2 + b^2}$.

Solution. A quadratic polynomial has exactly one root if and only if its determinant is zero, therefore for $7x^2 + Kx + 12 - 5i$, we have:

$$K^2 - 4(7)(12 - 5i) = 0 \Rightarrow K^2 = (4 \cdot 7 \cdot 12) - (4 \cdot 7 \cdot 5)i.$$

Note that for a complex number $K = a + bi$, then

$$|K| = \sqrt{a^2 + b^2} \text{ and } K^2 = (a + bi)(a + bi) = a^2 - b^2 + 2abi, \text{ note that}$$
$$(a^2 - b^2)^2 + (2ab)^2 = (a^2 + b^2)^2 \Rightarrow |K|^2 = a^2 + b^2 = \sqrt{(a^2 - b^2)^2 + (2ab)^2} = |K^2|$$

Hence, $|K|^2 = |K^2| = \sqrt{(4 \cdot 7 \cdot 12)^2 + (4 \cdot 7 \cdot 5)^2} = 28\sqrt{12^2 + 5^2} = 28 \cdot 13 = \boxed{364.}$. □

Problem 1.3.2 (Problem 2)**.** (*5 points*) Two circles have radius 9, and one circle has radius 7. Each circle is externally tangent to the other two circles, and each circle is internally tangent to two sides of an isosceles triangle, as shown. The sine of the base angle of the triangle is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. Let ω_1 be the circle with radius 7 with center F and ω_2 be one of the circles with radius 9 with center G. Let label the vertices of the triangles to be A, B, and C as shown in the diagram above. Let AD be the altitude from A to BC, E be the tangent point of the circles with radius 9, and H, I be the feet of the altitudes from F, G to AB, respectively. Let J be the foot of the altitudes from F to GJ.

Then

$$EG = 9, FG = 7 + 9 = 16 \Rightarrow EF = \sqrt{16^2 - 9^2} = \sqrt{175}$$
$$GJ = GI - IJ = GI - FH = 9 - 7 = 2 \Rightarrow FJ = \sqrt{16^2 - 2^2} = \sqrt{252}$$
$$\sin(\angle ABC) = \cos(\angle BAD) = \cos(\angle JFE) = \cos(\angle JFG + \angle GFE)$$
$$= \cos(\angle JFG)\cos(\angle GFE) - \sin(\angle JFG)\sin(\angle GFE)$$
$$= \frac{FJ}{FG}\frac{FE}{FG} - \frac{GJ}{FG}\frac{EG}{FG} = \frac{\sqrt{175} \cdot \sqrt{252} - 2 \cdot 9}{16^2} = \frac{210 - 18}{256} = \frac{3}{4}.$$

Hence, $m + n = \boxed{7.}$ □

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Problem 1.3.3 (Problem 3)**.** (*5 points*) There are two distinct pairs of positive integers $a_1 < b_1$ and $a_2 < b_2$ such that both $|(a_1+ib_1)(b_1-ia_1)|$ and $|(a_2+ib_2)(b_2-ia_2)|$ equal 2020, where $i = \sqrt{-1}$. Find $a_1+b_1+a_2+b_2$.

Note that for a complex number $x = a + bi$, $|x|$ denotes the absolute value of x and $|x| = \sqrt{a^2+b^2}$.

Solution. Note that

$$(a_1 + ib_1)(b_1 - ia_1) = 2a_1b_1 + i(b_1^2 - a_1^2) \Rightarrow |(a_1 + ib_1)(b_1 - ia_1)| = \sqrt{(2a_1b_1)^2 + (b_1^2 - a_1^2)^2} = a_1^2 + b_1^2$$

Thus $a_1^2 + b_1^2 = 2020$. Since a perfect square has a remainder of 0 or 1 when divided by 4, thus both a_1 and b_1 have to be even since $4 \mid 2020$. Therefore $\frac{a_1}{2}, \frac{b_1}{2}$ are positive integers and

$$\left(\frac{a_1}{2}\right)^2 + \left(\frac{b_1}{2}\right)^2 = 505.$$

Since $505 < 23^2 = 529$, by testing we can see that $\left(\frac{a_1}{2}, \frac{b_1}{2}\right) \in \{(12, 19), (8, 21)\}$.

Similarly for (a_2, b_2). By the given conditions (a_1, b_1) and (a_2, b_2) are distinct pairs, so they must be $(24, 38)$ and $(16, 42)$.

Hence, $a_1 + b_1 + a_2 + b_2 = 24 + 38 + 16 + 42 = \boxed{120.}$ □

Problem 1.3.4 (Problem 4)**.** (*5 points*) There are relatively prime positive integers s and t such that

$$\sum_{n=2}^{100}\left(\frac{n}{n^2-1} - \frac{1}{n}\right) = \frac{s}{t}.$$

Find $s + t$.

Solution. Note that

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

$$\sum_{n=2}^{100}\left(\frac{n}{n^2-1} - \frac{1}{n}\right) = \frac{1}{2}\sum_{n=2}^{100}\left(\frac{1}{n-1} - \frac{1}{n}\right) - \frac{1}{2}\sum_{n=2}^{100}\left(\frac{1}{n} - \frac{1}{n+1}\right) = \frac{1}{2}\left(\frac{1}{1} - \frac{1}{100}\right) - \frac{1}{2}\left(\frac{1}{2} - \frac{1}{101}\right) = \frac{5049}{20200}$$

Hence, $s + t = \boxed{25249.}$ □

Problem 1.3.5 (Problem 5)**.** (*5 points*) Let x be a real number such that $3\sin^4 x - 2\cos^6 x = -\dfrac{17}{25}$. Then $3\cos^4 x - 2\sin^6 x = \dfrac{m}{n}$, where m and n are relatively prime positive integers. Find $10m + n$.

Solution.

$$-\frac{17}{25} = 3\sin^4 x - 2\cos^6 x = 3\sin^4 x - 2(1 - \sin^2 x)^3 = 2\sin^6 x - 3\sin^4 x + 6\sin^2 x - 2$$
$$3\cos^4 x - 2\sin^6 x = 3(1 - \sin^2 x)^2 - 2\sin^6 x = 3 - 6\sin^2 x + 3\sin^4 x - 2\sin^6 x$$

Hence, $\dfrac{m}{n} = -\left(-\dfrac{17}{25} + 2\right) + 3 = \frac{42}{25}$, so $10m + n = 420 + 25 = \boxed{445.}$ □

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Problem 1.3.6 (Problem 6)**.** (*5 points*) Find the sum of all values of x such that the set

$$\{107, 122, 127, 137, 152, x\} \text{ has a mean that is equal to its median.}$$

Solution. First, let's simplify the problem by subtracting 107 from each of the elements, then the statement still stands for the set $\{0, 15, 20, 30, 45, x - 107\}$. Then, by dividing each of the elements by 5, it is the same assumption for the set $\{, y = \frac{x-107}{5}\}$. The mean of the set now is $\dfrac{0+3+4+6+9+y}{6} = \dfrac{22+y}{6}$.

Case 1: $y < 3$, then the median of the set is $\dfrac{3+4}{2} = \dfrac{7}{2}$, so $y = -1$.

Case 2: $3 \leq y \leq 6$, then the median of the set is $\dfrac{4+y}{2}$, so $y = 5$.

Case 3: $y < 6$, then the median of the set is $\dfrac{4+6}{2}$, so $y = 8$.

Hence, the sum of all values of x is

$$(-1 \cdot 5 + 107) + (5 \cdot 5 + 107) + (8 \cdot 5 + 107) = 102 + 132 + 147 = \boxed{381.}$$

□

Problem 1.3.7 (Problem 7)**.** (*5 points*) Find the maximum possible value of

$$\left(\frac{a^3}{b^2c} + \frac{b^3}{c^2a} + \frac{c^3}{a^2b}\right)^2$$

where a, b, and c are nonzero real numbers satisfying

$$a\sqrt[3]{\frac{a}{b}} + b\sqrt[3]{\frac{b}{c}} + c\sqrt[3]{\frac{c}{a}} = 0.$$

Solution.

$$\text{Let } x = a\sqrt[3]{\frac{a}{b}},\ y = b\sqrt[3]{\frac{b}{c}},\ z = c\sqrt[3]{\frac{c}{a}} \Rightarrow x + y + z = 0$$

$$x^3 + y^3 + z^3 - 3xyz = (x+y+z)(x^2+y^2+z^2-xy-yz-zx) = 3xyz$$

$$x^3 = \left(a\sqrt[3]{\frac{a}{b}}\right)^3 = (a^3)\left(\frac{a}{b}\right) = (abc)\left(\frac{a^3}{b^2c}\right), y^3 = (abc)\left(\frac{b^3}{c^2a}\right), z^3 = (abc)\left(\frac{c^3}{a^2b}\right)$$

$$\Rightarrow x^3 + y^3 + z^3 = (abc)\left(\frac{a^3}{b^2c} + \frac{b^3}{c^2a} + \frac{c^3}{a^2b}\right),\ 3xyz = 3a\sqrt[3]{\frac{a}{b}} \cdot b\sqrt[3]{\frac{b}{c}} \cdot c\sqrt[3]{\frac{c}{a}} = 3abc$$

$$\Rightarrow \left(\frac{a^3}{b^2c} + \frac{b^3}{c^2a} + \frac{c^3}{a^2b}\right)^2 = \left(\frac{x^3+y^3+z^3}{abc}\right)^2 = \left(\frac{3xyz}{abc}\right)^2 = \left(\frac{3abc}{abc}\right)^2 = \boxed{9.}$$

□

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Problem 1.3.8 (Problem 8)**.** (*5 points*) The following diagram shows four vertices connected by six edges. Suppose that each of the edges is randomly painted either red, white, or blue. The probability that the three edges adjacent to at least one vertex are colored with all three colors is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m+n$.

Solution. There are six edges in the diagrams, and there are 3 equally likely ways to paint each edge. Thus, there are 3^6 equally likely ways to paint all the edges.

To count the number of ways to paint the edges so that at least one vertex is adjacent to one edge of each colour, number the vertices 1, 2, 3, and 4 and let A_1, A_2, A_3, and A_4 be the sets of colouring patterns, where each of the vertices 1, 2, 3, and 4, respectively, is adjacent to edges of all three colours. Then, the number of colouring patterns in $A_1 \cup A_2 \cup A_3 \cup A_4$ is the number of ways to colouring the edges such that at least one vertex are colored with all three colors.

There are $3! = 6$ ways to paint the 3 edges adjacent to a particular vertex so that there is one edge of each colour, and there are 3^3 ways to paint the other three edges showing that for each j, the cardinality of A_j is $6 \cdot 3^3$.

A pattern is in $A_j \cap A_k$, for $j \neq k$ if the edges adjacent to vertex j are painted in one of 6 ways, the two edges adjacent to vertex k not adjacent to vertex j are painted in one of 2 ways, and the one edge not adjacent to either vertex j or vertex k is painted in one of 3 ways. This shows that $A_j \cap A_k$ containing $6 \cdot 2 \cdot 3 = 36$ patterns. This is true for all $\binom{4}{2} = 6$ pairs of j and k.

To obtain a pattern in $A_i \cap A_j \cap A_k$ for distinct i, j, and k, the edges adjacent to vertex i can be painted in one of 6 ways, then there is only one way to paint the edge between vertex j and vertex k, and this fixes how all the other edges must be painted, so there are only 6 patterns in $A_i \cap A_j \cap A_k$ for each of the $\binom{4}{3} = 4$ choices of i, j, k.

Similarly, there are 6 patterns in $A_1 \cap A_2 \cap A_3 \cap A_4$.

By the Inclusion - Exclusion Principle then the number of colouring patterns in $A_1 \cup A_2 \cup A_3 \cup A_4$ is:

$$\begin{aligned}
|A_1 \cup A_2 \cup A_3 \cup A_4| &= |A_1| + |A_2| + |A_3| + |A_4| \\
&\quad - |A_1 \cap A_2| - |A_1 \cap A_3| - |A_1 \cap A_4| - |A_2 \cap A_3| - |A_2 \cap A_4| - |A_3 \cap A_4| \\
&\quad + |A_1 \cap A_2 \cap A_3| + |A_1 \cap A_2 \cap A_4| + |A_1 \cap A_3 \cap A_4| + |A_2 \cap A_3 \cap A_4| \\
&\quad - |A_1 \cap A_2 \cap A_3 \cap A_4| \\
&= 4(6 \cdot 3^3) - 6(6 \cdot 2 \cdot 3) + 4 \cdot 6 - 6 = 6 \cdot 75
\end{aligned}$$

The required probability is $\dfrac{6 \cdot 75}{3^6} = \frac{50}{81}$. Hence, $m + n = 50 + 81 = \boxed{131.}$ □

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Problem 1.3.9 (Problem 9)**.** (*5 points*) In isosceles $\triangle ABC, AB = AC, \angle BAC$ is obtuse, and points E and F lie on sides AB and AC, respectively, so that $AE = 10, AF = 15$. The area of $\triangle AEF$ is 60, and the area of quadrilateral $BEFC$ is 102. Find BC.

Solution. Keep in mind that $\angle BAC > 90°$, so $\cos(\angle BAC) < 0$,

$$60 = [AEF] = \frac{1}{2}(AE \cdot AF)\sin(\angle EAF) = \frac{1}{2}(10 \cdot 15)\sin(\angle EAF) \Rightarrow \sin(\angle EAF) = \frac{4}{5}$$

$$[AEF] + [BEFC] = [ABC] = \frac{1}{2}(AB \cdot AC)\sin(\angle BAC) = \frac{1}{2}(AB^2)\frac{4}{5} \Rightarrow AB^2 = \frac{162 \cdot 2 \cdot 5}{4} = 405$$

$$BC^2 = AB^2 + AC^2 - 2(AB \cdot AC)\cos(\angle BAC) = 405(2)(1 - \cos(\angle BAC)) = 405(2)\left(1 + \frac{3}{5}\right) = 1296 = 36^2.$$

Hence, $BC = \boxed{36.}$ □

Problem 1.3.10 (Problem 10)**.** (*5 points*) Find the least prime number greater than 1000 that divides $2^{1010} \cdot 23^{2020} + 1$.

Solution. First, let $n = 2^{1010} \cdot 23^{2020}$, then

$$n = 2^{1010} \cdot 23^{2020} + 1 = (4 \cdot 23^4)^{505} + 1 \Rightarrow 4 \cdot 23^4 + 1 \mid n.$$

By Sophie Germain identity $a^4 + 4b^4 = (a^2 + 2b^2 - 2ab)(a^2 + 2b^2 + 2ab)$ for $a = 1, b = 23$,

$$4 \cdot 23^4 + 1 = (1 + 2 \cdot 23^2 - 2 \cdot 23)(1 + 2 \cdot 23^2 + 2 \cdot 23) = 1013 \cdot 1105 = 5 \cdot 13 \cdot 17 \cdot 1013.$$

Now, since $7 \mid 1001, 17 \mid 1003, 19 \mid 1007, 3 \mid 1011$, thus the only prime number larger than 1000 and less than 1013 is 1009. We shall prove that it is not a factor of n,

By Fermat's Little Theorem:

$$2^{1010} \equiv 2^2 \pmod{1009},\ 23^{2020} \equiv 23^4 \pmod{1009} \Rightarrow n \equiv 4 \cdot 23^4 + 1 \pmod{1009}.$$

From the factorization of $4 \cdot 23^4 + 1$ shown above, $1009 \nmid n$, hence the required prime is $\boxed{1013.}$ □

Problem 1.3.11 (Problem 11)**.** (*5 points*) Find the maximum possible value of

$$9\sqrt{x} + 8\sqrt{y} + 5\sqrt{z},$$

where x, y, and z are positive real numbers satisfying $9x + 4y + z = 128$.

Solution. By the Cauchy-Schwarz inequality,

$$9\sqrt{x} + 8\sqrt{y} + 5\sqrt{z} = (3)(\sqrt{9x}) + (4)(\sqrt{4y}) + (5)(\sqrt{z}) \leq \sqrt{(3^2 + 4^2 + 5^2)(9x + 4y + z)} = \sqrt{50 \cdot 128} = \boxed{80.}$$

□

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Problem 1.3.12 (Problem 12)**.** (*5 points*) Two congruent equilateral triangles $\triangle ABC$ and $\triangle DEF$ lie on the same side of line BC so that B, C, E, and F are collinear as shown. A line intersects AB, AC, DE, and EF at W, X, Y, and Z, respectively, such that $\dfrac{AW}{BW} = \frac{2}{9}$, $\dfrac{AX}{CX} = \frac{5}{6}$, and $\dfrac{DY}{EY} = \frac{9}{2}$. The ratio $\dfrac{EZ}{FZ}$ can then be written as $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. Without loss of generality, let the triangles have side length 11, so

$$AW = 2, BW = 9, AX = 5, CX = 6, DY = 9, EY = 2.$$

Let G be the intersection of lines AC and DE, then $\triangle AWX \sim GYX$, so

$$\frac{GE + EY}{GC + CX} = \frac{GY}{GX} = \frac{AW}{AX} = \frac{2}{5} \Rightarrow \frac{GE + 2}{GC + 6} = \frac{2}{5} \Rightarrow GC = GE = \frac{2}{3}.$$

By Menelaus' Theorem,

$$1 = \frac{AW}{BW} \cdot \frac{BZ}{CZ} \cdot \frac{CX}{AX} = \frac{2}{9} \cdot \frac{11 + CZ}{CZ} \cdot \frac{6}{5} \Rightarrow CZ = 4.$$
$$EZ = 4 - CE = 4 - \frac{2}{3} = \frac{10}{3} \Rightarrow \frac{EZ}{FZ} = \frac{\frac{10}{3}}{11 - \frac{10}{3}} = \frac{10}{23}$$

Thus the desired sum $m + n = 10 + 23 = \boxed{33.}$ $\square$

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Problem 1.3.13 (Problem 13)**.** (*5 points*) Find the number of permutations of the letters AAAABBBCC where no letter is next to another letter of the same type. For example, count ABCABCABA and ABABCABCA but not ABCCBABAA.

Solution. Let first consider the letters AAAABBB. There are three cases that could lead to permutations with no repeated letters.

Case 1: there is 1 permutation of As and Bs such that no two like letters are next to each other: $ABABABA$. For these, there are 8 positions around the 7 letters to place the two letters C, thus there are $\binom{8}{2} = 28$ ways to choose two distinct positions for Cs. Thus, in total, there are $1 \cdot 28 = 28$ ways for this case.

Case 2: there is 6 permutations of As and Bs that have one pair of like letters are adjacent. These are obtained by starting with $ABABABA$, removing the beginning or ending A, then placing that A next to one of another A (there are two ways to *insert* right before of or right after it.) Into this permutation, a letter C must be used to insert in between the two neighbouring letters A. For the second letter C there are $9 - 2 = 7$ positions not immediately next to the first letter C. Thus, in total, there are $6 \cdot 7 = 42$ ways for this case.

Case 3: there is 9 permutations of As and Bs such that there are two set of like letters adjacent.

- There are 2 permutations where three letters A appear together: $BAAABAB$ and $BABAAAB$.
- There is 1 permutations where four letters A appear in pairs: $BAABAAB$.
- There are 6 permutations where there is a pair of adjacent letters A and a pair of adjacent letters B:

$$AABBABA,\ AABABBA,\ ABBAABA,\ ABAABBA,\ ABBABAA,\ ABABBAA.$$

Into each of these permutation, two letter C must be used to insert in between the two neighbouring like letters. Thus, in total, there are $(2 + 1 + 6) \cdot 1 = 9$ ways for this case.

Therefore, altogether, there are $28 + 42 + 9 = \boxed{79}$ permutations. □

Problem 1.3.14 (Problem 14)**.** (*5 points*) There is a real number x between 0 and $\dfrac{\pi}{2}$ such that

$$\frac{\sin^3 x + \cos^3 x}{\sin^5 x + \cos^5 x} = \frac{12}{11}$$

and $\sin x + \cos x = \frac{\sqrt{m}}{n}$, where m and n are positive integers and n is not divisible by the square of any prime. Find $m + n$.

Solution. Let $u = \sin(x), v = \cos(x)$, then $\sin^3 x + \cos^3 x = u^3 + v^3, \sin^5 x + \cos^5 x = u^5 + v^5$, and $u^2 + v^2 = 1$, furthermore

$$\begin{aligned}
&u^3 + v^3 = (u + v)(u^2 - uv + v^2) = (u + v)(1 - uv)\\
&u^5 + v^5 = (u + v)(u^4 - u^3v + u^2v^2 + uv^3 + u^4) = (u + v)((u^2 + v^2)^2 - u^2v^2 - uv(u^2 + v^2))\\
&= (u + v)(1 - uv - u^2u^2)
\end{aligned}$$

Now, let $s = u + v$, then $uv = \frac{s^2-1}{2}$, therefore

$$\begin{aligned}
&\frac{12}{11} = \frac{\sin^3 x + \cos^3 x}{\sin^5 x + \cos^5 x} = \frac{s\left(1 - \frac{s^2-1}{2}\right)}{s\left(1 - \frac{s^2-1}{2} - \left(\frac{s^2-1}{2}\right)^2\right)} = \frac{2(3 - s^2)}{5 - s^4}\\
&\Rightarrow 6s^4 - 11s^2 + 3 = 0 \Rightarrow s^2 = \frac{3}{2} \text{ or } \frac{1}{2}.
\end{aligned}$$

Since $0 \le x \le \frac{\pi}{2}$, so $u, v \ge 0$, thus $s^2 = 1 + 2uv \ge 1$, therefore $s^2 = \frac{3}{2} \Rightarrow s = \frac{\sqrt{6}}{2}$. Hence, the desired sum $m + n = 6 + 2 = \boxed{8.}$ □

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Problem 1.3.15 (Problem 15)**.** (*5 points*) Points E and F lie on diagonal AC of square $ABCD$ with side length 24, such that $AE = CF = 3\sqrt{2}$. An ellipse with foci at E and F is tangent to the sides of the square. Find the sum of the distances from any point on the ellipse to the two foci.

Hint: Let P be the tangent point on AB. By the properties of the eclipse, a light ray passing from E to P that reflects of the eclipse will pass through point F. Because line AB is tangent to the eclipse, $\angle EPA = \angle FPB$.

Solution. Let P be the tangent point on AB. By the properties of the eclipse, a light ray passing from E to P that reflects of the eclipse will pass through point F. Because line AB is tangent to the eclipse, $\angle EPA = \angle FPB$. Let points G and H be the projections onto AB of points E and F, respectively. Then $\triangle EGP \sim \triangle FHP$,

$$AE = CF = 3\sqrt{2}, \angle CAB = 45^\circ \Rightarrow AG = BH = 3, FH = 24 - 3 = 21, GH = 24 - 2 \cdot 3 = 18$$
$$\frac{PG}{PH} = \frac{EG}{FH} = \frac{3}{21} = \frac{1}{7} \Rightarrow PG = GH \cdot \frac{PG}{PG + PH} = 18 \cdot \frac{PG}{PG + 7PG} = \frac{9}{4}$$
$$EP = \sqrt{EG^2 + PG^2} = \sqrt{3^2 + \left(\frac{9}{4}\right)^2} = \frac{15}{4}$$
$$FP = 7EP \Rightarrow EP + FP = 8EP = \boxed{30.}$$

□

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Problem 1.3.16 (Problem 16)**.** (*5 points*) A deck of eight cards has cards numbered $1, 2, 3, 4, 5, 6, 7, 8$, in that order, and a deck of five cards has cards numbered $1, 2, 3, 4, 5$, in that order. The two decks are riffle-shuffled together to form a deck with 13 cards with the cards from each deck in the same order as they were originally. Thus, numbers on the cards might end up in the order 1122334455678 or 1234512345678 but not 1223144553678. Find the number of possible sequences of the 13 numbers.

Solution. There is a one-on-one correspondence between possible orderings and the paths of length 13 in the coordinate plane from $(0, 0)$ to $(8, 5)$ where each step from point (x, y) is one unit to the right to $(x + 1, y)$ or one unit up to $(x, y + 1)$, and there is no point (x, y) on the path where $y > x$.

Indeed, given a possible ordering, construct a path by reading the numbers in order, and each time a number is seen for the first time, have the path take one step right (R), and each time a number is seen for the second time, have the path take one step up (U). This process take every possible number sequence and convert it into a path of the correct type, and the process is reversible showing that this correspondence is one-to-one.

It remains to count the number of paths from $(0, 0)$ to (8.5) that make unit steps to the right or upward that avoid points with $y > x$. Each such path make 8 steps right and 5 steps upward in some order.

Suppose one of these paths crosses a point (x, y) with $y > x$. For example the path $RURRUUURRURRR$ reaches $(3, 4)$ after making the steps $RURRUUU$. If, after this points all U steps are changed to R steps and all R steps are changed to U steps, the path become $RURUUUURUUU$ which ends up at $(4, 9)$.

In fact, if any path from $(0, 0)$ to $(8, 5)$ that reaches a point $(x.y)$ where $y > x$ is transformed by interchanging subsequent steps U and R, the path will reach the point $(4, 9)$ instead of point $(8, 5)$. The number of paths from $(0, 0)$ to $(4, 9)$ is $\binom{4+9}{4} = \binom{13}{4}$. This shows that the number of paths to $(8, 5)$ that do not contain point (x, y) with $y > x$ is:

$$\binom{5+8}{5} - \binom{4+9}{4} = \boxed{572.}$$

□

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Problem 1.3.17 (Problem 17)**.** (*5 points*) In $\triangle ABC$, $\angle A = 52°$, and $\angle B = 57°$. One circle centred at D passes through the points B, C, and the incenter I of $\triangle ABC$, and a second circle centred at E passes through the points A, C, and the circumcenter O of $\triangle ABC$. Find the degree measure of the acute angle at which the two circles intersect.

Hint: find the measure of the complementary angle of the angle $\angle DCE$.

Solution. First $\angle C = 180° - \angle A - \angle B = 71°$. Furthermore

$$\widehat{BI} = 2\angle BCI = \angle ACB,\ \widehat{CI} = 2\angle CBI = \angle ABC \Rightarrow \angle BDC = \widehat{BC} = \widehat{BI} + \widehat{CI} = \angle ACB + \angle ABC.$$

Since $\triangle BDC$ isosceles, in circle ω_1,

$$\angle BCD = \frac{1}{2}(180° - \angle BDC) = \frac{1}{2}(180° - \angle ACB + \angle ABC) = \frac{1}{2}\angle BAC.$$

On the other hand, in circle $O, \angle AOC = 2\angle AB$, so in circle ω_2,

$$\text{(major) } \widehat{AC} = 2\angle AOC = 4\angle ABC \Rightarrow \angle AEC = 360° - \widehat{AC} = 360° - 4\angle ABC.$$

Since $\triangle AEC$ is isosceles, in circle ω_2,

$$\angle ACE = \frac{1}{2}(180° - \angle AEC) = 2\angle ABC - 90°.$$

The diagram at the right shows both circles ω_1 and ω_2. Because the line tangent to a circle is perpendicular to the radius of the circle that ends at the point of tangency, it follows that the two circles intersect at an angle θ which satisfies $\angle DCE = 180° - \theta$, thus,

$$\theta = 180° - \angle DCE = 180° - (\angle BCD + \angle ACB + \angle ACE) = 180° - \left(\frac{1}{2}\angle BAC + \angle ACB + 2\angle ABC - 90°\right)$$

$$= 270° - (\frac{1}{2}52° + 71° + 2 \cdot 57°) = \boxed{59°.}$$

□

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Problem 1.3.18 (Problem 18)**.** (*5 points*) Three doctors, four nurses, and three patients stand in a line in random order. The probability that there is at least one doctor and at least one nurse between each pair of patients is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m+n$.

Solution. The required probability is equal to the probability that if the ten letters $DDDNNNNPPP$ are arranged in random order, then there is at least one D and one N between each pair of Ps. There are

$$\binom{10}{3,4,3} = \frac{10!}{3!4!3!}$$

equally likely ways to arrange the ten letters.

Consider first the possible arrangements of the Ps and Ds that result in at least one D between each pair of Ps. There are four possible arrangements:

$$DPDPDP, PDDPDP, PDPDDP, \text{ and } PDPDPD.$$

Now consider how many ways four Ns can be inserted into one of these lists of six letters.

Without regard to whether there are Ns between each pair of Ps, the number of ways of inserting four Ns into a sequence of six other letters is given by the sticks-and-stones technique as $\binom{4+6}{6} = 210$.

Let X be the set of such arrangements that leave no Ns between the first P and second P, and let Y be the set of such arrangements that leave no Ns between the second P and the third P.

There are now four cases to consider.

Case 1: In the case of inserting four Ns into $DPDPDP$, the sizes of X, Y, and $X \cap Y$ are given by

$$\binom{4+4}{4} = 70, \ \binom{4+4}{4} = 70, \ \binom{4+2}{2} = 15, \text{ respectively.}$$

Thus, by the Inclusion/Exclusion Principle, there are $70 + 70 - 15 = 125$ ways to insert four Ns into the sequence and not have at least one N between each pair of Ps. In each of these two cases there are, therefore, $210 - 125 = 85$ ways of inserting four Ns so that there is at least one N between each pair of Ps.

Case 2: There are also 85 arrangements associated with inserting four Ns into $PDPDPD$.

Case 3: In the case of inserting four Ns into $PDDPDP$, the sizes of X, Y, and $X \cap Y$ are given by

$$\binom{4+3}{3} = 35, \ \binom{4+4}{4} = 70, \ \binom{4+1}{1} = 5, \text{ respectively.}$$

Thus, by the Inclusion/Exclusion Principle, there are $435 + 70 - 5 = 100$ ways to insert four Ns into the sequence and not have at least one N between each pair of Ps. In each of these two cases there are, therefore, $210 - 100 = 110$ ways of inserting four Ns so that there is at least one N between each pair of Ps.

Case 4: There are also 110 arrangements associated with inserting four Ns into $PDPDDP$.

Thus, there are $2(85 + 110) = 390$ arrangements of the ten letters so that there is at least one D and one N between each pair of Ps. The required probability is

$$\frac{390}{\frac{10!}{3!4!3!}} = \frac{13}{140}.$$

Hence, the desired sum is $13 + 140 = \boxed{153.}$ □

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Problem 1.3.19 (Problem 19)**.** (*5 points*) Let p, q, and r be prime numbers such that $2pqr+p+q+r = 2020$. Find $pq + qr + rp$.

Solution. Note that $p + q + r = 2020 - 2pqr$, thus it is even, so at least one prime is even. WLOG, let $p = 2$.

$$4qr + q + r = 2018 \Rightarrow (4q + 1)(4r + 1) = 4 \cdot 2018 + 1 = 8073 = 3^3 \cdot 13 \cdot 23.$$

Thus, 8073 has 16 divisors. We are looking for those divisors in the form of $4k + 1$ and they are $1, 9, 13, 3 \cdot 23 = 69$. Easy to test and verify that the pair q, r is $17, 29$.

Hence, the desired sum is $pq + qr + rp = 2 \cdot 17 + 17 \cdot 29 + 29 \cdot 2 = \boxed{585.}$ □

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1.4 High School - Test

High school students: grade 9 (US, CA), grade 10 (FR, UK, VN) and above.

You have **30 minutes** to complete the test. You have to **submit only the answers**. No solution is required.

Note that you have to **follow the instructions by the COs** *for submitting the answers.*

- **Intermediate (I) level: Problems 1-10**
- **Advanced (A) level: Problems 4-13**
- **Olympiad (O) level: Problems 10-19**

If you submit solution based on coding, please make sure that your submission is compliant. Read the introduction chapter for more information.

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Problem 1.4.1 (Problem 1)**.** (*5 points*) There is a complex number K such that the quadratic polynomial $5x^2 + Kx + 4 - 3i$ has exactly one root, where $i = \sqrt{-1}$. Find $|K|^2$.

Note that for a complex number $x = a + bi$, $|x|$ denotes the absolute value of x and $|x| = \sqrt{a^2 + b^2}$.

Solution. A quadratic polynomial has exactly one root if and only if its determinant is zero, therefore for $5x^2 + Kx + 4 - 3i$, we have:

$$K^2 - 4(5)(4 - 3i) = 0 \Rightarrow K^2 = (4 \cdot 5 \cdot 4) - (4 \cdot 5 \cdot 3)i.$$

Note that for a complex number $K = a + bi$, then

$$|K| = \sqrt{a^2 + b^2} \text{ and } K^2 = (a + bi)(a + bi) = a^2 - b^2 + 2abi, \text{ note that}$$
$$(a^2 - b^2)^2 + (2ab)^2 = (a^2 + b^2)^2 \Rightarrow |K|^2 = a^2 + b^2 = \sqrt{(a^2 - b^2)^2 + (2ab)^2} = |K^2|$$

Hence, $|K|^2 = |K^2| = \sqrt{(4 \cdot 5 \cdot 4)^2 + (4 \cdot 5 \cdot 3)^2} = 20\sqrt{4^2 + 3^2} = 20 \cdot 5 = \boxed{100.}$. □

Problem 1.4.2 (Problem 2)**.** (*5 points*) Two circles have radius 25, and one circle has radius 14. Each circle is externally tangent to the other two circles, and each circle is internally tangent to two sides of an isosceles triangle, as shown. The sine of the base angle of the triangle is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. Let ω_1 be the circle with radius 10 with center F and ω_2 be one of the circles with radius 6 with center G. Let label the vertices of the triangles to be A, B, and C as shown in the diagram above. Let AD be the altitude from A to BC, E be the tangent point of the circles with radius 10, and H, I be the feet of the altitudes from F, G to AB, respectively. Let J be the foot of the altitudes from F to GJ.

Then

$$EG = 25, FG = 14 + 25 = 39 \Rightarrow EF = \sqrt{39^2 - 25^2} = \sqrt{896}$$
$$GJ = GI - IJ = GI - FH = 25 - 14 = 11 \Rightarrow FJ = \sqrt{39^2 - 11^2} = \sqrt{1400}$$
$$\sin(\angle ABC) = \cos(\angle BAD) = \cos(\angle JFE) = \cos(\angle JFG + \angle GFE)$$
$$= \cos(\angle JFG)\cos(\angle GFE) - \sin(\angle JFG)\sin(\angle GFE)$$
$$= \frac{FJ}{FG}\frac{FE}{FG} - \frac{GJ}{FG}\frac{EG}{FG} = \frac{\sqrt{1400} \cdot \sqrt{896} - 11 \cdot 25}{39^2} = \frac{5}{9}.$$

Hence, $m + n = 5 + 9 = \boxed{14.}$ □

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Problem 1.4.3 (Problem 3)**.** (*5 points*) There are three distinct pairs of positive integers $a_1 < b_1$, $a_2 < b_2$, and $a_3 < b_3$ such that

$$|(a_1 + ib_1)(b_1 - ia_1)| = |(a_2 + ib_2)(b_2 - ia_2)| = |(a_3 + ib_3)(b_3 - ia_3)| = 1025, \text{ where } i = \sqrt{-1}.$$

Find $a_1 + b_1 + a_2 + b_2 + a_3 + b_3$.

Note that for a complex number $x = a + bi$, $|x|$ denotes the absolute value of x and $|x| = \sqrt{a^2 + b^2}$.

Solution. Note that

$$(a_1 + ib_1)(b_1 - ia_1) = 2a_1b_1 + i(b_1^2 - a_1^2) \Rightarrow |(a_1 + ib_1)(b_1 - ia_1)| = \sqrt{(2a_1b_1)^2 + (b_1^2 - a_1^2)^2} = a_1^2 + b_1^2$$

Thus $a_1^2 + b_1^2 = 1025$. Since $1024 = 32^2$, by testing we can see that $(a_1, b_1) \in \{(1, 32), (8, 31), (20, 25)\}$.

Similarly for (a_2, b_2) and (a_3, b_3). By the given conditions they are distinct pairs, so they must be all these three pairs.

Hence, $a_1 + b_1 + a_2 + b_2 + a_3 + b_3 = 1 + 32 + 8 + 31 + 20 + 25 = \boxed{117.}$ □

Problem 1.4.4 (Problem 4)**.** (*5 points*) There are relatively prime positive integers s and t such that

$$\sum_{n=2}^{101} \left(\frac{n}{n^2 - 1} - \frac{1}{n} \right) = \frac{s}{t}.$$

Find $s + t$.

Solution. Note that

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

$$\sum_{n=2}^{101} \left(\frac{n}{n^2 - 1} - \frac{1}{n} \right) = \frac{1}{2}\sum_{n=2}^{101}\left(\frac{1}{n-1} - \frac{1}{n}\right) - \frac{1}{2}\sum_{n=2}^{101}\left(\frac{1}{n} - \frac{1}{n+1}\right) = \frac{1}{2}\left(\frac{1}{1} - \frac{1}{101}\right) - \frac{1}{2}\left(\frac{1}{2} - \frac{1}{102}\right) = \frac{2575}{10302}$$

Hence, $s + t = \boxed{12877.}$ □

Problem 1.4.5 (Problem 5)**.** (*5 points*) Let x be a real number such that $3\sin^4 x - 2\cos^6 x = \dfrac{17}{25}$. Then $3\cos^4 x - 2\sin^6 x = \dfrac{m}{n}$, where m and n are relatively prime positive integers. Find $10m + n$.

Solution.

$$\frac{17}{25} = 3\sin^4 x - 2\cos^6 x = 3\sin^4 x - 2(1 - \sin^2 x)^3 = 2\sin^6 x - 3\sin^4 x + 6\sin^2 x - 2$$
$$3\cos^4 x - 2\sin^6 x = 3(1 - \sin^2 x)^2 - 2\sin^6 x = 3 - 6\sin^2 x + 3\sin^4 x - 2\sin^6 x$$

Hence, $\dfrac{m}{n} = -\left(\dfrac{17}{25} + 2\right) + 3 = \frac{8}{25}$, so $10m + n = 80 + 25 = \boxed{105.}$ □

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Problem 1.4.6 (Problem 6)**.** (*5 points*) Find the sum of all values of x such that the set

$$\{108, 123, 128, 138, 153, x\} \text{ has a mean that is equal to its median.}$$

Solution. First, let's simplify the problem by subtracting 108 from each of the elements, then the statement still stands for the set $\{0, 15, 20, 30, 45, x-108\}$. Then, by dividing each of the elements by 5, it is the same assumption for the set $\{, y = \frac{x-108}{5}\}$. The mean of the set now is $\dfrac{0+3+4+6+9+y}{6} = \dfrac{22+y}{6}$.

Case 1: $y < 3$, then the median of the set is $\dfrac{3+4}{2} = \dfrac{7}{2}$, so $y = -1$.

Case 2: $3 \leq y \leq 6$, then the median of the set is $\dfrac{4+y}{2}$, so $y = 5$.

Case 3: $y < 6$, then the median of the set is $\dfrac{4+6}{2}$, so $y = 8$.

Hence, the sum of all values of x is

$$(-1 \cdot 5 + 108) + (5 \cdot 5 + 108) + (8 \cdot 5 + 108) = 103 + 133 + 148 = \boxed{384.}$$

□

Problem 1.4.7 (Problem 7)**.** (*5 points*) Find the **minimum** possible value of

$$\left(\frac{a^2}{b^3c^2} + \frac{b^2}{c^3a^2} + \frac{c^2}{a^3b^2}\right)^2$$

where $a > b > 0 > c$ are real numbers satisfying

$$a\sqrt[3]{\frac{a}{b}} + b\sqrt[3]{\frac{b}{c}} + c\sqrt[3]{\frac{c}{a}} = 0.$$

Solution.

$$\text{Let } x = a\sqrt[3]{\frac{a}{b}},\ y = b\sqrt[3]{\frac{b}{c}},\ z = c\sqrt[3]{\frac{c}{a}} \Rightarrow x + y + z = 0$$

$$x^3 + y^3 + z^3 - 3xyz = (x+y+z)(x^2+y^2+z^2-xy-yz-zx) = 3xyz$$

$$x^3 = \left(a\sqrt[3]{\frac{a}{b}}\right)^3 = (a^3)\left(\frac{a}{b}\right) = (abc)\left(\frac{a^3}{b^2c}\right), y^3 = (abc)\left(\frac{b^3}{c^2a}\right), z^3 = (abc)\left(\frac{c^3}{a^2b}\right)$$

$$\Rightarrow x^3 + y^3 + z^3 = (abc)\left(\frac{a^3}{b^2c} + \frac{b^3}{c^2a} + \frac{c^3}{a^2b}\right),\ 3xyz = 3a\sqrt[3]{\frac{a}{b}} \cdot b\sqrt[3]{\frac{b}{c}} \cdot c\sqrt[3]{\frac{c}{a}} = 3abc$$

$$\Rightarrow \left(\frac{a^3}{b^2c} + \frac{b^3}{c^2a} + \frac{c^3}{a^2b}\right)^2 = \left(\frac{x^3+y^3+z^3}{abc}\right)^2 = \left(\frac{3xyz}{abc}\right)^2 = \left(\frac{3abc}{abc}\right)^2 = \boxed{9.}$$

□

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Problem 1.4.8 (Problem 8)**.** (*5 points*) The following diagram shows four vertices connected by six edges. Suppose that each of the edges is randomly painted either red, white, or blue. The probability that the three edges adjacent to **at least two** vertices are colored with all three colors is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m+n$.

Solution. There are six edges in the diagrams, and there are 3 equally likely ways to paint each edge. Thus, there are 3^6 equally likely ways to paint all the edges.

To count the number of ways to paint the edges so that at least one vertex is adjacent to one edge of each colour, number the vertices 1, 2, 3, and 4 and let A_1, A_2, A_3, and A_4 be the sets of colouring patterns, where each of the vertices 1, 2, 3, and 4, respectively, is adjacent to edges of all three colours.

There are $3! = 6$ ways to paint the 3 edges adjacent to a particular vertex so that there is one edge of each colour, and there are 3^3 ways to paint the other three edges showing that for each j, the cardinality of A_j is $6 \cdot 3^3$.

A pattern is in $A_j \cap A_k$, for $j \neq k$ if the edges adjacent to vertex j are painted in one of 6 ways, the two edges adjacent to vertex k not adjacent to vertex j are painted in one of 2 ways, and the one edge not adjacent to either vertex j or vertex k is painted in one of 3 ways. This shows that $A_j \cap A_k$ containing $6 \cdot 2 \cdot 3 = 36$ patterns. This is true for all $\binom{4}{2} = 6$ pairs of j and k.

By the Inclusion - Exclusion Principle, the number of ways to colouring the edges such that *at least two vertices* are colored with all three colors is:

$$\begin{aligned}
&|A_1 \cap A_2| + |A_1 \cap A_3| + |A_1 \cap A_4| + |A_2 \cap A_3| + |A_2 \cap A_4| + |A_3 \cap A_4| \\
&- |A_1 \cap A_2 \cap A_3| - |A_1 \cap A_2 \cap A_4| - |A_1 \cap A_3 \cap A_4| - |A_2 \cap A_3 \cap A_4| \\
&+ |A_1 \cap A_2 \cap A_3 \cap A_4| \\
&= 6(6 \cdot 2 \cdot 3) - 4 \cdot 6 + 6 = 198
\end{aligned}$$

The required probability is $\dfrac{198}{3^6} = \frac{22}{81}$. Hence, $m + n = 22 + 81 = \boxed{103.}$ □

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Problem 1.4.9 (Problem 9)**.** (*5 points*) In isosceles $\triangle ABC, AB = AC, \angle BAC$ is obtuse, and points E and F lie on sides AB and AC, respectively, so that $AE = 20, AF = 30$. The area of $\triangle AEF$ is 240, and the area of quadrilateral $BEFC$ is 408. Find BC.

Solution. Keep in mind that $\angle BAC > 90°$, so $\cos(\angle BAC) < 0$,

$$240 = [AEF] = \frac{1}{2}(AE \cdot AF)\sin(\angle EAF) = \frac{1}{2}(20 \cdot 30)\sin(\angle EAF) \Rightarrow \sin(\angle EAF) = \frac{4}{5}$$
$$[AEF] + [BEFC] = [ABC] = \frac{1}{2}(AB \cdot AC)\sin(\angle BAC) = \frac{1}{2}(AB^2)\frac{4}{5} \Rightarrow AB^2 = \frac{648 \cdot 2 \cdot 5}{4} = 1620$$
$$BC^2 = AB^2 + AC^2 - 2(AB \cdot AC)\cos(\angle BAC) = 1620(2)(1 - \cos(\angle BAC)) = 1620(2)\left(1 + \frac{3}{5}\right) = 5184.$$

Hence, $BC = \sqrt{5184} = \boxed{72.}$ □

Problem 1.4.10 (Problem 10)**.** (*5 points*) Find the least prime number greater than 1000 that divides $2^{1010} \cdot 235^{2020} + 1$.

Solution. First, let $n = 2^{1010} \cdot 235^{2020}$, then

$$n = 2^{1010} \cdot 23^{2020} + 1 = (4 \cdot 235^4)^{505} + 1 \Rightarrow 4 \cdot 235^4 + 1 \mid n.$$

By Sophie Germain identity $a^4 + 4b^4 = (a^2 + 2b^2 - 2ab)(a^2 + 2b^2 + 2ab)$ for $a = 1, b = 235$,

$$4 \cdot 235^4 + 1 = (1 + 2 \cdot 235^2 - 2 \cdot 235)(1 + 2 \cdot 235^2 + 2 \cdot 235) = (109 \cdot 1009) \cdot (110921).$$

Now, since $7 \mid 1001, 17 \mid 1003, 5 \mid 1005, 19 \mid 1007$, thus $\boxed{1009}$ is the first prime number larger than 1000 that divides n. □

Problem 1.4.11 (Problem 11)**.** (*5 points*) Find the maximum possible value of

$$8\sqrt{x} + 9\sqrt{y} + 12\sqrt{z},$$

where x, y, and z are positive real numbers satisfying $4x + 9y + z = 256$.

Solution. By the Cauchy-Schwarz inequality,

$$8\sqrt{x}+9\sqrt{y}+12\sqrt{z} = (4)(\sqrt{4x})+(3)(\sqrt{9y})+(12)(\sqrt{z}) \leq \sqrt{(4^2 + 3^2 + 12^2)(4x + 9y + z)} = \sqrt{169 \cdot 256} = \boxed{208.}$$

□

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Problem 1.4.12 (Problem 12)**.** (*5 points*) Two congruent equilateral triangles $\triangle ABC$ and $\triangle DEF$ lie on the same side of line BC so that B, C, E, and F are collinear as shown. A line intersects AB, AC, DE, and EF at W, X, Y, and Z, respectively, such that $\dfrac{AW}{BW} = \frac{2}{9}$, $\dfrac{AX}{CX} = \frac{5}{6}$, and $\dfrac{DY}{EY} = \frac{9}{2}$. The ratio $\dfrac{XW}{XZ}$ can then be written as $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. Without loss of generality, let the triangles have side length 11, so

$$AW = 2, BW = 9, AX = 5, CX = 6, DY = 9, EY = 2.$$

Let G be the intersection of lines AC and DE, then $\triangle AWX \sim GYX$, so

$$\frac{GE + EY}{GC + CX} = \frac{GY}{GX} = \frac{AW}{AX} = \frac{2}{5} \Rightarrow \frac{GE + 2}{GC + 6} = \frac{2}{5} \Rightarrow GC = GE = \frac{2}{3}.$$

By Menelaus' Theorem for $\triangle ABC$ and line WXZ,

$$1 = \frac{AW}{BW} \cdot \frac{BZ}{CZ} \cdot \frac{CX}{AX} = \frac{2}{9} \cdot \frac{11 + CZ}{CZ} \cdot \frac{6}{5} \Rightarrow CZ = 4.$$

Again by Menelaus' Theorem for $\triangle BWZ$ and line AXC,

$$1 = \frac{BA}{AW} \cdot \frac{WX}{XZ} \cdot ZCCB = \frac{11}{2} \cdot \frac{WX}{XZ} \cdot \frac{4}{11} \Rightarrow \frac{WX}{XZ} = \frac{1}{2}.$$

Thus the desired sum $m + n = 1 + 2 = \boxed{3.}$ $\square$

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Problem 1.4.13 (Problem 13)**.** (*5 points*) Find the number of permutations of the letters AAABBCC where there are no two like letters adjacent. For example, count ABCABCA and ABABCAC but not ABCCBAA.

Solution. Let first consider the letters $AAABB$. There are three cases that could lead to permutations with no repeated letters.

Case 1: there is 1 permutation of As and Bs such that no two like letters are next to each other: $ABABA$. For these, there are 6 positions around the 5 letters to place the two letters C, thus there are $\binom{6}{2} = 15$ ways to choose two distinct positions for Cs. Thus, in total, there are $1 \cdot 15 = 15$ ways for this case.

Case 2: there is 4 permutations of As and Bs that have one pair of like letters are adjacent. These are obtained by starting with $ABABA$, removing the beginning or ending A, then placing that A next to one of another A (there are two ways to *insert* right before of or right after it.) Into this permutation, a letter C must be used to insert in between the two neighbouring letters A. For the second letter C there are $7 - 2 = 5$ positions not immediately next to the first letter C. Thus, in total, there are $4 \cdot 5 = 20$ ways for this case.

Case 3: there is 9 permutations of As and Bs such that there are two set of like letters adjacent.

- There are 1 permutations where three letters A appear together: $BAAAB$.
- There are 2 permutations where there is a pair of adjacent letters A and a pair of adjacent letters B:

$$AABBA, \ ABBAA.$$

Into each of these permutation, two letter C must be used to insert in between the two neighbouring like letters. Thus, in total, there are $(1 + 2) \cdot 1 = 3$ ways for this case.

Therefore, altogether, there are $15 + 20 + 3 = \boxed{38}$ permutations. □

Problem 1.4.14 (Problem 14)**.** (*5 points*) There is a real number x between 0 and $\dfrac{\pi}{2}$ such that

$$\frac{\sin^3 x + \cos^3 x}{\sin^5 x + \cos^5 x} = \frac{20}{19}$$

and $\sin x + \cos x = \frac{\sqrt{m}}{n}$, where m and n are positive integers and n is not divisible by the square of any prime. Find $m + n$.

Solution. Let $u = \sin(x), v = \cos(x)$, then $\sin^3 x + \cos^3 x = u^3 + v^3, \sin^5 x + \cos^5 x = u^5 + v^5$, and $u^2 + v^2 = 1$, furthermore

$$\begin{aligned}
&u^3 + v^3 = (u + v)(u^2 - uv + v^2) = (u + v)(1 - uv) \\
&u^5 + v^5 = (u + v)(u^4 - u^3v + u^2v^2 + uv^3 + u^4) = (u + v)((u^2 + v^2)^2 - u^2v^2 - uv(u^2 + v^2)) \\
&= (u + v)(1 - uv - u^2u^2)
\end{aligned}$$

Now, let $s = u + v$, then $uv = \frac{s^2-1}{2}$, therefore

$$\begin{aligned}
&\frac{20}{19} = \frac{\sin^3 x + \cos^3 x}{\sin^5 x + \cos^5 x} = \frac{s\left(1 - \frac{s^2-1}{2}\right)}{s\left(1 - \frac{s^2-1}{2} - \left(\frac{s^2-1}{2}\right)^2\right)} = \frac{2(3 - s^2)}{5 - s^4} \\
&\Rightarrow 10s^4 - 19s^2 + 7 = 0 \Rightarrow s^2 = \frac{7}{5} \text{ or } \frac{1}{2}.
\end{aligned}$$

Since $0 \le x \le \frac{\pi}{2}$, so $u, v \ge 0$, thus $s^2 = 1 + 2uv \ge 1$, therefore $s^2 = \frac{7}{5} \Rightarrow s = \frac{\sqrt{35}}{5}$. Hence, the desired sum $m + n = 35 + 5 = \boxed{40.}$ □

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Problem 1.4.15 (Problem 15)**.** (*5 points*) Points E and F lie on diagonal AC of square $ABCD$ with side length 24, such that $AE = CF = 3\sqrt{2}$. An ellipse with foci at E and F is tangent to the sides of the square. Let P be the tangent point of the eclipse with AB. Let points G and H be the projections onto AB of points E and F, respectively. Let $\frac{m}{n}$ be the value of $\cos EPF$, where m and n are relatively prime positive integers. Find $m + n$.

Hint: By the properties of the eclipse, a light ray passing from E to P that reflects of the eclipse will pass through point F. Because line AB is tangent to the eclipse, $\angle EPA = \angle FPB$.

Solution. Then $\triangle EGP \sim \triangle FHP$,

$$AE = CF = 3\sqrt{2}, \angle CAB = 45^\circ \Rightarrow AG = BH = 3, FH = 24 - 3 = 21, GH = 24 - 2 \cdot 3 = 18$$

$$\frac{PG}{PH} = \frac{EG}{FH} = \frac{3}{21} = \frac{1}{7} \Rightarrow PG = GH \cdot \frac{PG}{PG + PH} = 18 \cdot \frac{PG}{PG + 7PG} = \frac{9}{4}$$

$$EP = \sqrt{EG^2 + PG^2} = \sqrt{3^2 + \left(\frac{9}{4}\right)^2} = \frac{15}{4}, FP = 7EP = 7\left(\frac{15}{4}\right)$$

$$EF^2 = EP^2 + PF^2 - 2(EP \cdot PF)\cos(\angle EPF) \Leftrightarrow 648 = 50\left(\frac{15}{4}\right)^2 - 14\left(\frac{15}{4}\right)^2 \cos(\angle EPF)$$

$$\Leftrightarrow 648 = \left(\frac{15}{4}\right)^2 (50 - 14\cos(\angle EPF)) \Rightarrow \cos(\angle EPF) = \frac{1}{14}\left(50 - \frac{18^2 \cdot 2 \cdot 4^2}{15^2}\right) = \frac{7}{25}.$$

Hence, $m + n = 7 + 25 = \boxed{32.}$ □

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Problem 1.4.16 (Problem 16)**.** (*5 points*) A deck of eight cards has cards numbered $1, 2, 3, 4, 5, 6, 7$, in that order, and a deck of five cards has cards numbered $1, 2, 3, 4, 5, 6$ in that order. The two decks are riffle-shuffled together to form a deck with 13 cards with the cards from each deck in the same order as they were originally. Thus, numbers on the cards might end up in the order 1122334455667 or 1234561234567 but not 1223144553667. Find the number of possible sequences of the 13 numbers.

Solution. We show a coding solution. The 13-element *sequence* array is the one that holds a valid sequence. We use 7 loops, each to identify the indexes of the number $1, 2, 3, 4, 5, 6, 7$, when put them into the *sequence*. As you might see, we use the for loops in away that

$$0 \leq i_1 < i_2 < \ldots < i_7 \leq 12.$$

The indexes and the number $1, 2, 3, 4, 5, 6, 7$ are held temporarily in a dictionary d :

```
d = {i0: 1, i1:2, i2: 3, i3:4, i4: 5, i5: 6, i6:7}   # Python dictionary
```

Now, we go through a loop to fill the 13-element *sequence* array with the numbers $1, 2, 3, 4, 5, 6, 7$ by using the dictionary d, the rest of the positions in the array is filled with the numbers $1, 2, 3, 4, 5, 6$ whenever we find an empty slot

```
c = 1
for i in range(0, 13):
    if i in d:  # find an index that is mapped to a number in the dictionary
        sequence[i] = d[i]
    else:   # the dictionary does not has such index, fill it with the current number from 1, 2, 3, 4, 5, 6
        sequence[i] = c
        c += 1
```

Once the sequence is generated correctly, then we put it into the set *all_sequences* containing all strings representing the sequences. Because it is a set, *all_sequences* does not contain duplicates can will hold correctly the number of found sequences.

```
sequence = [None for i in range(0, 13)]
all_sequences = set()
for i0 in range(0, 6):
    for i1 in range(i0+1, 7):
        for i2 in range(i1+1, 8):
            for i3 in range(i2+1, 9):
                for i4 in range(i3+1, 10):
                    for i5 in range(i4+1, 11):
                        for i6 in range(i5+1, 12):
                            d = {i0: 1, i1:2, i2: 3, i3:4, i4: 5, i5: 6, i6:7}
                            c = 1
                            for i in range(0, 13):
                                if i in d:
                                    sequence[i] = d[i]
                                else:
                                    sequence[i] = c
                                    c += 1
                            all_sequences.add(''.join(str(e) for e in sequence))
print(len(all_sequences))
```

The answer is $\boxed{297.}$ □

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Problem 1.4.17 (Problem 17)**.** (*5 points*) In $\triangle ABC$, $\angle A = 50°$, and $\angle B = 59°$. One circle centred at D passes through the points B, C, and the incenter I of $\triangle ABC$, and a second circle centred at E passes through the points A, C, and the circumcenter O of $\triangle ABC$. Find the degree measure of the acute angle at which the two circles intersect.

Hint: find the measure of the complementary angle of the angle $\angle DCE$.

Solution. First $\angle C = 180° - \angle A - \angle B = 71°$. Furthermore

$$\widehat{BI} = 2\angle BCI = \angle ACB,\ \widehat{CI} = 2\angle CBI = \angle ABC \Rightarrow \angle BDC = \widehat{BC} = \widehat{BI} + \widehat{CI} = \angle ACB + \angle ABC.$$

Since $\triangle BDC$ isosceles, in circle ω_1,

$$\angle BCD = \frac{1}{2}(180° - \angle BDC) = \frac{1}{2}(180° - \angle ACB + \angle ABC) = \frac{1}{2}\angle BAC.$$

On the other hand, in circle $O, \angle AOC = 2\angle AB$, so in circle ω_2,

$$\text{(major) } \widehat{AC} = 2\angle AOC = 4\angle ABC \Rightarrow \angle AEC = 360° - \widehat{AC} = 360° - 4\angle ABC.$$

Since $\triangle AEC$ is isosceles, in circle ω_2,

$$\angle ACE = \frac{1}{2}(180° - \angle AEC) = 2\angle ABC - 90°.$$

Therefore

$$\angle ICO = \angle ACB - (\angle BCI + \angle ACO) = 180° - \left(\frac{1}{2}\angle BAC + \angle ACB + 2\angle ABC - 90°\right)$$
$$= 270° - (\frac{1}{2}50° + 71° + 2 \cdot 59°) = \boxed{56°.}$$

□

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Problem 1.4.18 (Problem 18)**.** (*5 points*) Three doctors, three nurses, and three patients stand in a line in random order. The probability that there is at least one doctor and at least one nurse between each pair of patients is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. We show a coding solution. The idea is to permute the given string 'DDDNNNPPP', then split it into smaller chunks, using the character P as a separator. The first and last chunks should be ignored. Then we verify if all chunks containing a D and an N letter.

```
from itertools import permutations
sequence = [e for e in 'DDDNNNPPP']
results = set()
for permutation in permutations(sequence):
    found = True
    chunks = (''.join(permutation)).split('P')
    chunks = chunks[1:-1] if len(chunks) == 4 else chunks[:-1] if permutation[0] ==
        'P' else chunks[1:]
    for s in chunks:
        if 'D' not in s or 'N' not in s:
            found = False
            break
    if found:
        results.add(''.join(permutation))
print(len(results))
```

The answer is $\boxed{114.}$ □

Problem 1.4.19 (Problem 19)**.** (*5 points*) Let p, q, and r be prime numbers such that $2pqr + p + q + r = 916$. Find $pq + qr + rp$.

Solution. Note that $p + q + r = 916 - 2pqr$, thus it is even, so at least one prime is even. WLOG, let $p = 2$.

$$4qr + q + r = 914 \Rightarrow (4q + 1)(4r + 1) = 4 \cdot 914 + 1 = 3657 = 3 \cdot 23 \cdot 53.$$

We are looking for pair of factors in the form of $4k + 1$ and they are $3 \cdot 23 = 69.$ and 53. Easy to test and verify that the pair q, r is $13, 17$.

Hence, the desired sum is $pq + qr + rp = 2 \cdot 13 + 13 \cdot 17 + 17 \cdot 2 = \boxed{281.}$ □

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Chapter 2

January Challenges

2.1 I-Level

For both middle school ang high school students. No solution based on coding is allowed.

Problem 2.1.1 (Problem 1)**.** (*10 points*) We divide an equilateral triangle with area 600 into two halves and then arrange them as shown below. Find the area of the $PQCR$.

Solution. First let a be the side length of the equilateral triangle, then $BC = \dfrac{a}{2}, AB = \dfrac{a\sqrt{3}}{2}$. Since $\angle EDC = \angle DCB$, so $\triangle QBC \sim \triangle CBA$, thus

$$\frac{[QBC]}{[CBA]} = \left(\frac{CB}{AB}\right)^2 = \left(\frac{1}{\sqrt{3}}\right)^2 = \frac{1}{3} \Rightarrow [QBC] = \frac{[CBA]}{3}.$$

Second, $\angle ECR = \angle PRC - \angle REC = \angle RAP + 90^\circ - 60^\circ = 60^\circ$. Thus $\triangle ECR$ is equilateral, and $RC = EC = CB = \frac{1}{2}AC$. because $RP \parallel CB$, so P is midpoint of AB, thus $[ARP] = \frac{1}{4}[ACB]$.

Therefore

$$[PQCR] = [ACB] - [ARP] - [QBC] = [ACB]\left(1 - \frac{1}{4} - \frac{1}{3}\right) = \frac{5}{12}[ACB] = \frac{5}{12}(300) = \boxed{125.}$$

□

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Problem 2.1.2 (Problem 2)**.** (*10 points*) Find all pairs of positive intergers (m, n) such that

$$1 \cdot 2 \cdots (m-1)(m) + 76 = n^2$$

Solution. For $m \geq 7$, we have that $1 \cdot 2 \cdots (m-1)(m) = m! \equiv 0 \pmod 7$, $m! + 76 \equiv 6 \pmod 7$. For any perfect square $n^2 \equiv 0, 1, 2, 4 \pmod 7$, so there is no solution for $m \geq 7$.

For $m \leq 7$, by testing $4! + 76 = 10^2, 5! + 76 = 14^2$, and there is no solution for other value of m. Hence the solutions are $\boxed{(4, 10), (5, 14).}$ □

Problem 2.1.3 (Problem 3)**.** (*10 points*) Eight black squares are place on the plane, see the diagram below on the left. Without moving any of them, four of the squares can be coloured white, so that they are divided into *two congruent sets of different coloured squares*: a set of four black squares and a set of four white squares, as show below. *Note that one set is the mirror image of the other.*

Now, 100 black squares are placed on the plane as shown below *(19 black squares in the* 10th *row.)*

In how many ways, without moving any of them, 50 of the squares can be can be coloured white, so that they are divided into two congruent sets of different coloured squares?

Solution. First, the bottom two corners are the only two tiles with one coordinate equal and the other differing by 18. Second, the only pairs in which both coordinates differ by 9 consists of the top corner and one of the bottom corners.

Now, suppose for a contradiction that a partition exists. By the Pigeonhole Principle, one set contains two of the three corners. By the two facts above, the other set cannot contain two tiles equivalently situated. □

Problem 2.1.4 (Problem 4)**.** (*10 points*) Let s be the sum of some integers, one of them has at least two digits. Two digits of one of the integers in s is chosen and they change places. The new sum is r. Which prime numbers 2, 3, 5, 7, 9, or 11 are always divisors of the difference $s - r$?

For example

$$s = 1 + 34 + 6 + 752 = 793,\ \underline{7}5\underline{2} \to \underline{2}5\underline{7} \Rightarrow r = 1 + 34 + 6 + 257 = 298 \Rightarrow s - r = 793 - 298 = 495.$$

Solution. First, since all different sums of integers are question, we can try a simple one to narrow down the possibility. Let $s = 21$, then $r = 12$ so $s - r = 9$. Thus the only possible primes are 3 and 9.

Now, for let n be the number in s whose two digits change their places:

$$n = \overline{\underbrace{\ldots a \ldots b}_{m}\underbrace{\ldots}_{n}} \to \overline{\underbrace{\ldots b \ldots a}_{m}\underbrace{\ldots}_{n}} \Rightarrow s - r = \overline{\underbrace{\ldots a \ldots b}_{m}\underbrace{\ldots}_{n}} - \overline{\underbrace{\ldots b \ldots a}_{m}\underbrace{\ldots}_{n}}$$

$$(a10^m + b10^n) - (b10^m + a10^n) = (10^m - 10^n)(a - b) = 10^n(9)(10^{m-n-1} + \cdots + 1).$$

Thus the difference is always divisible by $\boxed{3 \text{ and } 9.}$ □

2.2 A-Level

For both middle school ang high school students. No solution based on coding is allowed.

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2.3 O-Level

For both middle school ang high school students. No solution based on coding is allowed.

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Chapter 3

Entrance Tests

3.1 I-Level Entrance Test

For both middle school ang high school students. You are allowed to use books and calculator. No solution based on coding is allowed. No searching on the Internet for hints or solutions is permitted. **Full and detailed solution is required for every problem.**

Problem 3.1.1 (Problem 1)**.** (*10 points*) You are given a set of 10 positive integers. Summing nine of them in ten possible ways we get only nine different sums

$$86, 87, 88, 89, 90, 91, 93, 94, 95.$$

Find those numbers.

Solution. Let S be the sum of all ten positive integers and suppose x is the repeated sum. Call the elements $a_1, a_2, \ldots, a_10$, Then we have

$$S - a_1 = 86, S - a_2 = 87, \ldots, S - a_9 = 95, S - a_10 = x.$$

Adding these, $9S = 813 + x$. The only value of x from $86, 87, 88, \ldots, 95$ which makes $813 + x$ divisible by 9 is $x = 87$ and then $S = 100$. It follows that the ten numbers are respectively $\boxed{14, 13, 12, 11, 10, 9, 7, 6, 5, \text{ and } 13.}$ □

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Problem 3.1.2 (Problem 2)**.** (*10 points*) Replace the asterisks in the equilateral triangle by the numbers $1, 2, 3, 4, 5, 6, 7, 8, 9$ so that, starting from the second line, each number is equal to the absolute value of the difference of the nearest two numbers in the line above.

```
* * * * * * * * *
 * * * * * * * *
  * * * * * * *
   * * * * * *
    * * * * *
     * * * *
      * * *
       * *
        *
```

Note that: for this problem, submitting the equilateral triangle with all the asterisks replaced bu the number $1, 2, \ldots, 9$ *is considered as a solution. No additional explanation is required.*

Solution. Below is one of possible solutions.

```
1 7 8 1 9 8 1 7 6
 6 1 7 8 1 7 6 1
  5 6 1 7 6 1 5
   1 5 6 1 5 4
    4 1 5 4 1
     3 4 1 3
      1 3 2
       2 1
        1
```

□

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Problem 3.1.3 (Problem 3)**.** (*10 points*) In the diagram below, ABC is a right triangle, where $AB = 4, AC = 4$. Furthermore, each of the line segments $A_1B_1, A_2B_2, \ldots$ is perpendicular to AC, A_1 bisects segment AC, A_2 bisects segment A_1C, A_3 bisects segment A_2C, and so on. Find the sum of the lengths:

$$BA_1 + B_1A_2 + B_2A_3 + \ldots$$

Solution. Since A_1 bisects segment AC, $AA_1 = \frac{1}{2}AC = 2$, and $B_1A_1 = \frac{1}{2}BA = \frac{3}{2}$. By Pythagorean theorem,

$$BA_1 = \sqrt{BA^2 + AA_1^2} = \sqrt{3^2 + 2^2} = \sqrt{13}.$$

Each of the triangles $B_1A_1A_2$, $B_2A_2A_3, \ldots$ is similar to the triangle BAA_1, with the similarity ratio is $\frac{1}{2}$:

$$\frac{1}{2} = \frac{B_1A_1}{BA} = \frac{B_2A_2}{B_1A_1} = \frac{B_3A_3}{B_2A_2} = \cdots \Rightarrow \frac{1}{2} = \frac{B_1A_2}{BA_1} = \frac{B_2A_3}{B_1A_2} = \cdots$$

Therefore

$$BA_1 + B_1A_2 + B_2A_3 + \ldots = BA_1 + \left(\frac{1}{2}\right)BA_1 + \left(\frac{1}{2}\right)^2 BA_1 + \cdots = BA_1\frac{1}{1-\frac{1}{2}} = \boxed{2\sqrt{13}.}$$

□

Problem 3.1.4 (Problem 4)**.** (*10 points*) A four-digit number which is a perfect square is created by writing Lan's age in years followed by Nam's age in years. Similarly, after 31 years, their ages in the same order will again form a four-digit perfect square. Determine the present ages of Lan and Nam.

Note: for example if Lan's is 19 years old and Name is 11 years old then the four-digit number which is a perfect square is created by writing Lan's age in years followed by Nam's age in years is 1911.

Solution. After 31 years, each of these ages is a number with at least two digits, and then their ages in the same order will again form a four-digit perfect square, thus their ages then should be two-digit numbers. Since currently their ages in the same order form a four-digit perfect square, thus their present ages are also two-digit numbers.

Now let $\ell_1\ell_2$ and n_1n_2 be the their present ages, then $\ell_3\ell_4 = \ell_1\ell_2 + 31$, $n_3n_4 = n_1n_2 + 31$ are their ages after 31 years, then

$$\overline{\ell_3\ell_4n_3n_4} - \overline{\ell_1\ell_2n_1n_2} = (\overline{\ell_3\ell_4}\cdot 100 + \overline{n_3n_4}) - (\overline{\ell_1\ell_2}\cdot 100 + \overline{n_1n_2}) = (\overline{\ell_3\ell_4} - \overline{\ell_1\ell_2})\cdot 100 + (\overline{n_3n_4}) - \overline{n_1n_2}) = 31\cdot 100 + 31$$

Now, let the two perfect squares be $x^2 = \overline{\ell_1\ell_2n_1n_2}$, $y^2 = \overline{\ell_3\ell_4n_3n_4}$, then

$$y^2 - x^2 = 3131 = 31 \cdot 101 \Rightarrow \begin{cases} y - x = 31 \\ y + x = 101 \end{cases} \Rightarrow x = 35, y = 66 \Rightarrow x^2 = 1225, y^2 = 4356.$$

Thus, Lan's age now is 12, Nam's age now is 25. □

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Chapter 4

Session 2: Feb 02 - Feb 10

4.1 Middle School - Assignment

Middle school students: grade 8 (US, CA), grade 9 (FR, UK, VN) and younger.

- **Submission deadline: Friday, February 9**
- **Test: Saturday, February 10**
- **Official solutions: Monday, January 29**
- **Intermediate (I) level: Problems 1-10**
- **Advanced (A) level: Problems 6-15**

If you submit solution based on coding, please make sure that your submission is compliant. Read the introduction chapter for more information.

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Problem 4.1.1 (Problem 1)**.** (*5 points*) Find the number of three-digit positive integers where the digits are three different prime numbers. For example, count 235 but not 553

Solution. There are 4 prime numbers that are digits: 2, 3, 5, and 7. They are all distinct. Thus, there are $4 \cdot 3 \cdot 2 = \boxed{24}$ three-digit positive integers where the digits are three different prime numbers. □

Problem 4.1.2 (Problem 2)**.** (*5 points*) Melanie has $4\frac{2}{5}$ cups of flour. The recipe for one batch of cookies calls for $1\frac{1}{2}$ cups of flour. Melanie plans to make $2\frac{1}{2}$ batches of cookies. When she is done, she will have $\frac{m}{n}$ cups of flour remaining, where m and n are relatively prime positive integers. Find $m + n$.

Solution. The number of cups of flour remaining is:

$$4\frac{2}{5} - 2\frac{1}{2} \cdot 1\frac{1}{2} = \frac{22}{5} - \frac{5}{2} \cdot \frac{3}{2} = \frac{13}{20}.$$

Hence, $m + n = 13 + 20 = \boxed{33.}$ □

Problem 4.1.3 (Problem 3)**.** (*5 points*) The figure below has a 1×1 square, a 2×2 square, a 3×3 square, a 4×4 square, and a 5×5 square. Each of the larger squares shares a corner with the 1×1 square. Find the area of the region covered by the 1×1, 2×2, 3×3, and 4×4 squares, and the 5×5 square.

Solution. Let $S_1, S_2, \ldots, S_5$ denote the area of the squares 1×1, 2×2, ..., and 5×5.

It is easy to see that the area cover by the squares 1×1, 2×2 is the square 2×2.

If we add the area cover by the squares 3×3 to it we can see that they overlap a 1×2 area, thus three of them cover $4 + 9 - 2 = 11$.

If we add the area cover by the squares 4×4 to it we can see that they overlap a 1×3 area, thus four of them cover $16 + 11 - 3 = 24$.

If we add the area cover by the squares 5×5 to it we can see that they overlap the squares 1×1, 1×1, and 1×3 thus five of them cover $24 + 25 - (1 + 1 + 3) = \boxed{44.}$ □

Problem 4.1.4 (Problem 4)**.** (*5 points*) Find the value of x such that $2^{x+3} - 2^{x-3} = 2016$.

Solution.

$$2016 = 2^{x+3} - 2^{x-3} = 2^{x-3}(2^6 - 1) \Rightarrow 2^{x-3} = 32 \Rightarrow x = \boxed{8}.$$

□

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Problem 4.1.5 (Problem 5)**.** (*5 points*) Mildred the cow is tied with a rope to the side of a square shed with side length 10 meters. The rope is attached to the shed at a point two meters from one corner of the shed. The rope is 14 meters long. The area of grass growing around the shed that Mildred can reach is given by $n\pi$ square meters, where n is a positive integer. Find n.

Solution. The total area is the sum of the areas of:

- half of the blue circle centred at E, where the rope is tied to, with radius 14;
- a quarter of the orange circle centred at A with radius $14 - 8 = 6$;
- a quarter of the green circle centred at D with radius $14 - 2 = 12$;
- a quarter of the red circle centred at C with radius $14 - 2 - 10 = 2$.

Thus, $\left(\frac{14^2}{2} + \frac{6^2}{4} + \frac{12^2}{4} + \frac{2^2}{4}\right)\pi = \boxed{144}\pi$. □

Problem 4.1.6 (Problem 6)**.** (*5 points*) One evening a theater sold 300 tickets for a concert. Each ticket sold for \$40, and all tickets were purchased using \$5, \$10, and \$20 bills. At the end of the evening the theater had received twice as many \$10 bills as \$20 bills, and 20 more \$5 bills than \$10 bills. How many bills did the theater receive altogether?

Solution. Let n be the number of \$20 bills the theater received. Then the number of \$10 bills they received is $2n$, and the number of \$5 bills they received is $2n + 20$, for a total amount collected equalling

$$5(2n + 20) + 10(2n) + 20n = 300 \cdot 40 \Rightarrow 50n + 100 = 12000.$$

The amount of bills is

$$n + 2n + 2n + 20 = 5n + 20 = \frac{12000}{10} + 10 = \boxed{1210.}$$

□

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Problem 4.1.7 (Problem 7)**.** (*5 points*) Find the number of squares such that the sides of the square are segments in the following diagram and where the shaded area is inside the square.

Solution. To count the square let's seletc one of the three vertical line segments to the left of the shaded square and one of the 3 vertical line segments to the right.

Of these $3 \cdot 3 = 9$, ways to select vertical line segments. 1 selection gives segments a distance 1 apart, 2 selections give segments a distance 2 apart, 3 selections give segments a distance 3 apart, 2 selections give segments a distance 4 apart, and 1 selection gives segments a distance 5 apart.

There is the same number of ways of selecting horizontal line segments a distance k apart that make up the side of a square containing the shaded square as there are selecting vertical line segments a distance k apart, so the total number of ways of selecting line segments that make up the sides of a square containing the shaded area is $1^2 + 2^2 + 3^2 + 2^2 + 1^2 = \boxed{19.}$ □

Problem 4.1.8 (Problem 8)**.** (*5 points*) One afternoon Elizabeth noticed that twice as many cars on the expressway carried only a driver as compared to the number of cars that carried a driver and one passenger.

She also noted that twice as many cars carried a driver and one passenger as those that carried a driver and two passengers.

10% of the cars carried a driver and three passengers, and no car carried more than four people.

Any car containing at least three people was allowed to use the fast lane. Elizabeth calculated that $\frac{m}{n}$ of the people in cars on the expressway were allowed to ride in the fast lane, where m and n are relatively prime positive integers. Find $m + n$.

Solution. Let n be the number of the cars that have a driver and two passengers, then

Car type	Number of cars	Number of people
Only a driver	$4n$	$1 \cdot 4n$
A driver and one passenger	$2n$	$2 \cdot 2n$
A driver and two passengers	n	$3 \cdot n$
A driver and three passengers	$\frac{n+2n+4n}{9}$	$4 \cdot \frac{7n}{9}$

The number of people in cars that can use the fast lane is the number of people in cars carrying a driver and two or three passengers, which is $3n + \frac{28n}{9} = \frac{55n}{9}$. The total number of people is $4n + 4n + 3n + \frac{28n}{9} = \frac{127n}{9}$.

The ratio of the people in cars were allowed to ride in the fast lane is $\frac{55n}{9} : \frac{127n}{9} = \frac{55}{127}$.

Hence, $m + n = 55 + 127 = \boxed{182.}$ □

Problem 4.1.9 (Problem 9)**.** (*5 points*) Find the number of positive integers n such that a regular polygon with n sides has internal angles with measures equal to an integer number of degrees.

Solution. The measure of an internal angle, in degrees, of a regular polygon with n sides is:

$$\frac{(n-2)180}{n} = 180 - \frac{360}{n}.$$

This measure is an integer if and only if n is at least 3 and it is a divisor of $360 = 2^3 \cdot 3^2 \cdot 5$.

Since 360 has $(3+1)(2+1)(1+1) = 24$ divisors, and $\boxed{22}$ of them are at least 3. □

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Problem 4.1.10 (Problem 10)**.** (*5 points*) The real numbers x, y, and z satisfy the system of equations

$$\begin{cases} x^2 + 27 = -8y + 10z \\ y^2 + 196 = 18z + 13x \\ z^2 + 119 = -3x + 30y. \end{cases}$$

Find $x + 3y + 5z$.

Solution. Adding the equations yields

$$x^2 + y^2 + z^2 + 342 = 10x + 22y + 28z \Rightarrow (x-5)^2 + (y-11)^2 + (z-14)^2 = 0 \Rightarrow x = 5, y = 11, z = 14.$$

Hence, $x + 3y + 5z = 5 + 3 \cdot 11 + 5 \cdot 14 = \boxed{108.}$ □

Problem 4.1.11 (Problem 11)**.** (*5 points*) The figure below shows a barn in the shape of two congruent pentagonal prisms that intersect at right angles and have a common center. The ends of the prisms are made of a 12 foot by 7 foot rectangle surmounted by an isosceles triangle with sides 10 feet, 10 feet, and 12 feet. Each prism is 40 feet long. Find the volume of the barn in cubic feet.

Solution. The volume is the sum of the volume of the 2 pentagonal prisms minus the common center area.

Lets split the pentagonal prism into 2 parts: the top part which is where the isoceles triangle is and the bottom part which is the rectangle underneath the isoceles triangle. The top part is a triangular prism with a triangular base $10, 10, 12$, height 40, so its volume is 1920. The bottom part is a box with side lengths $7, 12, 40$, thus its volume is $7 \cdot 12 \cdot 40 = 3360$. Consequently, the volume of a pentagonal prism is $1920 + 3360 = 5280$.

Now all we need to find the volume of the common center. We can split the common center place into 2 parts as well. The top part which is a pyramid and the bottom which is a box. The top part volume is a pyramid with base side length 12, height 8, so its volume is $\frac{12 \cdot 12 \cdot 8}{3} = 384$. The bottom part is a box which has side lengths $12, 12, 7$ thus its volume is $12 \cdot 12 \cdot 7 = 1008$ Therefore, the total volume of the common center is $1008 + 384 = 1392$.

Thus, the answer is $2 \cdot 5280 - 1392 = \boxed{9168}$. □

Problem 4.1.12 (Problem 12)**.** (*5 points*) Suzie flips a fair coin 6 times. The probability that Suzie flips 3 heads in a row but not 4 heads in a row is given by $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. Three consecutive head, but not four:

HHHTXX, THHHTX, XTHHHT, XXTHHH

where H denote head, T denote tail and X denote either head or tail.

There are 2 string of the format THHHTX, because X can be fill in 2 ways, 2 string of the format XTHHHT, because X can be fill in 2 ways, $2 \cdot 2$ strings of HHHTXX, and $2 \cdot 2$ strings of XXTHHH. Thus total number of favourable cases are $2 + 2 + 4 + 4 = 12$.

Total possible outcome is $2^6 = 64$. Hence probability is $\frac{12}{64} = \frac{3}{16}$.

Hence $m = 3, n = 16$ and $m + n = \boxed{19}$. □

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Problem 4.1.13 (Problem 13)**.** (*5 points*) Find the least positive integer N that is 50 times the number of positive integer divisors that N has.

Solution. Let $N = p_1^a p_2^b \cdots$ for distinct prime numbers $p_1, p_2, \ldots$ and $a, b, \ldots$ positive integers. Then N has $(a+1)(b+1)\cdots$ divisors. Since $50 = 2 \cdot 5^2$ so the *least* N must have

$$p_1^a p_2^b \cdots = 2^1 5^2 (a+1)(b+1)\cdots$$

Thus two of the primes $p_1, p_2, \ldots$ must be 2 and 5.

Case 1: $N = 2^a 5^b$.

$$N = 2^a 5^b = 2^1 5^2 (a+1)(b+1) \Rightarrow b \geq 2.$$

Case 1a: $b = 2$. Then $3 \mid 2^a 5^b$, impossible.

Case 1b: $b = 3$. Then $5^b = 5^3$, thus $5 \mid a+1$, or $a \geq 4$, so $N \geq 2^4 5^3 = 2000$.

Case 1c: $b \geq 4$. It is easy to prove that $5^b \geq 5(b+1)$, thus $a+1 \geq 10$, or $a \geq 9$, so $N \geq 2^9 5^2 > 2000$.

Case 2: $N = 2^a 3^b 5^c$.

$$N = 2^a 3^b 5^c = 2^1 5^2 (a+1)(b+1)(c+1).$$

With the least possible of $c = 2$, then $b = 2, a = 3$, then $N = \boxed{1800}$ is a solution.

For $N = 2^a 5^b p^c$, where $p \geq 7$ leads to $N > 2000$. □

Problem 4.1.14 (Problem 14)**.** (*5 points*) Find the positive integer n such that the least common multiple of n and $n - 30$ is $n + 1320$.

Solution. First, since $n + 1320 = \text{lcm}(n, n-30)$, so $n(n-30) \geq n + 1320$, or $n \geq 55$.

Second, $n \mid n + 1320$, so $n \mid 1320$, the divisors of 1320 that are at least 55 are 55, 60, 66, 88, 110, 120, 132, 165, 220, 264, 330, 440, 660, and 1320.

Third, $n - 30 \mid (n + 1320) - (n - 30) = 1350$. Only $n = 55, 60, 120$, and 165 satisfies $n - 30 \mid 1350$.

By testing, it is easy to see that only $n = \boxed{165}$ satisfies $n + 1320 = \text{lcm}(n, n-30)$. □

Problem 4.1.15 (Problem 15)**.** (*5 points*) The 24 unshaded squares in the 5×5 grid below can be tiled with twelve 1×2 tiles. One such tiling is shown below.

Find the number of ways the grid can be tiled.

Solution. Call the two-squares pairs that align with the shaded central square *bridges* which are shaded in the left diagram below. An organized way to count the tilings is to consider how many of these four bridges are tiled by a single tile.

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Case 1: First, note that if any one bridge is tiled by two different tiles that do not aligned, then there is only one way to complete the tiling of remaining unshaded squares. Thus, there are only two tilings of this type, both shown above.

Case 2: If all four bridge are each tiled by a single tile as in the first diagram below, it leaves four 2×2 grids which can each be tiled in 2 different ways. Thus, this accounts for $2^4 = 16$ tilings.

Case 3: If exactly three bridges are each tiled by a single tile as shown in the second diagram below, then there are 4 ways to select the one bridge that is not tiled by a single tile. There are two ways to tile the bridge that is tiled by two tiles. This leaves three 2×2 grids that can each be tiled in 2 ways. Thus, this accounts for $4 \cdot 2 \cdot 2^3 = 64$ tilings.

Case 4: If exactly two bridges are each tiled by a single tile, then the two bridges tiled by a single tile can be across the center from each other as shown in the third diagram below, or the two bridges tiled by a single tile can be adjacent bridges as shown in the fourth diagram below.

In the first case, there are 2 ways to select the two bridges each tiled by a single tile, and that leaves two 5×2 grids which can each be tiled in one of 4 ways (2 ways to tile the included bridge and 2 ways to tile a 2×2 grid that remains.) This accounts for $2 \cdot 4^2 = 32$ tilings.

In the second case, there are 4 ways to select the two bridges each tile by a single bridge. That leaves 3 ways to tile the remaining two bridges, and each of these 3 ways leaves two 2×2 grids, each to be tiled in one of 2 ways. This accounts for $4 \cdot 3 \cdot 2^2 = 48$. tilings.

Thus, there are $32 + 48 = 80$ tilings where exactly two bridges are each tiled by a single tile.

Case 5: If exactly one bridge is tile by a single tile as shown in the first diagram below, then there are 4 ways to select the one bridge that is tiled by a single tile. There are then two ways to tile the bridge on the opposite side of the center square. This determines how to tile the grid, except for on 5×2 grid that can be tiles in one of 4 ways. This accounts for $4 \cdot 2 \cdot 4 = 32$ tilings.

Case 6: If none of the bridges are tiled by a single tile, there are two ways to tile the grid as shown in the second and third diagrams below accounting for 2 tilings.

Hence, the number of tilings is $2 + 16 + 64 + 80 + 32 + 2 = \boxed{196.}$ $\square$

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4.2 Middle School - Test

You have **30 minutes** to complete the test. You have to **submit only the answers**. No solution is required.

Note that you have to **follow the instructions by the COs** *for submitting the answers.*

- **Intermediate (I) level: Problems 1-10**
- **Advanced (A) level: Problems 6-15**

If you submit solution based on coding, please make sure that your submission is compliant. Read the introduction chapter for more information.

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Problem 4.2.1 (Problem 1)**.** (*5 points*) Find the number of four-digit positive integers where the digits are four different prime numbers. For example, count 2357 but not 5537

Solution. There are 4 prime numbers that are digits: 2, 3, 5, and 7. They are all distinct. Thus, there are $4 \cdot 3 \cdot 2 \cdot 1 = \boxed{24}$ three-digit positive integers where the digits are three different prime numbers. □

Problem 4.2.2 (Problem 2)**.** (*5 points*) Melanie has $3\frac{4}{5}$ cups of flour. The recipe for one batch of cookies calls for $1\frac{1}{2}$ cups of flour. Melanie plans to make $2\frac{1}{2}$ batches of cookies. When she is done, she will have $\frac{m}{n}$ cups of flour remaining, where m and n are relatively prime positive integers. Find $m + n$.

Solution. The number of cups of flour remaining is:

$$3\frac{4}{5} - 2\frac{1}{2} \cdot 1\frac{1}{2} = \frac{19}{5} - \frac{5}{2} \cdot \frac{3}{2} = \frac{1}{20}.$$

Hence, $m + n = 1 + 20 = \boxed{21.}$ □

Problem 4.2.3 (Problem 3)**.** (*5 points*) The figure below has a 1×1 square, a 2×2 square, a 3×3 square, a 4×4 square, and a 5×5 square. Each of the larger squares shares a corner with the 1×1 square. Find the area of the region covered by the 1×1, 2×2, 3×3, and 4×4 squares, but not covered by the 5×5 square.

Solution. Let $S_1, S_2, \ldots, S_5$ denote the area of the squares 1×1, 2×2, ..., and 5×5.

It is easy to see that the area cover by the squares 1×1, 2×2 is the square 2×2.

If we add the area cover by the squares 3×3 to it we can see that they overlap a 1×2 area, thus three of them cover $4 + 9 - 2 = 11$.

If we add the area cover by the squares 4×4 to it we can see that they overlap a 1×3 area, thus four of them cover $16 + 11 - 3 = 24$.

Now, we need to remove the area covered by the square 5×5 overlapping with it, and it is a 1×1, a 1×1, and a 1×3 thus $24 - 1 - 1 - 3 = \boxed{19.}$ □

Problem 4.2.4 (Problem 4)**.** (*5 points*) Find the value of x such that $2^{x+5} - 3 \cdot 2^{x-3} = 2024$.

Solution.

$$2024 = 2^{x+5} - 3 \cdot 2^{x-3} = 2^{x-3}(2^8 - 3) \Rightarrow 2^{x-3} = 8 \Rightarrow x = \boxed{6}.$$

□

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Problem 4.2.5 (Problem 5)**.** (*5 points*) Mildred the cow is tied with a rope to the side of a square shed with side length 10 meters. The rope is attached to the shed at a point two meters from one corner of the shed. The rope is 13 meters long. The area of grass growing around the shed that Mildred can reach is given by $\frac{m\pi}{n}$ square meters, where m and n are relatively prime positive integers. Find $m+n$.

Solution. The total area is the sum of the areas of:

- half of the blue circle centred at E, where the rope is tied to, with radius 13;
- a quarter of the orange circle centred at A with radius $13-8=5$;
- a quarter of the green circle centred at D with radius $13-2=11$;
- a quarter of the red circle centred at C with radius $13-2-10=1$.

Thus, $\left(\frac{13^2}{2}+\frac{5^2}{4}+\frac{11^2}{4}+\frac{1^2}{4}\right)\pi = \frac{485\pi}{4}$.

Hence $m+n = 485+4 = \boxed{489.}$ □

Problem 4.2.6 (Problem 6)**.** (*5 points*) One evening a theater sold 300 tickets for a concert. Each ticket sold for \$40, and all tickets were purchased using \$5, \$10, and \$20 bills. At the end of the evening the theater had received twice as many \$10 bills as \$20 bills, and 10 more \$5 bills than \$10 bills. How many bills did the theater receive altogether?

Solution. Let n be the number of \$20 bills the theater received. Then the number of \$10 bills they received is $2n$, and the number of \$5 bills they received is $2n+10$, for a total amount collected equalling

$$5(2n+10)+10(2n)+20n = 300\cdot 40 \Rightarrow 50n+50 = 12000.$$

The amount of bills is

$$n+2n+2n+10 = 5n+10 = \frac{12000}{10}+5 = \boxed{1205.}$$

□

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Problem 4.2.7 (Problem 7)**.** (*5 points*) The 5×5 grid below is made up by *unit* squares. The center square is shaded. Find the number of squares with side lengths 1, 3, or 5, such that the sides of the square are segments in the grid, and the shaded area is inside the square.

Solution. To count the square let's select one of the three vertical line segments to the left of the shaded square and one of the 3 vertical line segments to the right.

Of these $3 \cdot 3 = 9$, ways to select vertical line segments. 1 selection gives segments a distance 1 apart, 2 selections give segments a distance 2 apart, 3 selections give segments a distance 3 apart, 2 selections give segments a distance 4 apart, and 1 selection gives segments a distance 5 apart.

There is the same number of ways of selecting horizontal line segments a distance k apart that make up the side of a square containing the shaded square as there are selecting vertical line segments a distance k apart, so the total number of ways of selecting line segments that make up the sides of a square with **odd area** containing the shaded area is $1^2 + 3^2 + 1^2 = \boxed{11.}$ □

Problem 4.2.8 (Problem 8)**.** (*5 points*) One afternoon Elizabeth noticed that twice as many cars on the expressway carried only a driver as compared to the number of cars that carried a driver and one passenger.

She also noted that twice as many cars carried a driver and one passenger as those that carried a driver and two passengers.

10% of the cars carried a driver and three passengers, and no car carried more than four people.

Any car containing at least three people was allowed to use the fast lane. Elizabeth calculated that $\frac{m}{n}$ of the people in cars on the expressway were **not** allowed to ride in the fast lane, where m and n are relatively prime positive integers. Find $m + n$.

Solution. Let n be the number of the cars that have a driver and two passengers, then

Car type	Number of cars	Number of people
Only a driver	$4n$	$1 \cdot 4n$
A driver and one passenger	$2n$	$2 \cdot 2n$
A driver and two passengers	n	$3 \cdot n$
A driver and three passengers	$\frac{n+2n+4n}{9}$	$4 \cdot \frac{7n}{9}$

The number of people in cars that can not use the fast lane is the number of people in cars carrying a driver and at most one passenger, which is $4n + 4n = 8n$. The total number of people is $4n + 4n + 3n + \frac{28n}{9} = \frac{127n}{9}$.

The ratio of the people in cars were allowed to ride in the fast lane is $8n : \frac{127n}{9} = \frac{72}{127}$.

Hence, $m + n = 72 + 127 = \boxed{199.}$ □

Problem 4.2.9 (Problem 9)**.** (*5 points*) Find the number of **odd** positive integers n such that a regular polygon with n sides has internal angles with measures equal to an integer number of degrees.

Solution. The measure of an internal angle, in degrees, of a regular polygon with n sides is:

$$\frac{(n-2)180}{n} = 180 - \frac{360}{n}.$$

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This measure is an integer if and only if n is at least 3 and it is a divisor of $360 = 2^3 \cdot 3^2 \cdot 5$.

Since n must be odd, so n is a divisor of $3^2 \cdot 5$, and there are $(2+1)(1+1) = 6$ such divisors, and $\boxed{5}$ of them are at least 3: $3, 5, 9, 15$, and 45. □

Problem 4.2.10 (Problem 10)**.** (*5 points*) The real numbers x, y, and z satisfy the system of equations

$$\begin{cases} x^2 + 27 = -8y + 10z \\ y^2 + 196 = 18z + 13x \\ z^2 + 119 = -3x + 30y. \end{cases}$$

Find $5x + 3y + z$.

Solution. Adding the equations yields

$$x^2 + y^2 + z^2 + 342 = 10x + 22y + 28z \Rightarrow (x-5)^2 + (y-11)^2 + (z-14)^2 = 0 \Rightarrow x = 5, y = 11, z = 14.$$

Hence, $5x + 3y + z = 5 \cdot 5 + 3 \cdot 11 + 14 = \boxed{72.}$ □

Problem 4.2.11 (Problem 11)**.** (*5 points*) The figure below shows a barn in the shape of two congruent pentagonal prisms that intersect at right angles and have a common center. The ends of the prisms are made of a 6 foot by 4 foot rectangle surmounted by an isosceles triangle with sides 5 feet, 5 feet, and 6 feet. Each prism is 40 feet long. Find the volume of the barn in cubic feet.

Solution. The volume is the sum of the volume of the 2 pentagonal prisms minus the common center area.

Lets split the pentagonal prism into 2 parts: the top part which is where the isoceles triangle is and the bottom part which is the rectangle underneath the isoceles triangle. The top part is a triangular prism with a triangular base $5, 5, 6$, height 40, so the area of the triangle is 12, its volume is 480.

The bottom part is a box with side lengths $4, 6, 40$, thus its volume is $4 \cdot 6 \cdot 40 = 960$. Consequently, the volume of a pentagonal prism is $480 + 960 = 1440$.

Now all we need to find the volume of the common center. We can split the common center place into 2 parts as well. The top part which is a pyramid and the bottom which is a box. The top part volume is a pyramid with base side length 6, height 4, so its volume is $\frac{6 \cdot 6 \cdot 4}{3} = 48$. The bottom part is a box which has side lengths $6, 6, 4$ thus its volume is $6 \cdot 6 \cdot 4 = 144$ Therefore, the total volume of the common center is $48 + 144 = 192$.

Thus, the answer is $2 \cdot 1440 - 192 = \boxed{2688}$. □

Problem 4.2.12 (Problem 12)**.** (*5 points*) Suzie flips a fair coin 7 times. The probability that Suzie flips 4 heads in a row but not 5 heads in a row is given by $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

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Solution. Four consecutive heads, but not five:

$$\text{HHHHTXX},\ \text{THHHHTX},\ \text{XTHHHHT},\ \text{XXTHHHH},$$

where H denote head, T denote tail and X denote either head or tail.

There are 4 string of the format HHHHTXX because XX can be fill in 4 ways, 2 string of the format THHHHTX because X can be fill in 2 ways, 2 strings of XTHHHHT and 4 strings of XXTHHHH. Thus total number of favourable cases are $4 + 2 + 2 + 4 = 12$.

Total possible outcome is $2^7 = 128$. Thus, the probability is $\frac{12}{128} = \frac{3}{32}$.

Hence $m = 3, n = 32$ and $m + n = \boxed{35}$. □

Problem 4.2.13 (Problem 13)**.** (*5 points*) Find the least positive integer N that is 49 times the number of positive integer divisors that N has.

Solution. [Solution 1] Let $N = p_1^a p_2^b \cdots$ for distinct prime numbers $p_1, p_2, \ldots$ and $a, b, \ldots$ positive integers. Then N has $(a+1)(b+1)\cdots$ divisors. Since $50 = 2 \cdot 5^2$ so the *least* N must have

$$p_1^a p_2^b \cdots = 7^2(a+1)(b+1)\cdots$$

Thus one of the primes $p_1, p_2, \ldots$ must be 7. *Case 1*: $N = 2^a 7^b$.

$$N = 2^a 7^b = 7^2(a+1)(b+1).$$

Case 1a: $b = 2$. Then $3 \mid 2^a 7^b$, impossible.

Case 1b: $b = 3$. Then $7^b = 7^3$, thus $7 \mid a+1$, or $a \geq 6$, With $a = 6$ then $N \geq 2^6 7^3 > 2000$.

Case 1c: $b \geq 4$. Then $N > 2000$.

Case 2: $N = 3^a 7^b$.

$$N = 3^a 7^b = 7^2(a+1)(b+1).$$

For $b = 2 : 3^a = (a+1)3$, so $a = 2$ thus $N = \boxed{441}$. □

Solution. [Solution 2] We show a coding solution. The *count_divisor* function count all divisors of n between 2 and $\left\lfloor \frac{n}{2} \right\rfloor$.

```
def count_divisors(n):
    c = 2
    for i in range(2, n+1 // 2):
        if n % i == 0:
            c += 1
    return c

n = 1
while True:
    n_dc = count_divisors(n)
    if n_dc * 49 == n:
        print(n)
        break
    n += 1
```

Thus $N = \boxed{441}$. □

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Problem 4.2.14 (Problem 14)**.** (*5 points*) Find the positive integer n such that the least common multiple of n and $n-30$ is $n+4900$.

Solution. First, since $n+4900 = \operatorname{lcm}(n, n-30)$, so $n(n-30) \geq n+4900$, or $n \geq 87$.

Second, $n \mid n+4900$, so $n \mid 4900$, the divisors of 4900 that are at least 87 are 98, 100, 140, 175, 196, 245, 350, 490, 700, 980, 1225, 2450, and 4900.

Third, $n-30 \mid (n+4900)-(n-30) = 4930$. The divisors of 4930 that are at least 57 are 58, 85, 145, 170, 290, 493, 986, 3465, and 4930.

Only $n = \boxed{175}$ satisfies $n-30 \mid 4930$. □

Problem 4.2.15 (Problem 15)**.** (*5 points*) The 24 unshaded squares in the 5×5 grid below (the left diagram) are already tiled by three 1×2 tiles (the right diagram).

Find the number of ways the rest of the grid can be tiled by nine 1×2 tiles.

Solution. For the upper left 2×5 grid as shown below, we can consider three cases, as show below.

The first case has 2 ways to tile the right 2×2 grid. For each of the second and third cases there are 3 ways to tile the right 2×3 grid. Thus, there 8 ways to tile this 2×5 grid. Each of the 2×2 grids on the bottom left and bottom right can each be tiled in 2 ways. Hence, the number of tilings is $8 \times 2 \times 2 = \boxed{32.}$ □

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4.3 High School - Assignment

High school students: grade 9 (US, CA), grade 10 (FR, UK, VN) and above.

- **Submission deadline: Friday, February 9**
- **Test: Saturday, February 10**
- **Official solutions: Monday, January 29**
- **Intermediate (I) level: Problems 1-10**
- **Advanced (A) level: Problems 6-15**
- **Olympiad (O) level: Problems 12-21**

If you submit solution based on coding, please make sure that your submission is compliant. Read the introduction chapter for more information.

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Problem 4.3.1 (Problem 1)**.** (*5 points*) Jeremy wrote all the three-digit integers from 100 to 999 on a blackboard. Then Allison erased each of the 2700 digits Jeremy wrote and replaced each digit with the square of that digit. Thus, Allison replaced every 1 with a 1, every 2 with a 4, every 3 with a 9, every 4 with a 16, and so forth. The proportion of all the digits Allison wrote that were ones is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m+n$.

Solution. Jeremy wrote 2700 digits. If he had also written $000, 001, 002, \ldots, 099$, he would have written 3000 digits in all which would have consisted of 300 of each of the 10 digits. In the list of those 100 numbers that he did not write, each nonzero digit appears $\frac{200}{10} = 20$ times, and 0 appear $20 + 100 = 120$ times.

Thus, among the digits Jeremy actually wrote, the digit 0 appears $300 - 120 = 180$ times, and each of the digits each appear $300 - 20 = 280$ times. Allison replaces each $0, 1, 2$, and 3 with one-digit numbers, and each of $4, 5, 6, 7, 8, 9$ with a two-digit number, so Allison wrote a total of

$$180 + 3 \cdot 280 + 2 \cdot 6 \cdot 280 = 180 + 15 \cdot 280 \text{ digits.}$$

Allison wrote one digit 1 each time she squared 1, 4, and 9 accounting for $3 \cdot 280$ digits that were 1. The required proportion is,

$$\frac{3 \cdot 280}{180 + 15 \cdot 280} = \frac{28}{6 + 5 \cdot 28} = \frac{14}{73}.$$

Hence, $m + n = 14 + 73 = \boxed{87.}$ □

Problem 4.3.2 (Problem 2)**.** (*5 points*) Find the number of three-digit positive integers which have three distinct digits where the sum of the digits is an even number such as 925 and 824.

Solution. If the hundred digit is even, then the other two digit must be both odd or even. There are 4 choices for the hundred digit and $5 \cdot 4 + 4 \cdot 3 = 32$ ways to choose the following digits, (5 choices for the odd tens then 4 choices for the odd unit digit or 4 choices for the even tens and 3 choices for the even unit digit), altogether $4 \cdot 32 = 128$ numbers.

If the hundred digit is odd, then it is followed by one even and one odd digit. There are 5 choices for the hundred digit and $5 \cdot 4 + 4 \cdot 5 = 40$ ways to choose the following digits, altogether $5 \cdot 40 = 200$.

Hence, there are $128 + 200 = \boxed{328}$ such numbers. □

Problem 4.3.3 (Problem 3)**.** (*5 points*) Find the number whose reciprocal is the sum of the reciprocal of $9 + 15i$ and the reciprocal of $9 - 15i$.

Solution.

$$\frac{1}{9 + 15i} + \frac{1}{9 - 15i} = \frac{18}{9^2 + 15^2} = \frac{1}{17}.$$

The number is $\boxed{17.}$ □

Problem 4.3.4 (Problem 4)**.** (*5 points*) In $\triangle ABC$, $AB = AC$, $AF = EF$, $\angle CHE = \angle FGH$, and $EH = CH = DH = GH = DG = BG$. Find $\angle BAC$.

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Solution. Let $x = \angle ABC$,

$$\triangle BAC \sim \triangle BGD \Rightarrow \angle BDG = \angle DBG = x \angle BGD + \angle GDH + \angle HDC = 180^\circ \Rightarrow \angle HDC = 120^\circ - x$$
$$\angle HCD = \angle HDC,\ \angle ECH = \angle ACB - \angle HCD \Rightarrow \angle ECH = x - (120^\circ - x) = 2x - 120^\circ$$
$$\angle EHC = 180^\circ - 2(2x - 120^\circ) = 420^\circ - 4x,\ \angle FGH = 180^\circ - \angle HGD - \angle DGB$$
$$\Rightarrow \angle HGF = 180^\circ - 60^\circ - (180^\circ - 2x) = 2x - 60^\circ$$
$$\angle CHE = \angle FGH \Rightarrow 420^\circ - 4x = 2x - 60^\circ \Rightarrow x = 80^\circ$$

Therefore, $\boxed{\angle BAC = 180^\circ - 2 \cdot 80^\circ = 20^\circ.}$ □

Problem 4.3.5 (Problem 5)**.** (*5 points*) Find the greatest possible value of $pq + r$, where p, q, and r are (not necessarily distinct) prime numbers satisfying $pq + qr + rp = 2016$.

Solution. If each of p, q, and r is an odd prime, then $pq + qr + rp$ is odd, thus cannot be equal to 2016.

If $p = 2$, then $qr + 2(q + r) = 2016$, so qr is even, so q or r is even. If $q = 2$ then $4 + 4r = 2016 \Rightarrow r = 503$.

Now, in order to maximize $pq + r$, p or q must be 503, and $pq + r = 2(503 + 1) = \boxed{1008.}$ □

Problem 4.3.6 (Problem 6)**.** (*5 points*) Find the least positive integer of the form $\overline{abaaba}$, where a and b are distinct digits, such that the integer can be written as a product of six distinct primes.

Solution. Let $n = \overline{aba}$, then the given number is $1001n = 7 \cdot 11 \cdot 13 \cdot n$. Thus n must be the least three-digit number that is a product of three distinct primes other than 7, 11, 13.

Now if $a = 1$, then n is odd and $n \geq 3 \cdot 5 \cdot 17 = 255 > \overline{1b1} = n$.

If $a = 2$, then n is even so one of the prime factor of n is 2. 5 cannot be a factor of n since it ends in 2. So $n \geq 2 \cdot 17 \cdot 19 = 646 > \overline{2n2}$. It leaves the only possible case if n has 2 and 3 as prime factors. Now $\frac{300}{6} = 50$, $\frac{200}{6} > 33$, so we can test the primes between 37 and 47. It turns out that $282 = 2 \cdot 3 \cdot 47$ is what we are looking for.

Thus $n = \boxed{282282.}$ □

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Problem 4.3.7 (Problem 7)**.** (*5 points*) Henry rolls a fair die. If the die shows the number k, Henry will then roll the die k more times. The probability that Henry will never roll a 3 or a 6 either on his first roll or on one of the k subsequent rolls is given by $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m+n$.

Solution. In order to never roll a 3 or 6, Henry needs to roll $k = 1, 2, 4$, or 5 on his first roll, and then no 3 or 6, on any of the k subsequent rolls.

The probability that Henry does not roll a 3 or 6, on a single throw is $\frac{4}{6} = \frac{2}{3}$. Thus, the probability that Henry will never roll a 3 or a 6 on any of his roll is

$$\frac{1}{6}\left(\frac{2}{3}\right)^1 + \frac{1}{6}\left(\frac{2}{3}\right)^2 + \frac{1}{6}\left(\frac{2}{3}\right)^4 + \frac{1}{6}\left(\frac{2}{3}\right)^5 = \frac{175}{729}.$$

Hence, $m + n = 175 + 729 = \boxed{904.}$ □

Problem 4.3.8 (Problem 8)**.** (*5 points*) The cubic polynomials $p(x)$ and $q(x)$ satisfy

$$\begin{cases} p(1) = q(2) \\ p(3) = q(4) \\ p(5) = q(6) \\ p(7) = q(8) + 13 \end{cases}$$

Find $p(9) - q(10)$.

Solution. Since $p(x)$ and $q(x)$ are cubic polynomials, thus $r(x) = p(x) - q(x+1)$ is also a cubic polynomial. Furthermore $r(1) = r(3) = r(5) = 0$, thus $1, 3$, and 5 are all of its roots, therefore:

$$r(x) = a(x-1)(x-3)(x-5), \text{ where } a \text{ is a real constant.}$$

$r(7) = 13 \Rightarrow a(6)(4)(2) = 13 \Rightarrow a = \frac{13}{48}$.

Hence, $p(9) - q(10) = r(10) = \frac{13}{48}(8)(6)(4) = \boxed{52.}$ □

Problem 4.3.9 (Problem 9)**.** (*5 points*) The Tasty Candy Company always puts the same number of pieces of candy into each one-pound bag of candy they sell. Mike bought 4 one-pound bags and gave each person in his class 15 pieces of candy. Mike had 23 pieces of candy left over. Betsy bought 5 one-pound bags and gave 23 pieces of candy to each teacher in her school. Betsy had 15 pieces of candy left over. Find the least number of pieces of candy the Tasty Candy Company could have placed in each one-pound bag.

Solution. Let n be the number of pieces of candies in each bag. Then Mike's purchase shows that $4n \equiv 23 \pmod{15}$, and Betsy purchase shows that $5n \equiv 15 \pmod{23}$. Multiplying the first congruence by 4 shows that

$$16n = 4 \cdot 4n \equiv 4 \cdot 23 = 92 \pmod{15} \Rightarrow n \equiv 2 \pmod{15}.$$

Dividing the second congruence by 5,

$$n \equiv 3 \pmod{23}.$$

There exists integer k such that

$$n = 3 + 23k \equiv 3 + 8k \pmod{15},\ n \equiv 2 \pmod{15} \Rightarrow 8k + 3 \equiv 2 \pmod{15} \Rightarrow k \equiv 13 \pmod{15}$$

With $k = 13$, then $n = 3 + 23 \cdot 13$ satisfy the required conditions. This solution is unique modulo $15 \cdot 23$ (modulo 345), thus the least number of bad is $3 + 23 \cdot 13 = \boxed{302.}$ □

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Problem 4.3.10 (Problem 10)**.** (*5 points*) Jar #1 contains five red marbles, three blue marbles, and one green marble. Jar #2 contains five blue marbles, three green marbles, and one red marble. Jar #3 contains five green marbles, three red marbles, and one blue marble.

You randomly select one marble from each jar.

Given that you select one marble of each color, the probability that the red marble came from jar #1, the blue marble came from jar #2, and the green marble came from jar #3 can be expressed as $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m+n$.

Solution. Let the triple (a,b,c) represent the event that the red marble came from jar #a, the blue marble came from jar #b, and the green marble came from jar #c, then the probability of $(1,2,3)$ is $\left(\frac{5}{9}\right)^3$, the probabilities of $(1,3,2)$, $(2,1,3)$, and $(3,2,1)$ are each $\frac{5}{9}\frac{3}{9}\frac{1}{9}$, the probability of $(3,1,2)$ is $\left(\frac{3}{9}\right)^3$, and the probability of $(2,3,1)$ is $\left(\frac{1}{9}\right)^3$.

Thus, the required probability is

$$\frac{\left(\frac{5}{9}\right)^3}{\left(\frac{5}{9}\right)^3+3\frac{5}{9}\frac{3}{9}\frac{1}{9}+\left(\frac{3}{9}\right)^3+\left(\frac{1}{9}\right)^3}=\frac{125}{198}.$$

Thus $m+n=125+198=\boxed{323.}$ □

Problem 4.3.11 (Problem 11)**.** (*5 points*) Positive integers a,b,c,d, and e satisfy the equations

$$\begin{cases}(a+1)(3bc+1)=d+3e+1\\(b+1)(3ca+1)=3d+e+13\\(c+1)(3ab+1)=4(26-d-e)-1\end{cases}$$

Find d^2+e^2.

Solution. Adding the three equations together yields

$$9abc+3(ab+bc+ca)+(a+b+c)+3=117\Rightarrow 27abc+9(ab+bc+ca)+3(a+b+c)+1=343$$
$$\Rightarrow(3a+1)(3b+1)(3c+1)=7^3.$$

Since a,b,c are positive integers, thus $3a+1,3b+1,3c+1\geq 4$, so the only possible factorization of 7^3 into a product of three factors each at least 4 isosceles $3a+1=3b+1=3c+1=7$, so $a=b=c=4$.

Thus $d+3e+1=38, 3d+e+13=38$, so $d=5, e=11$. Hence $d^2+e^2=25+121=\boxed{146.}$ □

Problem 4.3.12 (Problem 12)**.** (*5 points*) On equilateral $\triangle ABC$ point D lies on BC a distance 1 from B, point E lies on AC a distance 1 from C, and point F lies on AB a distance 1 from A. Segment AD, BE, and CF intersect in pairs at points G, H, and J which are the vertices of another equilateral triangle. The area of $\triangle ABC$ is twice the area of $\triangle GHJ$. The side length of $\triangle ABC$ can be written $\dfrac{r+\sqrt{s}}{t}$, where r,s, and t are relatively prime positive integers. Find $r+s+t$.

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Solution. Let d be the side length of $\triangle ABC$. Let point K, L, and M be the projections onto side BC of points G, A, and E, respectively, as shown. Let x and y be the length of BK and GK.

Because $\triangle ECM$ is $30-60-90$ with hypotenuse $CE = 1$, so $EM = \frac{\sqrt{3}}{2}$, and $CM = \frac{1}{2}$.

$$\triangle EMB \sim \triangle GKB \Rightarrow \frac{EM}{MB} = \frac{GK}{KB} \Rightarrow \frac{\frac{\sqrt{3}}{2}}{d - \frac{1}{2}} = \frac{y}{x}$$

$$\triangle ALD \sim \triangle GKD \Rightarrow \frac{AL}{LD} = \frac{GK}{KD} \Rightarrow \frac{\frac{d\sqrt{3}}{2}}{\frac{d}{2} - 1} = \frac{y}{x-1}$$

$$\Rightarrow \frac{x\sqrt{3}}{2d-1} = \frac{d\sqrt{3}(x-1)}{d-2} \Rightarrow x = \frac{d(2d-1)}{2(d^2-d+1)},\ y = \frac{d\sqrt{3}}{2(d^2-d+1)}.$$

$$[ABC] = \frac{d^2\sqrt{3}}{4} \Rightarrow [GHJ] = \frac{d^2\sqrt{3}}{8}$$

$$[BCE] = [CAF] = [ABD] = \frac{d\sqrt{3}}{4},\ [BDG] = [CEH] = [AFJ] = \frac{y}{2} = \frac{d\sqrt{3}}{4(d^2-d+1)}$$

$$\Rightarrow \frac{d^2\sqrt{3}}{8} = 3\frac{d\sqrt{3}}{4} - 3\frac{d\sqrt{3}}{4(d^2-d+1)} \Rightarrow d(d^2-7d+7) = 0,\ d > 1 \Rightarrow d = \frac{7+\sqrt{21}}{2}$$

Thus the desired sum $7 + 21 + 2 = \boxed{30.}$ $\square$

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Problem 4.3.13 (Problem 13)**.** (*5 points*) In $\triangle ABC$, $\cos(\angle A) = \frac{2}{3}$, $\cos(\angle B) = \frac{1}{9}$, and $BC = 24$. Find the length AC.

Solution. It is easy to see that $\sin(\angle A) = \sqrt{1 - \cos^2(\angle A)} = \frac{\sqrt{5}}{3}$ (note that $\sin(\angle A) > 0$), similarly $\sin(\angle B) = \frac{4\sqrt{5}}{9}$. By the Law of Sines:

$$\frac{AC}{\sin(\angle B)} = \frac{BC}{\sin(\angle A)} \Rightarrow AC = \frac{4\sqrt{5}}{9} \cdot \frac{24}{\frac{\sqrt{5}}{3}} = \boxed{32.}$$

□

Problem 4.3.14 (Problem 14)**.** (*5 points*) Sixteen dots are arranged in a four by four grid as shown. The distance between any two dots in the grid is the minimum number of horizontal and vertical steps along the grid lines it takes to get from one dot to the other. For example, two adjacent dots are a distance 1 apart, and two dots at opposite corners of the grid are a distance 6 apart.

The mean distance between two distinct dots in the grid is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. There are $\binom{16}{2} = 120$ pairs of points in the grid.

For $4 \cdot \binom{4}{2} = 24$ of the pairs of points (the same column), the horizontal distance between the points is 0.

For $3 \cdot 4 \cdot 4 = 48$ of the pairs of points, the horizontal distance between the points is 1.

For $2 \cdot 4 \cdot 4 = 32$ of the pairs of points, the horizontal distance between the points is 2.

For $4 \cdot 4 = 16$ of the pairs of points, the horizontal distance between the points is 3.

Thus, the sum of all the horizontal distances between pairs of points for all the pairs is

$$0 \cdot 24 + 1 \cdot 48 + 2 \cdot 32 + 3 \cdot 16 = 160.$$

This also is the sum of all the vertical distances between pairs of points for all the pairs.

Thus, the mean distances between points is $\dfrac{2 \cdot 160}{120} = \dfrac{8}{3}$. Hence $m + n = 8 + 3 = \boxed{11.}$ □

Problem 4.3.15 (Problem 15)**.** (*5 points*) Find the largest prime p such that p divides $2^{p+1}+3^{p+1}+5^{p+1}+7^{p+1}$.

Solution. Fermat's Little Theorem states that if p is a prime that does not divides a, then $a^{p-1} \equiv 1 \pmod{p}$.

Let's assume that $p > 7$, then

$$2^{p+1} + 3^{p+1} + 5^{p+1} + 7^{p+1} \equiv 2^2 + 3^2 + 5^2 + 7^2 = 87 \pmod{p}.$$

Thus $p \mid 87$. The largest such prime is $\boxed{29}$. □

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Problem 4.3.16 (Problem 16)**.** (*5 points*) For n measured in degrees,

$$\text{let } T(n) = \cos^2(30^\circ - n) - \cos(30^\circ - n)\cos(30^\circ + n) + \cos^2(30^\circ + n). \text{ Evaluate } 4\sum_{n=1}^{30} n \cdot T(n).$$

Solution. By the Double Angle formula for cosine and the Prosthaphaeresis formulas, and $\cos(60^\circ) = \frac{1}{2}$, thus

$$\begin{cases} 2\cos^2(30^\circ - n) = 1 + \cos(60^\circ - 2n) = 1 + \cos(60^\circ)\cos(2n) + \sin(60^\circ)\sin(2n) \\ 2\cos(30^\circ - n)\cos(30^\circ + n) = \cos(60^\circ) + \cos(2n) \\ 2\cos^2(30^\circ + n) = 1 + \cos(60^\circ + 2n) = 1 + \cos(60^\circ)\cos(2n) - \sin(60^\circ)\sin(2n) \end{cases}$$

$$\Rightarrow 2T(n) = 2 + 2\cos(60^\circ)\cos(2n) - \cos(60^\circ) - \cos(2n) = \frac{3}{2}$$

Hence

$$4\sum_{n=1}^{30} n \cdot T(n) = 4 \cdot \sum_{n=1}^{30} n \cdot \frac{3}{4} = 3 \cdot \frac{30 \cdot 31}{2} = \boxed{1395.}$$

□

Problem 4.3.17 (Problem 17)**.** (*5 points*) Find the sum of all values of a such that there are positive integers a and b satisfying $(a-b)\sqrt{ab} = 2016$.

Solution. Let $d = \gcd(a, b)$, then $d \mid \sqrt{ab}, d \mid a - b \Rightarrow d^2 \mid 2016 = 2^5 \cdot 3^2 \cdot 7$. Thus d is $1, 2, 3, 4, 6$, or 12.

Furthermore, let $a = dr, b = ds$, then $\gcd(r, s) = 1$. Since $d^2(r-s)\sqrt{rs} = 2016$, thus each of r and s is a perfect square. In other words, there exist positive integers m and n,

$$a = dm^2,\ b = dn^2,\ \gcd(m, n) = 1,\ d^2(m^2 - n^2)mn = 2^5 \cdot 3^2 \cdot 7.$$

Case 1: $d = 1$.

$$(m-n)(m+n)mn = 2^5 \cdot 3^2 \cdot 7.$$

If one of m or n is even, then the other has to be odd and both $m - n, m + n$ are odd, thus 2^5 divides m or n. In that case $mn \geq 2^5 = 32$, $m + n \geq 33$, thus

$$2016 = (m-n)(m+n)mn \geq (m-n)(33)(32) = 1056(m-n) \Rightarrow m - n = 1$$

It is easy to test with m as multiple of 32 that there is no solution.

If both m or n are odd, then one of them is divisible by 7 and the other is divisible by 9. In fact $m = 9, n = 7$ satisfy above equality and $(a, b) = (81, 49)$ is a solution.

Case 2: $d = 2$.

$$(m-n)(m+n)mn = 2^3 \cdot 3^2 \cdot 7.$$

If both m or n are odd, it is easy to test that there is no solution.

If m is divisible by 2^3 then $m + n \geq 9$ and $(m-n)(m+n) \leq 63$, thus $m = 8, n = 1$ and $(a, b) = (128, 2)$ is a solution.

Case 3: $d = 3$.

$$(m-n)(m+n)mn = 2^5 \cdot 7.$$

If both m or n are odd, then $m = 7, n = 1$ leading to no solution.

If m is divisible by 2^5 then $m + n \geq 33$ and $(m-n)(m+n)$ is too large.

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Case 4: $d \geq 4$.

$$(m-n)(m+n)mn \leq 2 \cdot 3^2 \cdot 7 = 126.$$

One of $m-n, m+n, m$, or n is divisible by 7.

If $m \geq 7$, then $m+n \geq 8$, $(m-n)n \geq 3$, thus $(m-n)(m+n)mn \geq 8 \cdot 7 \cdot 3 > 126$.

If $m \leq 6$, then $m+n = 7$, $(m-n)mn \leq \frac{126}{7} = 18$. Thus $(m,n) = (4,3)$. It is easy to test that there is no such solution.

Hence, there are two solutions $\{(81,49),(128,2)\}$, and the sum of all values of a is $81+128 = \boxed{209.}$ □

Problem 4.3.18 (Problem 18)**.** (*5 points*) A container the shape of a pyramid has a 12×12 square base, and the other four edges each have length 11. The container is partially filled with liquid so that when one of its triangular faces is lying on a flat surface, the level of the liquid is half the distance from the surface to the top edge of the container.

Find the volume of the liquid in the container.

Solution. A square pyramid with base side b and base to the apex height h has a volume $\frac{1}{3}b^2h$. Let s be the length of the other four edges. The height to the apex can be calculated considering the cross section of the pyramid that contains the apex, and two opposite corners of the square base. This cross section is an isosceles triangle with base $b\sqrt{2}$ and two sides equal to s,

$$h^2 = s^2 - \left(\frac{1}{2}b\sqrt{2}\right)^2 = s^2 - \frac{b^2}{2} \Rightarrow h = 7 \Rightarrow V = \frac{1}{3}b^2h = 336.$$

When lying on its side, the portion of the pyramid containing no liquid can be partitioned into two sections, one shaped like the original pyramid by half its size and a skewed triangular prism.

The volume of the pyramid is $\frac{1}{2^3}336 = 42$. The prism has a triangular cross section with base equal to $\frac{b}{2} = 6$ and height equal to $\frac{h}{2} = \frac{7}{2}$ so the area of the triangle is $\frac{21}{2}$. The length of the prism is $\frac{b}{2} = 6$, so the volume of the prism is $6 \cdot \frac{21}{2} = 63$.

This means that the volume of the portion of the container that does not contain liquid is $42+63 = 105$. Hence, the volume of the liquid is $336 - 105 = \boxed{231.}$ □

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Problem 4.3.19 (Problem 19)**.** (*5 points*) Find the sum of all the possible values of the product xy such that x and y are positive integers satisfying

$$(x^2+1)(y^2+1)+2(x-y)(1-xy)=4(1+xy)+140.$$

Solution. Note that

$$\begin{aligned}(x^2+1)(y^2+1)&=(xy)^2+x^2+y^2+1=(xy)^2-2xy+1+x^2-2xy+y^2+4xy\\&=(1-xy)^2+(x-y)^2+4xy=(1-xy+x-y)^2-2(x-y)(1-xy)+4xy\\\Rightarrow 144&=(x^2+1)(y^2+1)+2(x-y)(1-xy)-4xy=(1-xy+x-y)^2\Rightarrow(1+x)^2(1-y)^2=144.\end{aligned}$$

Since x, y are positive integers, thus

$$(x+1,y-1)\in\{(2,6),(3,4),(4,3),(6,2),(12,1)\}\Rightarrow(x,y)\in\{(1,7),(2,5),(3,4),(5,3),(11,2)\}.$$

Hence, $xy\in\{7,10,12,15,22\}$, and the desired sum is $7+10+12+15+22=\boxed{66.}$ □

Problem 4.3.20 (Problem 20)**.** (*5 points*) Ten square tiles are placed in a row, and each can be painted with one of the four colors red (R), yellow (Y), blue (B), and white (W). Find the number of ways this can be done so that each block of five adjacent tiles contains at least one tile of each color. That is, count the patterns RWBWYRRBWY and WWBYRWYBWR but not RWBYYBWWRY because the five adjacent tiles colored BYYBW does not include the color red.

Solution. Suppose that the colouring $C_1C_2\ldots C_9C_{10}$ is an acceptable colouring. Then each sequence of five colours $C_kC_{k+1}C_{k+2}C_{k+3}C_{k+4}$ contains exactly one colour that is repeated.

Call a tile *repeated* if its colour appears among one of the following four tiles immediately to its right. For example, in the pattern $RWBWYRRBWY$, tiles 2 and 6 are repeated tiles:

$$R\underline{W}B\underline{W}YRRBWY,\ RWBWY\underline{RR}BWY.$$

In the pattern $WWBYRWYBWR$, tiles 1, 2, 4, and 6 are repeated tiles:

$$\underline{WW}BYRWYBWR,\ W\underline{W}BYR\underline{W}YBWR, WWB\underline{Y}RW\underline{Y}BWR, WWBYR\underline{W}YB\underline{W}R.$$

Note that each sequence of the four tiles: 1234, 2345, 3456, 4567, 5678, and 6789 must include exactly one repeated tile. It follows that the sequence of repeated tiles is an increasing sequence of k positive integers $a_1<a_2<\cdots<a_k$, where a_1 is one of 1, 2, 3, 4, the difference between two adjacent terms $a_{j+1}-a_j$ cannot exceed 4, the final term a_k is one of 6, 7, 8, 9, and there can be only one term with value greater than 5.

Given any sequence of repeated values that satisfy these conditions, it is easy to construct an acceptable colouring with that sequence of repeated values. For example, the repeated tile sequence 1, 2, 5, 9 comes from the acceptable pattern $\underline{RB}WY\underline{RBR}WW\underline{YY}$.

Also note that if the colour are known for the first tiles, and the repeated sequence is known, then the complete sequence of ten tile colours can be determined. For example, if the colour pattern for the first five tiles is $RBWYR$, and the repeated sequence is 1,2,5,9, then the sixth rile by be a B so that the second tile becomes repeated. Then the seventh tile must be R so the tile 5 becomes repeated. Then the eight tile must be W so the tiles 5678 has a W, the ninth tile must be Y so tiles 6789 has an Y, and finally the tenth tile must be Y so the ninth tile becomes repeated.

Let m_j be the number of ways a repeated sequence containing the number j can be completed by adding terms to the right of j. Then $m_9=m_8=m_7=m_6=1$ because any repeated sequence containing a 6, 7, 8, 9 must end with that term and have no terms to the right of it. For j between 1 and 5, a repeated sequence that includes a term equal to j must be follow by a term with value $j+1, j+2, j+3$, or $j+4$ showing

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that $m_j = m_{j+1} + m_{j+2} + m_{j+3} + m_{j+4}$. Thus $m_5 = m_6 + m_7 + m_8 + m_9 = 4$, $m_4 = 7$, $m_3 = 13$, $m_2 = 25$, $m_1 = 49$.

Because every repeated sequence must begin with exactly one of 1, 2, 3, or 4, it follows that there are

$$m_1 + m_2 + m_3 + m_4 = 49 + 25 + 13 + 7 = 94 \text{ repeated sequences.}$$

A repeated sequence does not determine a colour pattern. A repeated sequence together with the first five colours of an acceptable colour pattern does determine a full pattern.

If a repeated sequence begins with 4, it means that tile 4 and 5 are coloured the same in the associated colour pattern. There are 4! ways to set a sequence of five tiles using 24 colours when tiles 4 and 5 are colour the same. So there are $4! \cdot a_4 = 24 \cdot 7$ acceptable colour patterns where tiles 4 and 5 are colour the same.

Similarly, a repeated sequence begins with 3, then tile 3 must be coloured the same as either tile 4 or tile 5. Thus, there are $24 \cdot 2 \cdot a_3 = 24 \cdot 26$ acceptable colour patterns where a repeated sequence begins with 3.

The number of acceptable colour patterns where a repeated sequence begins with 2 is $24 \cdot 3 \cdot a_2 = 24 \cdot 75$.

The number of acceptable colour patterns where a repeated sequence begins with 1 is $24 \cdot 4 \cdot a_1 = 24 \cdot 196$.

Hence, the total number of acceptable colour patterns is $24 \cdot (196 + 75 + 26 + 7) = \boxed{7296.}$ □

Problem 4.3.21 (Problem 21)**.** (*5 points*) Some identically sized spheres are piled in n layers in the shape of a square pyramid with one sphere in the top layer, 4 spheres in the second layer, 9 spheres in the third layer, and so forth so that the bottom layer has a square array of n^2 spheres. In each layer the centers of the spheres form a square grid so that each sphere is tangent to any sphere adjacent to it on the grid. Each sphere in an upper level is tangent to the four spheres directly below it.

The diagram shows how the first three layers of spheres are stacked.

A square pyramid is built around the pile of spheres so that the sides of the pyramid are tangent to the spheres on the outside of the pile. There is a positive integer m such that as n gets large, the ratio of the volume of the pyramid to the total volume inside all of the spheres approaches $\frac{\sqrt{m}}{\pi}$. Find m.

Solution. Let assume that each of the spheres has a radius equal to 1. Then the center of any two adjacent spheres are a distance 2 apart. If four spheres in one layer have their centers at four vertices of a 2×2 square, then the centers of the spheres across the square from each other are a distance of $2\sqrt{2}$ apart.

Consider the diagram below on the left showing a cross section of the pile of spheres passing through the center of the sphere on the top layer labelled A, the center of the sphere in the third layer directly below the top sphere labeled C, and the center of a sphere across a 2×2 square from there labeled B. Because AC is vertical, BC is horizontal, $\triangle ABC$ is right triangle with $AB = 4$, $BC = 2\sqrt{2}.$, thus $AC = 2\sqrt{2}$. It follows that the vertical distance between the plane containing the centers of spheres at one level of the pile, and the plane containing the center of spheres at the next lower level of the pile is $\sqrt{2}$.

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Now, consider the diagram above on the right showing a cross section of the pile of spheres and the enclosing pyramid that passes through the top vertex of the pyramid, the center of the top sphere labeled A, the center of the sphere directly below A in the third level labeled C, and the center of an adjacent sphere in the third level labeled D. Then ACD is a right triangle with legs $AC = 2\sqrt{2}$, $CD = 2$, thus $AD = 2\sqrt{3}$. Let G be a point where the top sphere is tangent to the side of the pyramid. Since $\triangle AFG \sim \triangle CAD$ and $AG = 1$, thus $AF = \sqrt{3}$.

If the pile of sphere has n layers, then the distance between a horizontal plane passing through point A and a plane passing through the centers of the bottom layers is $(n-1)\sqrt{2}$. Since $AF = \sqrt{3}$, and the centers of the spheres are a distance 1 from the bottom of the pyramid, the height of the pyramid is given by

$$(n-1)\sqrt{2} + 1 + \sqrt{3}.$$

Because the side of the pyramid is parallel to AD, by similarity, so the side of the base square of the pyramid is:

$$2 \cdot \frac{\sqrt{2}}{2}\left((n-1)\sqrt{2} + 1 + \sqrt{3}\right) = 2(n-1) + \sqrt{2} + \sqrt{6}.$$

The volume of the pyramid is equal to $\frac{1}{3}$ times the area of its base, times its height, so the volume is:

$$\frac{1}{3}\left(2(n-1) + \sqrt{2} + \sqrt{6}\right)^2 \cdot \left((n-1)\sqrt{2} + 1 + \sqrt{3}\right).$$

The number of spheres in this pile is given by:

$$1^2 + 1^2 + \cdots + n^2 = \frac{n(n+1)(2n+1)}{6}.$$

So the volume of all the spheres is:

$$\frac{4\pi}{3}\frac{n(n+1)(2n+1)}{6}.$$

Now, since the limit of ratio of volumes is:

$$\lim_{n\to+\infty} \frac{\frac{1}{3}\left(2(n-1) + \sqrt{2} + \sqrt{6}\right)^2 \cdot \left((n-1)\sqrt{2} + 1 + \sqrt{3}\right)}{\frac{4\pi}{3}\frac{n(n+1)(2n+1)}{6}} = \frac{\frac{2^2\sqrt{2}}{3}}{\frac{4\pi}{3}\frac{2}{6}} = \frac{\frac{4\sqrt{2}}{3}}{\frac{4\pi}{9}} = \frac{3\sqrt{2}}{\pi} = \frac{\sqrt{18}}{\pi}.$$

Thus $m = \boxed{18.}$ $\square$

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4.4 High School - Test

High school students: grade 9 (US, CA), grade 10 (FR, UK, VN) and above.

You have **30 minutes** to complete the test. You have to **submit only the answers**. No solution is required.

Note that you have to **follow the instructions by the COs** *for submitting the answers.*

- **Intermediate (I) level: Problems 1-10**
- **Advanced (A) level: Problems 6-15**
- **Olympiad (O) level: Problems 12-21**

If you submit solution based on coding, please make sure that your submission is compliant. Read the introduction chapter for more information.

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Problem 4.4.1 (Problem 1)**.** (*5 points*) Jeremy wrote all the three-digit integers from 100 to 999 on a blackboard. Then Allison erased each of the 2700 digits Jeremy wrote and replaced each digit with the square of that digit. Thus, Allison replaced every 1 with a 1, every 2 with a 4, every 3 with a 9, every 4 with a 16, and so forth. The proportion of all the digits Allison wrote that were **twos** is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m+n$.

Solution. Jeremy wrote 2700 digits. If he had also written $000, 001, 002, \ldots, 099$, he would have written 3000 digits in all which would have consisted of 300 of each of the 10 digits. In the list of those 100 numbers that he did not write, each nonzero digit appears $\frac{200}{10} = 20$ times, and 0 appear $20 + 100 = 120$ times.

Thus, among the digits Jeremy actually wrote, the digit 0 appears $300 - 120 = 180$ times, and each of the digits each appear $300 - 20 = 280$ times. Allison replaces each $0, 1, 2$, and 3 with one-digit numbers, and each of $4, 5, 6, 7, 8, 9$ with a two-digit number, so Allison wrote a total of

$$180 + 3 \cdot 280 + 2 \cdot 6 \cdot 280 = 180 + 15 \cdot 280 \text{ digits.}$$

Allison wrote one digit 2 each time she squared 5 accounting for $1 \cdot 280$ digits that were 5. The required proportion is,

$$\frac{1 \cdot 280}{180 + 15 \cdot 280} = \frac{14}{219}.$$

Hence, $m + n = 14 + 219 = \boxed{233.}$ □

Problem 4.4.2 (Problem 2)**.** (*5 points*) Find the number of three-digit positive integers which have three distinct digits where the sum of the digits is an odd number such as 935 and 834.

Solution. If the hundred digit is even, then it is followed by one even and one odd digit. There are 4 choices for the hundred digit and $5 \cdot 4 + 4 \cdot 5 = 40$ ways to choose the following digits, (5 choices for the odd tens then 4 choices for the even unit digit or 4 choices for the even tens and 5 choices for the odd unit digit), altogether $4 \cdot 40 = 160$.

If the hundred digit is odd, then the other two digit must be both odd or even. There are 5 choices for the hundred digit and $4 \cdot 3 + 5 \cdot 4 = 32$ ways to choose the following digits, (4 choices for the odd tens then 3 choices for the odd unit digit or 5 choices for the even tens and 4 choices for the even unit digit), altogether $5 \cdot 32 = 160$.

Hence, there are $160 + 160 = \boxed{320}$ such numbers. □

Problem 4.4.3 (Problem 3)**.** (*5 points*) The sum of the reciprocal of $5 + 12i$ and the reciprocal of $5 - 12i$ is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution.

$$\frac{1}{5 + 12i} + \frac{1}{5 - 12i} = \frac{10}{5^2 + 12^2} = \frac{10}{169}.$$

Hence, $m + n = 10 + 169 = \boxed{179.}$ □

Problem 4.4.4 (Problem 4)**.** (*5 points*) In $\triangle ABC$, $AB = AC$, $AF = EF$, $\angle CHE = \angle FGH$, and $EH = CH = DH = GH = DG = BG$. Find $\angle GFE$.

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Solution. Let $x = \angle ABC$,

$$\triangle BAC \sim \triangle BGD \Rightarrow \angle BDG = \angle DBG = x \angle BGD + \angle GDH + \angle HDC = 180^\circ \Rightarrow \angle HDC = 120^\circ - x$$
$$\angle HCD = \angle HDC,\ \angle ECH = \angle ACB - \angle HCD \Rightarrow \angle ECH = x - (120^\circ - x) = 2x - 120^\circ$$
$$\angle EHC = 180^\circ - 2(2x - 120^\circ) = 420^\circ - 4x,\ \angle FGH = 180^\circ - \angle HGD - \angle DGB$$
$$\Rightarrow \angle HGF = 180^\circ - 60^\circ - (180^\circ - 2x) = 2x - 60^\circ$$
$$\angle CHE = \angle FGH \Rightarrow 420^\circ - 4x = 2x - 60^\circ \Rightarrow x = 80^\circ$$

Therefore, $\angle BAC = 180^\circ - 2 \cdot 80^\circ = 20^\circ$, so $\angle GFE = 2\angle FAE = \boxed{40^\circ.}$ □

Problem 4.4.5 (Problem 5)**.** (*5 points*) Find the greatest possible value of $pq + r$, where p, q, and r are (not necessarily distinct) prime numbers satisfying $pq + qr + rp = 2024$.

Solution. If each of p, q, and r is an odd prime, then $pq + qr + rp$ is odd, thus cannot be equal to 2016.

If $p = 2$, then $qr + 2(q + r) = 2024$, so qr is even, so q or r is even. If $q = 2$ then $4 + 4r = 2024 \Rightarrow r = 505$.

But then r is not a prime number. Thus there is $\boxed{\text{no solution.}}$ □

Problem 4.4.6 (Problem 6)**.** (*5 points*) n the least positive integer of the form $\overline{abbabb}$, where a and b are distinct digits, such that the integer can be written as a product of six distinct primes. Find the sum of these primes.

Solution. Let $n = \overline{abb}$, then the given number is $1001n = 7 \cdot 11 \cdot 13 \cdot n$. Thus n must be the least three-digit number that is a product of three distinct primes other than 7, 11, 13.

Now if $a = 1$, then n is odd and $n \geq 3 \cdot 5 \cdot 17 = 255 > \overline{1b1} = n$.

If $a = 2$, and since 3, 5, 17 are the least primes that satisfy $3 \cdot 5 \cdot 17 = 255$, Thus $n = 255255$.

Hence $3 + 5 + 7 + 11 + 13 + 17 = \boxed{56.}$ □

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Problem 4.4.7 (Problem 7)**.** (*5 points*) Henry rolls a fair die. If the die shows the number k, Henry will then roll the die k more times. The probability that Henry will never roll a 1, 3 or a 6 either on his first roll or on one of the k subsequent rolls is given by $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m+n$.

Solution. In order to never roll a $1, 3$ or 6, Henry needs to roll $k = 2, 4$, or 5 on his first roll, and then no $1, 3$ or 6, on any of the k subsequent rolls.

The probability that Henry does not roll a $1, 3$ or 6, on a single throw is $\frac{3}{6} = \frac{1}{2}$. Thus, the probability that Henry will never roll a 1, 3 or a 6 on any of his roll is

$$\frac{1}{6}\left(\frac{1}{2}\right)^2 + \frac{1}{6}\left(\frac{1}{2}\right)^4 + \frac{1}{6}\left(\frac{1}{2}\right)^5 = \frac{11}{192}.$$

Hence, $m + n = 11 + 192 = \boxed{203.}$ □

Problem 4.4.8 (Problem 8)**.** (*5 points*) The cubic polynomials $p(x)$ and $q(x)$ satisfy

$$\begin{cases} p(1) = q(2) \\ p(3) = q(4) \\ p(5) = q(6) \\ p(7) = q(8) + 13 \end{cases}$$

Find $p(11) - q(12)$.

Solution. Since $p(x)$ and $q(x)$ are cubic polynomials, thus $r(x) = p(x) - q(x+1)$ is also a cubic polynomial. Furthermore $r(1) = r(3) = r(5) = 0$, thus $1, 3$, and 5 are all of its roots, therefore:

$$r(x) = a(x-1)(x-3)(x-5), \text{ where } a \text{ is a real constant.}$$

$r(7) = 13 \Rightarrow a(6)(4)(2) = 13 \Rightarrow a = \frac{13}{48}$.

Hence, $p(11) - q(12) = r(11) = \frac{13}{48}(10)(8)(6) = \boxed{130.}$ □

Problem 4.4.9 (Problem 9)**.** (*5 points*) The Tasty Candy Company always puts the same number of pieces of candy into each one-pound bag of candy they sell. Mike bought 4 one-pound bags and gave each person in his class 15 pieces of candy. Mike had 19 pieces of candy left over. Betsy bought 5 one-pound bags and gave 19 pieces of candy to each teacher in her school. Betsy had 15 pieces of candy left over. Find the least number of pieces of candy the Tasty Candy Company could have placed in each one-pound bag.

Solution. We show a coding solution. The problem is equivalent to look for the first positive integer n in ascending order such that:

$$\begin{cases} 4n \equiv 19 \pmod{15} \\ 5n \equiv 15 \pmod{19} \end{cases}$$

```
n = 1
while True:
    if (4*n - 19 )% 15 == 0 and (5*n - 15 )% 19 == 0:
        print(n)
        break
    n +=1
```

The answer is $\boxed{136.}$ □

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Problem 4.4.10 (Problem 10)**.** (*5 points*) Jar #1 contains five red marbles, three blue marbles, and one green marble. Jar #2 contains five blue marbles, three green marbles, and one red marble. Jar #3 contains five green marbles, three red marbles, and one blue marble.

You randomly select one marble from each jar.

Given that you select one marble of each color, the probability that the red marble came from jar #2, the blue marble came from jar #3, and the green marble came from jar #1 can be expressed as $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m+n$.

Solution. Let the triple (a,b,c) represent the event that the red marble came from jar #a, the blue marble came from jar #b, and the green marble came from jar #c, then the probability of $(1,2,3)$ is $\left(\frac{5}{9}\right)^3$, the probabilities of $(1,3,2)$, $(2,1,3)$, and $(3,2,1)$ are each $\frac{5}{9}\frac{3}{9}\frac{1}{9}$, the probability of $(3,1,2)$ is $\left(\frac{3}{9}\right)^3$, and the probability of $(2,3,1)$ is $\left(\frac{1}{9}\right)^3$.

Thus, the required probability is

$$\frac{\left(\frac{1}{9}\right)^3}{\left(\frac{5}{9}\right)^3+3\frac{5}{9}\frac{3}{9}\frac{1}{9}+\left(\frac{3}{9}\right)^3+\left(\frac{1}{9}\right)^3}=\frac{1}{198}.$$

Thus $m+n=1+198=\boxed{199.}$ □

Problem 4.4.11 (Problem 11)**.** (*5 points*) Positive integers a,b,c,d, and e satisfy the equations

$$\begin{cases}(a+1)(3bc+1)=d+3e+1\\(b+1)(3ca+1)=3d+e+13\\(c+1)(3ab+1)=4(26-d-e)-1\end{cases}$$

Find $a+b+c+d+e$.

Solution. Adding the three equations together yields

$$9abc+3(ab+bc+ca)+(a+b+c)+3=117\Rightarrow 27abc+9(ab+bc+ca)+3(a+b+c)+1=343$$
$$\Rightarrow(3a+1)(3b+1)(3c+1)=7^3.$$

Since a,b,c are positive integers, thus $3a+1,3b+1,3c+1\geq 4$, so the only possible factorization of 7^3 into a product of three factors each at least 4 isosceles $3a+1=3b+1=3c+1=7$, so $a=b=c=4$.

Thus $d+3e+1=38, 3d+e+13=38$, so $d=5, e=11$. Hence $a+b+c+d+e=2+2+2+5+11=\boxed{24.}$ □

Problem 4.4.12 (Problem 12)**.** (*5 points*) On equilateral $\triangle ABC$ point D lies on BC a distance 1 from B, point E lies on AC a distance 1 from C, and point F lies on AB a distance 1 from A. Segment AD, BE, and CF intersect in pairs at points G, H, and J which are the vertices of another equilateral triangle. The area of $\triangle ABC$ is twice the area of $\triangle GHJ$. The side length of $\triangle ABC$ can be written $\frac{r+\sqrt{s}}{t}$, where r,s, and t are relatively prime positive integers. Find the value of the product rst.

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Solution. Let d be the side length of $\triangle ABC$. Let point K, L, and M be the projections onto side BC of points G, A, and E, respectively, as shown. Let x and y be the length of BK and GK.

Because $\triangle ECM$ is $30-60-90$ with hypotenuse $CE = 1$, so $EM = \frac{\sqrt{3}}{2}$, and $CM = \frac{1}{2}$.

$$\triangle EMB \sim \triangle GKB \Rightarrow \frac{EM}{MB} = \frac{GK}{KB} \Rightarrow \frac{\frac{\sqrt{3}}{2}}{d - \frac{1}{2}} = \frac{y}{x}$$

$$\triangle ALD \sim \triangle GKD \Rightarrow \frac{AL}{LD} = \frac{GK}{KD} \Rightarrow \frac{\frac{d\sqrt{3}}{2}}{\frac{d}{2} - 1} = \frac{y}{x-1}$$

$$\Rightarrow \frac{x\sqrt{3}}{2d-1} = \frac{d\sqrt{3}(x-1)}{d-2} \Rightarrow x = \frac{d(2d-1)}{2(d^2-d+1)},\ y = \frac{d\sqrt{3}}{2(d^2-d+1)}.$$

$$[ABC] = \frac{d^2\sqrt{3}}{4} \Rightarrow [GHJ] = \frac{d^2\sqrt{3}}{8}$$

$$[BCE] = [CAF] = [ABD] = \frac{d\sqrt{3}}{4},\ [BDG] = [CEH] = [AFJ] = \frac{y}{2} = \frac{d\sqrt{3}}{4(d^2-d+1)}$$

$$\Rightarrow \frac{d^2\sqrt{3}}{8} = 3\frac{d\sqrt{3}}{4} - 3\frac{d\sqrt{3}}{4(d^2-d+1)} \Rightarrow d(d^2-7d+7) = 0,\ d > 1 \Rightarrow d = \frac{7+\sqrt{21}}{2}$$

Thus the desired product $7 \cdot 21 \cdot 2 = \boxed{294.}$ $\square$

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Problem 4.4.13 (Problem 13)**.** (*5 points*) In $\triangle ABC$, $\cos(\angle A) = \frac{\sqrt{5}}{5}$, $\cos(\angle B) = \frac{3}{5}$, $BC = 17$. Find AB.

Solution. It is easy to see that $\sin(\angle A) = \sqrt{1 - \cos^2(\angle A)} = \frac{2\sqrt{5}}{5}$ ($\sin(\angle A) > 0$), similarly $\sin(\angle B) = \frac{4}{5}$.

$$\sin(\angle C) = \sin(\angle A + \angle B) = \sin(\angle A)\cos(\angle B) + \sin(\angle B)\cos(\angle A) = \frac{2\sqrt{5}}{5} \cdot \frac{3}{5} + \frac{4}{5} \cdot \frac{\sqrt{5}}{5} = \frac{2\sqrt{5}}{5}$$

Thus $\angle C = \angle A$, so $AB = BC = \boxed{17.}$ □

Problem 4.4.14 (Problem 14)**.** (*5 points*) Nine dots are arranged in a three by three grid as shown. The distance between any two dots in the grid is the minimum number of horizontal and vertical steps along the grid lines it takes to get from one dot to the other. For example, two adjacent dots are a distance 1 apart, and two dots at opposite corners of the grid are a distance 6 apart.

The mean distance between two distinct dots in the grid is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. There are $\binom{9}{2} = 36$ pairs of points in the grid.

For $3 \cdot \binom{3}{2} = 9$ of the pairs of points (the same column), the horizontal distance between the points is 0.

For $2 \cdot 3 \cdot 3 = 18$ of the pairs of points, the horizontal distance between the points is 1.

For $1 \cdot 3 \cdot 3 = 9$ of the pairs of points, the horizontal distance between the points is 2.

Thus, the sum of all the horizontal distances between pairs of points for all the pairs is

$$0 \cdot 9 + 1 \cdot 18 + 2 \cdot 9 = 36.$$

This also is the sum of all the vertical distances between pairs of points for all the pairs.

Thus, the mean distances between points is $\dfrac{2 \cdot 36}{36} = \dfrac{2}{1}$. Hence $m + n = 2 + 1 = \boxed{3.}$ □

Problem 4.4.15 (Problem 15)**.** (*5 points*) Find the largest prime p such that p divides $2^{p+2}+3^{p+2}+5^{p+2}+7^{p+2}$.

Solution. Fermat's Little Theorem states that if p is a prime that does not divides a, then $a^{p-1} \equiv 1 \pmod{p}$.

Let's assume that $p > 7$, then

$$2^{p+1} + 3^{p+1} + 5^{p+1} + 7^{p+1} \equiv 2^3 + 3^3 + 5^3 + 7^3 = 503 \pmod{p}.$$

Thus $p \mid 503$. The largest such prime is $\boxed{503}$. □

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Problem 4.4.16 (Problem 16)**.** (*5 points*) For n measured in degrees,

$$\text{let } T(n) = \cos^2(30^\circ - n) - \cos(30^\circ - n)\cos(30^\circ + n) + \cos^2(30^\circ + n). \text{ Evaluate } 4\sum_{n=1}^{2024} n \cdot T(n).$$

Solution. By the Double Angle formula for cosine and the Prosthaphaeresis formulas, and $\cos(60^\circ) = \frac{1}{2}$, thus

$$\begin{cases} 2\cos^2(30^\circ - n) = 1 + \cos(60^\circ - 2n) = 1 + \cos(60^\circ)\cos(2n) + \sin(60^\circ)\sin(2n) \\ 2\cos(30^\circ - n)\cos(30^\circ + n) = \cos(60^\circ) + \cos(2n) \\ 2\cos^2(30^\circ + n) = 1 + \cos(60^\circ + 2n) = 1 + \cos(60^\circ)\cos(2n) - \sin(60^\circ)\sin(2n) \end{cases}$$

$$\Rightarrow 2T(n) = 2 + 2\cos(60^\circ)\cos(2n) - \cos(60^\circ) - \cos(2n) = \frac{3}{2}$$

$$\Rightarrow 4\sum_{n=1}^{2024} n \cdot T(n) = 4 \cdot \sum_{n=1}^{2024} n \cdot \frac{3}{4} = 3 \cdot \frac{2024 \cdot 2025}{2} = \boxed{6147900.}$$

□

Problem 4.4.17 (Problem 17)**.** (*5 points*) Find the sum of all values of b such that there are positive integers a and b satisfying $(a-b)\sqrt{ab} = 840$.

Solution. Let $d = \gcd(a, b)$, then $d \mid \sqrt{ab}, d \mid a - b \Rightarrow d^2 \mid 840 = 2^3 \cdot 3 \cdot 5 \cdot 7$. This means that d is 1 or 2.

Furthermore, let $a = dr, b = ds$, then $\gcd(r, s) = 1$. Since $d^2(r-s)\sqrt{rs} = 840$, thus each of r and s is a perfect square. In other words, there exist positive integers m and n,

$$a = dm^2,\ b = dn^2,\ \gcd(m, n) = 1,\ d^2(m^2 - n^2)mn = 2^3 \cdot 3 \cdot 5 \cdot 7.$$

Case 1: $d = 1$.

$$(m-n)(m+n)mn = 2^3 \cdot 3 \cdot 5 \cdot 7.$$

If one of m or n is even, then the other has to be odd and both $m - n, m + n$ are odd. Thus one of m or n is divisible by 8.

If n is divisible by 8, then $m - n \geq 1$, $mn \geq 72$, $m + n \geq 15$, which is too large.

Thus m is divisible by 8, then if m is divisible by 3, 5, or 7, then $mn \geq 24$, $m + n \geq 25$ and $(m-n)(m+n)mn \geq 24 \cdot 25(m-n) = 600(m-n)$, so $m - n = 1$, thus

$$(2m-1)m(m-1) = 840 > 2(m-1)^3 \Rightarrow 7 \geq m.$$

Thus m is divisible by 8, and it cannot be divisible by 3, 5, or 7, and so $m = 8$. In that case $n = 7$, and $(a, b) = (64, 49)$ is a solution.

If both m and n are odd, it is easy to see that $n > 1$. So if $m > 7$, then $m \geq 3 \cdot 5 = 15$, thus

$$(m-n)(m+n)mn \geq 2 \cdot (3 + 15) \cdot 15 \cdot 3 = 1620 > 840.$$

Thus $m = 7$, then

$$(7-n)(7+n)7(n) = 840 \Rightarrow n = 5 \text{ or } 3.$$

And $(a, b) = (49, 25)$, or $(a, b) = (49, 9)$.

Case 2: $d = 2$.

$$(m-n)(m+n)mn = 2 \cdot 3 \cdot 5 \cdot 7.$$

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Both m or n cannot be even, and since both cannot be odd, so one is even and the other is odd.

If $n = 1$ then $(m^2 - 1)m = 210 \Rightarrow m = 6$, then $(a, b) = (72, 2)$.

If $n > 1$ then $n, m - n, m, m + n$ are four different pair-wise relatively prime numbers, whose product is $2 \cdot 3 \cdot 5 \cdot 7$. It is easy to see that $m - n$ can only be 3 there for $n = 2$, thus $m = 5$, and $(a, b) = (50, 8)$.

Hence, there are four solutions $\{(64, 49), (49, 25), (49, 9), (72, 2), (50, 8)\}$, and the sum of all values of a is $49 + 25 + 9 + 2 + 8 = \boxed{93.}$ □

Problem 4.4.18 (Problem 18)**.** (*5 points*) A container the shape of a pyramid has a 8×8 square base, and the other four edges each have length 9. The container is partially filled with liquid so that when one of its triangular faces is lying on a flat surface, the level of the liquid is half the distance from the surface to the top edge of the container.

The volume of the liquid in the container is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. A square pyramid with base side b and base to the apex height h has a volume $\frac{1}{3}b^2h$. Let s be the length of the other four edges. The height to the apex can be calculated considering the cross section of the pyramid that contains the apex, and two opposite corners of the square base. This cross section is an isosceles triangle with base $b\sqrt{2}$ and two sides equal to s,

$$h^2 = s^2 - \left(\frac{1}{2}b\sqrt{2}\right)^2 = s^2 - \frac{b^2}{2} = 9^2 - \frac{8^2}{2} \Rightarrow h = 7 \Rightarrow V = \frac{1}{3}b^2h = \frac{448}{3}.$$

When lying on its side, the portion of the pyramid containing no liquid can be partitioned into two sections, one shaped like the original pyramid by half its size and a skewed triangular prism.

The volume of the pyramid is $\frac{1}{2^3}\frac{448}{3} = \frac{56}{3}$. The prism has a triangular cross section with base equal to $\frac{b}{2} = 4$, and height equal to $\frac{h}{2} = \frac{7}{2}$ so the area of the triangle is $\frac{1}{2} \cdot 4 \cdot \frac{7}{2} = 7$. The length of the prism is $\frac{b}{2} = 4$, so the volume of the prism is $4 \cdot 7 = 28$.

This means that the volume of the portion of the container that does not contain liquid is $\frac{56}{3} + 28 = \frac{140}{3}$. Hence, the volume of the liquid is $\frac{448}{3} - \frac{140}{3} = \frac{136}{1}$, and $m + n = 136 + 1 = \boxed{137.}$ □

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Problem 4.4.19 (Problem 19)**.** (*5 points*) Find the sum of all the possible values of the product xy such that x and y are positive integers satisfying

$$(x^2+1)(y^2+1)+2(x-y)(1-xy)=4(1+xy)+96.$$

Solution. Note that

$$\begin{aligned}(x^2+1)(y^2+1)&=(xy)^2+x^2+y^2+1=(xy)^2-2xy+1+x^2-2xy+y^2+4xy\\&=(1-xy)^2+(x-y)^2+4xy=(1-xy+x-y)^2-2(x-y)(1-xy)+4xy\\\Rightarrow 100&=(x^2+1)(y^2+1)+2(x-y)(1-xy)-4xy=(1-xy+x-y)^2\Rightarrow(1+x)^2(1-y)^2=100.\end{aligned}$$

Since x, y are positive integers, thus

$$(x+1,y-1)\in\{(2,5),(5,2),(10,1)\}\Rightarrow(x,y)\in\{(1,6),(4,3),(9,2)\}\Rightarrow xy\in\{6,12,18\}$$

Hence, the desired sum is $6+12+18=\boxed{36.}$ □

Problem 4.4.20 (Problem 20)**.** (*5 points*) Eight square tiles are placed in a row, and each can be painted with one of the three colors red (R), yellow (Y), and blue (B). Find the number of ways this can be done so that each block of four adjacent tiles contains at least one tile of each color. That is, count the patterns RBYRBYB and BYRYBRY but not RBYYBRYR because the four adjacent tiles colored BYYB does not include the color red.

Solution. We show a coding solution. The problem is equivalent to count all a base-3 number between 0 and 3^8. For the numbers has less then 8 digits, we add as many digits 0 to the left of the numbers as needed to create a 8-digit base-3 numbers Then for each of these base-3 number, we look at every block of 3 consecutive digit to make sure that it contains three different digits.

```
def to_base(number, base):
    digits = []
    while number:
        digits.append(number % base)
        number //= base
    return list(reversed(digits))

count = 0
for i in range(0, 3**10):
    s = to_base(i, 3)
    if len(s) < 8:
        s = [0 for j in range(len(s), 8)] + s
    found = True
    for j in range(0, 5):
        if len(set([e for e in s[j: j+4]])) < 3:
            found = False
            break
    if found:
        count +=1
print(count)
```

The answer is $\boxed{444.}$ □

Problem 4.4.21 (Problem 21)**.** (*5 points*) Some **unit** spheres are piled in 10 layers in the shape of a square pyramid with one sphere in the top layer, 4 spheres in the second layer, 9 spheres in the third layer, and so forth so that the bottom layer has a square array of 100 spheres. In each layer the centers of the spheres form a square grid so that each sphere is tangent to any sphere adjacent to it on the grid. Each sphere in an upper level is tangent to the four spheres directly below it.

The diagram shows how the first three layers of spheres are stacked.

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A square pyramid is built around the pile of spheres so that the sides of the pyramid are tangent to the spheres on the outside of the pile. The height of the pyramid is $a + b\sqrt{2} + c\sqrt{3}$, where a, b, and c are positive integers. Find $a + b + c$.

Solution. Let'ss assume that there are n layers. Then the center of any two adjacent spheres are a distance 2 apart. If four spheres in one layer have their centers at four vertices of a 2×2 square, then the centers of the spheres across the square from each other are a distance of $2\sqrt{2}$ apart.

Consider the diagram below on the left showing a cross section of the pile of spheres passing through the center of the sphere on the top layer labelled A, the center of the sphere in the third layer directly below the top sphere labeled C, and the center of a sphere across a 2×2 square from there labeled B. Because AC is vertical, BC is horizontal, $\triangle ABC$ is right triangle with $AB = 4$, $BC = 2\sqrt{2}$., thus $AC = 2\sqrt{2}$. It follows that the vertical distance between the plane containing the centers of spheres at one level of the pile, and the plane containing the center of spheres at the next lower level of the pile is $\sqrt{2}$.

Now, consider the diagram above on the right showing a cross section of the pile of spheres and the enclosing pyramid that passes through the top vertex of the pyramid, the center of the top sphere labeled A, the center of the sphere directly below A in the third level labeled C, and the center of an adjacent sphere in the third level labeled D. Then ACD is a right triangle with legs $AC = 2\sqrt{2}$, $CD = 2$, thus $AD = 2\sqrt{3}$. Let G be a point where the top sphere is tangent to the side of the pyramid. Since $\triangle AFG \sim \triangle CAD$ and $AG = 1$, thus $AF = \sqrt{3}$.

If the pile of sphere has n layers, then the distance between a horizontal plane passing through point A and a plane passing through the centers of the bottom layers is $(n-1)\sqrt{2}$. Since $AF = \sqrt{3}$, and the centers of the spheres are a distance 1 from the bottom of the pyramid, the height of the pyramid is given by

$$(n-1)\sqrt{2} + 1 + \sqrt{3}.$$

Now, since $n = 10$, thus the height is

$$a + b\sqrt{2} + c\sqrt{3} = 1 + 9\sqrt{2} + \sqrt{3} \Rightarrow a = 1, b = 9, c = 1.$$

Thus $a + b + c = \boxed{11.}$ $\square$

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Chapter 5

Session 3: Feb 16 - Feb 24

5.1 Middle School - Assignment

Middle school students: grade 8 (US, CA), grade 9 (FR, UK, VN) and younger.

- **Submission deadline: Friday, February 23**
- **Test: Saturday, February 24**
- **Official solutions: Monday, February 26**
- **Intermediate (I) level: Problems 1-10**
- **Advanced (A) level: Problems 6-15**

If you submit solution based on coding, please make sure that your submission is compliant. Read the introduction chapter for more information.

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Problem 5.1.1 (Problem 1)**.** (*5 points*) A picture with an area of 160 square inches is surrounded by a 2 inch border. The picture with its border is a rectangle twice as long as it is wide. How many inches long is that rectangle?

Solution. Let the width and length of the rectangle be w and $2w$. Then the picture is $w-4$ wide and $2w-4$ long. Its area $(w-4)(2w-4)$ is 160, so $w^2-6w-72=0$, so $w=12$. Thus $2w=\boxed{24.}$ □

Problem 5.1.2 (Problem 2)**.** (*5 points*) Pete's research shows that the number of nuts collected by the squirrels in any park is proportional to the square of the number of squirrels in that park. If Pete notes that four squirrels in a park collect 60 nuts, how many nuts are collected by 20 squirrels in a park?

Solution. The ratio of the number of nuts collected by 20 squirrels to the number collected by four squirrels is $\left(\frac{20}{4}\right)^2=25$. Thus 20 squirrels will collect $60\cdot 25=\boxed{1500.}$ □

Problem 5.1.3 (Problem 3)**.** (*5 points*) How many seven-digit positive integers do not either start or end with 7?

Solution. When selecting the seven-digit positive integer which does not either start or end with 7, there are 8 choices for the first digit (neither 0 or 7), 9 choices for the last digit (not 7), and 10 choices for each of the other five digits. Thus, there are $8\cdot 9\cdot 10^5=\boxed{7\ 200\ 000}$ choices. □

Problem 5.1.4 (Problem 4)**.** (*5 points*) Asheville, Bakersfield, Charter, and Darlington are four small towns along a straight road in that order. The distance from Bakersfield to Charter is one-third the distance from Asheville to Charter and one-quarter the distance from Bakersfield to Darlington. If it is 12 miles from Bakersfield to Charter, how many miles is it from Asheville to Darlington?

Solution. Since the distance from Bakersfield to Charter is one-third the distance from Asheville to Charter, the distance from Asheville to Charter is $3\cdot 12=36$. Similarly, the distance from Bakersfield to Darlington is $4\cdot 12=48$. It follows that the distance from Asheville to Darlington is $36+48-12=\boxed{72.}$ □

Problem 5.1.5 (Problem 5)**.** (*5 points*) Find the sum of all four-digit integers whose digits are a rearrangement of the digits 1, 2, 3, 4, such as 1234, 1432, or 3124.

Solution. There are 4! permutations of the digits 1234. In these permutations each of the four digits appear in each location (thousands, hundreds, tens, unit) exactly 6 times. Thus the sum of all the numbers is $6(1+2+3+4)(1111)=\boxed{66660.}$ □

Problem 5.1.6 (Problem 6)**.** (*5 points*) Find the least positive integer k so that the mean of the numbers $k, k+1, k+2, k+3, \ldots, 2k$ exceeds 200.

Solution. The numbers $k, k+1, k+2, k+3, \ldots, 2k$ form an arithmetic sequence, thus the mean is the average of the first and last terms:

$$\frac{k+2k}{2}=\frac{3k}{2}.$$

If this exceeds 200, then $k>\frac{2\cdot 200}{3}$, or $k\geq\boxed{134.}$ □

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Problem 5.1.7 (Problem 7)**.** (*5 points*) In the following diagram two sides of a square are tangent to a circle with diameter 8. One corner of the square lies on the circle. There are positive integers m and n so that the area of the square is $m + \sqrt{n}$. Find $m + n$.

Solution. Let the center of the circle be A, and the corner of the square on the circle be D. Let B and F be points on the sides of the squares so BF perpendicular to the sides of the square so that A lies on BF as shown.

$\triangle ADF$ is isosceles, AD is the radius of length 4, thus $AF = \frac{4}{\sqrt{2}} = 2\sqrt{2}$.

$$BF = AB + AF = 4 + 2\sqrt{2}.$$

So the area of the square is $(4 + 2\sqrt{2})^2 = 24 + 16\sqrt{2} = 24 + \sqrt{512}$. Thus, $m + n = 24 + 512 = \boxed{536.}$ □

Problem 5.1.8 (Problem 8)**.** (*5 points*) Find integer n such that both $n - 86$ and $n + 86$ are perfect squares.

Solution. Let $k^2 = n + 86, \ell^2 = n - 86$, then $k^2 - \ell^2 = 172 = 2^2 \cdot 43$. Thus $(k - \ell)(k + \ell) = 2^2 \cdot 43$. Since both $k - \ell, k + \ell$ have the same parity and their product is even, so both are even: $k - \ell = 2, k + \ell = 86$, so $k = 44, \ell = 42$.

Hence, $n = 42^2 + 86 = \boxed{1850.}$ □

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Problem 5.1.9 (Problem 9)**.** (*5 points*) Find n so that $4^{4^{4^2}} = 2^{8^n}$.

Solution.

$$4^{4^{4^2}} = 2^{2\cdot 4^{4^2}},\ 8^n = 2^{3n} \Rightarrow 2\cdot 4^{4^2} = 2^{3n} \Rightarrow 2^{2\cdot 4^2} = 2^{3n-1} \Rightarrow 2\cdot 4^2 = 3n-1 \Rightarrow n = \boxed{11.}$$

□

Problem 5.1.10 (Problem 10)**.** (*5 points*) How many triangles appear in the diagram below?

Solution. First, note that all of the triangles in the diagram are isosceles right triangles whose hypotenuses are either horizontal, vertical, of on an 45° diagonal.

The diagram is made up of 16 small squares which each contain two small triangles. This accounts for 32 small triangles.

Now, count the larger triangles with horizontal hypotenuses, 12 have hypotenuses made up of sides of two of the small squares, and 2 have hypotenuses made up of side of four of small squares for a total of 14 triangles.

Similarly, there are also 14 triangles with vertical hypotenuses.

There are 16 triangles whose hypotenuses are diagonal lines made up of the diagonals from two small squares, and 8 triangles whose hypotenuses are diagonal lines made up of the diagonals from three small squares.

Hence, the number of triangles is $32 + 14 + 14 + 16 + 8 = \boxed{84.}$ □

Problem 5.1.11 (Problem 11)**.** (*5 points*) Let a, b, and c be positive real numbers such that $a^2+b^2+c^2 = 989$ and $(a+b)^2 + (b+c)^2 + (c+a)^2 = 2013$. Find $a+b+c$.

Solution.

$$1024 = 2013-989 = \left[(a+b)^2 + (b+c)^2 + (c+a)^2\right] - \left(a^2+b^2+c^2\right) = a^2+b^2+c^2+2ab+2bc+2ca = (a+b+c)^2$$

Thus, $a+b+c = \boxed{32.}$ □

Problem 5.1.12 (Problem 12)**.** (*5 points*) A quarry wants to sell a large pile of gravel. At full price, the gravel would sell for 3200 dollars. But during the first week the quarry only sells 60% of the gravel at full price. The following week the quarry drops the price by 10%, and, again, it sells 60% of the remaining gravel. Each week, thereafter, the quarry reduces the price by another 10% and sells 60% of the remaining gravel. This continues until there is only a handful of gravel left. How many dollars does the quarry collect for the sale of all its gravel?

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Solution. The first week 60% of the gravel is sold for the revenue of 3200(0.6)

The following week the revenue is 3200(0.4)(0.9)(0.6). Each week, 40% of the gravel from the previous week remains, and 60% of it is sold at 90% of the previous price. Thus, during week k, the quarry has a revenue of $3200(0.6)[(0.9)(0.4)]^{k-1}$.

It follows that the total revenue to the quarry is given by the geometric series

$$\sum_{k=1}^{\infty} 3200(0.6)[(0.9)(0.4)]^{k-1} = 3200(0.6)\sum_{k=0}^{\infty}(0.36)^k = 3200(0.6)\frac{1}{1-0.36} = \frac{3200(0.6)}{0.64} = \boxed{3000.}$$

□

Problem 5.1.13 (Problem 13)**.** (*5 points*) A rectangle has side lengths 6 and 8. There are relatively prime positive integers m and n so that $\frac{m}{n}$ is the probability that a point randomly selected from the inside of the rectangle is closer to a side of the rectangle than to either diagonal of the rectangle. Find $m+n$.

Solution. Let the vertices of the rectangle be A, B, C, and D with side $AB = 6$ and $AD = 8$. Let E be the center of the rectangle. Then

$$AE = BE = CE = DE = \frac{1}{2}AC = \frac{1}{2}\sqrt{6^2+8^2} = 5.$$

Let F and r be the incenter and inradius of the $\triangle AED$. Then

$$[AED] = \frac{1}{2}(8\cdot 3) = \frac{8r+5r+5r}{2} \Rightarrow r = \frac{4}{3}.$$

The region with in $\triangle AED$ where the points are closer to side AD to either diagonal AE or DE is the $\triangle AFD$. The area of $\triangle AFD$ is $\frac{1}{2}\cdot 8\cdot\frac{4}{3} = \frac{16}{3}$.

Similarly the area of the region of $\triangle AEB$ of points closer to AB than to either diagonal AE or BE is $\frac{9}{2}$.

The desired probability is

$$\frac{2\frac{16}{3}+2\frac{9}{2}}{6\cdot 8} = \frac{59}{144} \Rightarrow m+n = 59+144 = \boxed{203.}$$

□

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Problem 5.1.14 (Problem 14)**.** (*5 points*) Six children stand in a line outside their classroom. When they enter the classroom, they sit in a circle in random order. There are relatively prime positive integers m and n so that $\frac{m}{n}$ is the probability that no two children who stood next to each other in the line end up sitting next to each other in the circle. Find $m + n$.

Solution. Let the children be numbered $1, 2, 3, 4, 5$, and 6 in order that they were standing in the line. There are $5! = 120$ equally likely arrangements of these children when they sit in a circle.

To count the number of arrangements where no child sits next to a child that he/she was next to in the original line, consider where the children number 3 and 4 sit.

If child 3 sits opposite child 4, then children 2 and 5 can either sit opposite each other (2 ways) or next to each other (4 ways).

If child 3 and 4 sit with one child between them, then the child between them must be either 1 (2 ways) or 6 (2 ways).

This gives 10 possible arrangements of the children as shown in the diagram below.

The desired probability is $\frac{10}{120} = \frac{1}{12}$. The sum is $m + n = 1 + 12 = \boxed{13}$. □

Problem 5.1.15 (Problem 15)**.** (*5 points*) For positive integer n let an be the integer consisting of n digits of 9 followed by the digits 488. For example, $a_3 = 999,488$ and $a_7 = 9,999,999,488$. Find the value of n so that a_n is divisible by the highest power of 2.

Solution. Note that

$$a_n = 10^{n+3} - 512 = 2^{n+3}5^{n+3} - 2^9.$$

If $n < 6$, then $a_n = 2^{n+3}(5^{n+3} - 2^{6-n})$, and the highest power of 2 divides a_n is $2^{n+3} < 2^9$.

If $n > 6$, then $a_n = 2^9(2^{n-6}5^{n+3} - 1)$, and the highest power of 2 divides a_n is 2^9.

If $n = 6$, then $a_6 = 2^9(5^9 - 1)$, which is divisible by at least 2^{10}.

Hence, the value of n is $\boxed{6}$. □

5.2 Middle School - Test

You have **30 minutes** to complete the test. You have to **submit only the answers**. No solution is required.

Note that you have to **follow the instructions by the COs** *for submitting the answers.*

- **Intermediate (I) level: Problems 1-10**
- **Advanced (A) level: Problems 6-15**

If you submit solution based on coding, please make sure that your submission is compliant. Read the introduction chapter for more information.

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Problem 5.2.1 (Problem 1)**.** (*5 points*) A picture with an area of 180 square inches is surrounded by a 1 inch border. The picture with its border is a rectangle twice as long as it is wide. How many inches long is that rectangle?

Solution. Let the width and length of the rectangle be w and $2w$. Then the picture is $w-2$ wide and $2w-2$ long. Its area $(w-2)(2w-2)$ is 180, so $w^2-3w-88=0$, so $w=11$. Thus $2w=\boxed{22.}$ □

Problem 5.2.2 (Problem 2)**.** (*5 points*) Pete's research shows that the number of nuts collected by the squirrels in any park is proportional to the square of the number of squirrels in that park. If Pete notes that four squirrels in a park collect 15 nuts, how many nuts are collected by 16 squirrels in a park?

Solution. The ratio of the number of nuts collected by 16 squirrels to the number collected by four squirrels is $\left(\frac{16}{4}\right)^2=16$. Thus 16 squirrels will collect $15\cdot 16=\boxed{240.}$ □

Problem 5.2.3 (Problem 3)**.** (*5 points*) How many six-digit positive integers do not either start or end with 7?

Solution. When selecting the six-digit positive integer which does not either start or end with 7, there are 8 choices for the first digit (neither 0 or 7), 9 choices for the last digit (not 7), and 10 choices for each of the other four digits. Thus, there are $8\cdot 9\cdot 10^4=\boxed{720\ 000}$ choices. □

Problem 5.2.4 (Problem 4)**.** (*5 points*) Asheville, Bakersfield, Charter, and Darlington are four small towns along a straight road in that order. The distance from Bakersfield to Charter is one-third the distance from Asheville to Charter and one-quarter the distance from Bakersfield to Darlington. If it is 18 miles from Bakersfield to Charter, how many miles is it from Asheville to Darlington?

Solution. Since the distance from Bakersfield to Charter is one-third the distance from Asheville to Charter, the distance from Asheville to Charter is $3\cdot 18=54$. Similarly, the distance from Bakersfield to Darlington is $4\cdot 18=72$. It follows that the distance from Asheville to Darlington is $54+72-18=\boxed{108.}$ □

Problem 5.2.5 (Problem 5)**.** (*5 points*) Find the sum of all three-digit integers whose digits are a rearrangement of the digits 1, 2, 3, 4, such as 123, 142, or 324.

Solution. There are $\binom{4}{3}=4$ ways to choose three digits out of 1,2,3,4, let them be a,b,c.

There are 3! permutations of the three chosen digits a,b,c. In these permutations each of the three digits appear in each location (hundreds, tens, unit) exactly 2 times. Thus the sum of all the numbers is $2(a+b+c)(111)$.

The total is $222((1+2+3)+(1+2+4)+(1+3+4)+(2+3+4))=\boxed{6660.}$ □

Problem 5.2.6 (Problem 6)**.** (*5 points*) Find the least positive integer k so that the mean of the numbers $k,k+1,k+2,k+3,\ldots,2k$ exceeds 300.

Solution. The numbers $k,k+1,k+2,k+3,\ldots,2k$ form an arithmetic sequence, thus the mean is the average of the first and last terms:

$$\frac{k+2k}{2}=\frac{3k}{2}.$$

If this exceeds 300, then $k>\frac{2\cdot 300}{3}=200$, or $k\geq\boxed{201.}$ □

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Problem 5.2.7 (Problem 7)**.** (*5 points*) In the following diagram two sides of a square are tangent to a circle with diameter 8. One corner of the square lies on the circle. There are positive integers m and n so that the area of the square is $m + \sqrt{n}$. Find $n - m$.

Solution. Let the center of the circle be A, and the corner of the square on the circle be D. Let B and F be points on the sides of the squares so BF perpendicular to the sides of the square so that A lies on BF as shown.

$\triangle ADF$ is isosceles, AD is the radius of length 4, thus $AF = \frac{4}{\sqrt{2}} = 2\sqrt{2}$.

$$BF = AB + AF = 4 + 2\sqrt{2}.$$

So the area of the square is $(4 + 2\sqrt{2})^2 = 24 + 16\sqrt{2} = 24 + \sqrt{512}$. Thus, $n - m = 512 - 24 = \boxed{488.}$ $\square$

Problem 5.2.8 (Problem 8)**.** (*5 points*) Find the sum of all values of n such that both $n - 70$ and $n + 70$ are perfect squares.

Solution. Let $k^2 = n + 70, \ell^2 = n - 70$, then $k^2 - \ell^2 = 140 = 2^2 \cdot 5 \cdot 7$. Thus $(k - \ell)(k + \ell) = 2^2 \cdot 5 \cdot 7$. Since both $k - \ell, k + \ell$ have the same parity and their product is even, so both are even:

$$\begin{cases} k - \ell = 2, k + \ell = 70 \Rightarrow k = 36, \ell = 34 \Rightarrow n = 1226 \\ k - \ell = 10, k + \ell = 14 \Rightarrow k = 12, \ell = 2 \Rightarrow n = 74 \end{cases}$$

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Hence, the sum of all values of n is $1226 + 74 = \boxed{1300.}$ □

Problem 5.2.9 (Problem 9)**.** (*5 points*) Find n so that $4^{4^{4^2}} = 16^{2^n}$.

Solution.

$$4^{4^{4^2}} = 4^{4^{16}} = 4^{2^{32}} = 4^{2\cdot 2^{31}} = 16^{2^{31}} \Rightarrow n = \boxed{31.}$$

□

Problem 5.2.10 (Problem 10)**.** (*5 points*) The diagram below is made up of 16 unit squares which each contain two small triangles. How many triangles appear in the diagram below which is **not half of a unit square**?

Solution. First, note that all of the triangles in the diagram are isosceles right triangles whose hypotenuses are either horizontal, vertical, of on an 45° diagonal.

The diagram below is made up of 16 small squares which each contain two small triangles. This accounts for 32 small triangles. These are not the ones we want.

Now, count the larger triangles with horizontal hypotenuses, 12 have hypotenuses made up of sides of two of the small squares, and 2 have hypotenuses made up of side of four of small squares for a total of 14 triangles.

Similarly, there are also 14 triangles with vertical hypotenuses.

There are 16 triangles whose hypotenuses are diagonal lines made up of the diagonals from two small squares, and 8 triangles whose hypotenuses are diagonal lines made up of the diagonals from three small squares.

Hence, the number of triangles is $14 + 14 + 16 + 8 = \boxed{52.}$ □

Problem 5.2.11 (Problem 11)**.** (*5 points*) Let a, b, and c be positive real numbers such that $ab+bc+ca = 432$ and $(a+b)^2 + (b+c)^2 + (c+a)^2 = 2024$. Find $a + b + c$.

Solution.

$$2(a^2 + b^2 + c^2) = \left[(a+b)^2 + (b+c)^2 + (c+a)^2\right] - 2(ab + bc + ca) = 1160$$
$$\Rightarrow (a+b+c)^2 = a^2 + b^2 + c^2 + 2ab + 2bc + 2ca = \frac{1160}{2} + 2(432) = 1444.$$

Thus, $a + b + c = \boxed{38.}$ □

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Problem 5.2.12 (Problem 12)**.** (*5 points*) A quarry wants to sell a large pile of gravel. At full price, the gravel would sell for 1600 dollars. But during the first week the quarry only sells 60% of the gravel at full price. The following week the quarry drops the price by 10%, and, again, it sells 60% of the remaining gravel. Each week, thereafter, the quarry reduces the price by another 10% and sells 60% of the remaining gravel. This continues until there is only a handful of gravel left. How many dollars does the quarry collect for the sale of all its gravel?

Solution. The first week 60% of the gravel is sold for the revenue of 1600(0.6)

The following week the revenue is 1600(0.4)(0.9)(0.6). Each week, 40% of the gravel from the previous week remains, and 60% of it is sold at 90% of the previous price. Thus, during week k, the quarry has a revenue of $1600(0.6)[(0.9)(0.4)]^{k-1}$.

It follows that the total revenue to the quarry is given by the geometric series

$$\sum_{k=1}^{\infty} 1600(0.6)[(0.9)(0.4)]^{k-1} = 1600(0.6)\sum_{k=0}^{\infty}(0.36)^k = 1600(0.6)\frac{1}{1-0.36} = \frac{1600(0.6)}{0.64} = \boxed{1500.}$$

□

Problem 5.2.13 (Problem 13)**.** (*5 points*) A rectangle has side lengths 6 and 8. There are relatively prime positive integers m and n so that $\frac{m}{n}$ is the probability that a point randomly selected from the inside of the rectangle is closer to a side of the rectangle than to either diagonal of the rectangle. Find $n - m$.

Solution. Let the vertices of the rectangle be A, B, C, and D with side $AB = 6$ and $AD = 8$. Let E be the center of the rectangle. Then

$$AE = BE = CE = DE = \frac{1}{2}AC = \frac{1}{2}\sqrt{6^2 + 8^2} = 5.$$

Let F and r be the incenter and inradius of the $\triangle AED$. Then

$$[AED] = \frac{1}{2}(8 \cdot 3) = \frac{8r + 5r + 5r}{2} \Rightarrow r = \frac{4}{3}.$$

The region with in $\triangle AED$ where the points are closer to side AD to either diagonal AE or DE is the $\triangle AFD$. The area of $\triangle AFD$ is $\frac{1}{2} \cdot 8 \cdot \frac{4}{3} = \frac{16}{3}$.

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Similarly the area of the region of $\triangle AEB$ of points closer to AB than to either diagonal AE or BE is $\frac{9}{2}$.

The desired probability is

$$\frac{2\frac{16}{3} + 2\frac{9}{2}}{6 \cdot 8} = \frac{59}{144} \Rightarrow n - m = 144 - 59 = \boxed{85.}$$

□

Problem 5.2.14 (Problem 14)**.** (*5 points*) Six children stand in a line outside their classroom. When they enter the classroom, they sit in a circle in random order. There are relatively prime positive integers m and n so that $\frac{m}{n}$ is the probability that no two children who stood next to each other in the line end up sitting next to each other in the circle. Find the difference $n - m$.

Solution. Let the children be numbered $1, 2, 3, 4, 5$, and 6 in order that they were standing in the line. There are $5! = 120$ equally likely arrangements of these children when they sit in a circle.

To count the number of arrangements where no child sits next to a child that he/she was next to in the original line, consider where the children number 3 and 4 sit.

If child 3 sits opposite child 4, then children 2 and 5 can either sit opposite each other (2 ways) or next to each other (4 ways).

If child 3 and 4 sit with one child between them, then the child between them must be either 1 (2 ways) or 6 (2 ways).

This gives 10 possible arrangements of the children as shown in the diagram below.

The desired probability is $\frac{10}{120} = \frac{1}{12}$. The sum is $n - m = 12 - 1 = \boxed{11}$. □

Problem 5.2.15 (Problem 15)**.** (*5 points*) For positive integer n let an be the integer consisting of n digits of 9 followed by the digits 1808. For example, $a_2 = 991,808$ and $a_6 = 9,999,991,808$. Find the value of n so that a_n is divisible by the highest power of 2.

Solution. Note that

$$a_n = 10^{n+4} - 8192 = 2^{n+4}5^{n+4} - 2^{13}.$$

If $n < 9$, then $a_n = 2^{n+4}(5^{n+4} - 2^{9-n})$, and the highest power of 2 divides a_n is $2^{n+4} < 2^{13}$.

If $n > 9$, then $a_n = 2^{13}(2^{n-9}5^{n+4} - 1)$, and the highest power of 2 divides a_n is 2^{13}.

If $n = 9$, then $a_9 = 2^{13}(5^{13} - 1)$, which is divisible by at least 2^{14}.

Hence, the value of n is $\boxed{9}$. □

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5.3 High School - Assignment

High school students: grade 9 (US, CA), grade 10 (FR, UK, VN) and above.

- **Submission deadline: Friday, February 23**
- **Test: Saturday, February 24**
- **Official solutions: Monday, February 26**
- **Intermediate (I) level: Problems 1-10**
- **Advanced (A) level: Problems 8-17**
- **Olympiad (O) level: Problems 16-25**

If you submit solution based on coding, please make sure that your submission is compliant. Read the introduction chapter for more information.

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Problem 5.3.1 (Problem 1)**.** (*5 points*) Find the least positive integer n so that both n and $n+1$ have prime factorizations with exactly four (not necessarily distinct) prime factors.

Solution. One of n and $n+1$ is an odd number. The smallest integer with four prime factors is $3^4 = 81$. But neither 80 or 82 has 4 prime factors. The second smallest is $3^3 \cdot 5 = 135$ and $134 = 2 \cdot 67$, $136 = 2^3 \cdot 17$. The latter one has the desired property. The answer is $\boxed{135.}$ □

Problem 5.3.2 (Problem 2)**.** (*5 points*) Two convex polygons have a total of 33 sides and 243 diagonals. Find the number of diagonals in the polygon with the greater number of sides.

Solution. A convex polygon has n sides then it has $\frac{n(n-1)}{2} - n = \frac{n^2-3n}{2}$ diagonals.

Now

$$243 = \frac{n^2-3n}{2} + \frac{(33-n)^2 - 3(33-n)}{2} = n^2 - 33n + 495 \Rightarrow n^2 - 33n + 252 = 0 \Rightarrow n = 12 \text{ or } n = 21$$

The number of diagonals of the polygon with 21 sides is $\frac{21^2-3\cdot 21}{2} = \boxed{189.}$ □

Problem 5.3.3 (Problem 3)**.** (*5 points*) In the tribe of Zimmer, being able to hike long distances and knowing the roads through the forest are both extremely important, so a boy who reaches the age of manhood is not designated as a man by the tribe until he completes an interesting rite of passage. The man must go on a sequence of hikes. The first hike is a 5 kilometer hike down the main road. The second hike is a $5\frac{1}{4}$ kilometer hike down a secondary road. Each hike goes down a different road and is a quarter kilometer longer than the previous hike. The rite of passage is completed at the end of the hike where the cumulative distance walked by the man on all his hikes exceeds 1000 kilometers. So in the tribe of Zimmer, how many roads must a man walk down, before you call him a man?

Solution. The total distance a man walked in the n hikes is

$$5 + 5\frac{1}{4} + 5\frac{1}{2} + \cdots + \frac{19+n}{4} = \sum_{k=1}^{n} \frac{19+k}{4} = \frac{1}{4}\left(19n + \frac{n(n+1)}{2}\right) = \frac{n(n+39)}{8}$$

The smallest n for $n^2 + 39n > 8 \cdot 1000$ is $n = \boxed{73.}$ □

Problem 5.3.4 (Problem 4)**.** (*5 points*) Find the value of x that satisfies $\log_3(\log_9 x) = \log_9(\log_3 x)$.

Solution. Note that

$$\log_9 x = \frac{\log_3 x}{\log_3 9} \Rightarrow \begin{cases} \log_3(\log_9 x) = \log_3\left(\frac{\log_3 x}{\log_3 9}\right) = \log_3\left(\frac{\log_3 x}{2}\right) \\ \log_9(\log_3 x) = \frac{\log_3(\log_3 x)}{\log_3 9} = \frac{\log_3(\log_3 x)}{2} \end{cases}$$

$$\Rightarrow \log_3\left(\frac{\log_3 x}{2}\right) = \frac{\log_3(\log_3 x)}{2} \Rightarrow 2\log_3\left(\frac{\log_3 x}{2}\right) = \log_3(\log_3 x) \Rightarrow \log_3\left(\frac{\log_3 x}{2}\right)^2 = \log_3(\log_3 x)$$

Thus $\left(\frac{\log_3 x}{2}\right)^2 = \log_3 x$. Since $\log_3 x > 0$, $\log_3 x = 4 \Rightarrow x = \boxed{81.}$ □

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Problem 5.3.5 (Problem 5)**.** (*5 points*) Consider a sequence of eleven squares that have side lengths $3, 6, 9, 12, \ldots, 33$. Eleven copies of a single square each with area A have the same total area as the total area of the eleven squares of the sequence. Find A.

Solution. It is easy to see that the total area of eleven squares is:

$$3 \cdot 3 + 6 \cdot 6 + \cdots + 33 \cdot 33 = 9(1^2 + 2^2 + \cdots + 11^2) = 9 \cdot \frac{11 \cdot 12 \cdot 23}{6} = 11 \cdot 414 = 11 \cdot A$$

Hence, the area $A = \boxed{414.}$ □

Problem 5.3.6 (Problem 6)**.** (*5 points*) Define $f(x) = 2x + 3$and suppose that $g(x+2) = f(f(x-1) \cdot f(x+1) + f(x))$. Find $g(6)$.

Solution.

$$g(6) = g(4+2) = f(f(4-1) \cdot f(4+1) + f(4)) = f(f(3)f(5) + f(4)) = f(9 \cdot 13 + 11) = f(128) = \boxed{259.}$$

□

Problem 5.3.7 (Problem 7)**.** (*5 points*) Ted flips seven fair coins. There are relatively prime positive integers m and n so that $\frac{m}{n}$ is the probability that Ted flips at least two heads given that he flips at least three tails. Find $m + n$.

Solution. The total number of possibilities of flipping k tails with seven flips is $\binom{7}{k}$, thus the probability that Ted flips at least three tails is

$$\frac{\binom{7}{3} + \binom{7}{4} + \binom{7}{5}}{\binom{7}{3} + \binom{7}{4} + \binom{7}{5} + \binom{7}{6} + \binom{7}{7}} = \frac{91}{99}.$$

The answer is $m + n = 91 + 99 = \boxed{190.}$ □

Problem 5.3.8 (Problem 8)**.** (*5 points*) Find the least n for which $n!(n+1)!(2n+1)! - 1$ ends in thirty digits that are all 9's.

Solution. If $n!(n+1)!(2n+1)! - 1$ ends in thirty digits that are all 9's then $n!(n+1)!(2n+1)!$ ends in thirty digits that are all 0's.

Let's try to find if the least $n < 100$. The number of trailing zeros in $n!$ is the number of factors of 5 in $n!$, which is $\left\lfloor \frac{n}{5} \right\rfloor + \left\lfloor \frac{n}{25} \right\rfloor$.

So we are trying to find an n such that the following sum is at least 30:

$$S(n) = \left\lfloor \frac{n}{5} \right\rfloor + \left\lfloor \frac{n}{25} \right\rfloor + \left\lfloor \frac{n+1}{5} \right\rfloor + \left\lfloor \frac{n+1}{25} \right\rfloor + \left\lfloor \frac{2n+1}{5} \right\rfloor + \left\lfloor \frac{2n+1}{25} \right\rfloor + \left\lfloor \frac{2n+1}{125} \right\rfloor$$

For example $S(25) = 5 + 1 + 5 + 1 + 10 + 2 = 24$, $S(27) = 6 + 6 + 11 + 2 = 25$. By continuing doing so $S(34) = 30$. Hence, the answer is $\boxed{34.}$ □

Problem 5.3.9 (Problem 9)**.** (*5 points*) A circle in the first quadrant with center on the curve $y = 2x^2 - 27$ is tangent to the $y-$axis and the line $4x = 3y$. The radius of the circle is $\frac{m}{n}$ where m and n are relatively prime positive integers. Find $m + n$.

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Solution. The distance from a point $A(x_0, y_0)$ to the line $4x = 3y$ is given by the normal form for the equation of the line $(4)x + (-3)y + 0 = 0$,

$$\frac{|4x_0 + (-3)y_0 + 0|}{\sqrt{(4^2 + (-3)^2)}} = \frac{|4x_0 - 3y_0|}{5}.$$

If point A, in the first quadrant, is on the curve $y = 2x^2 - 27$ at the same distance from the $y-$axis and the line $4x = 3y$, then the distance to the $y-$axis, or its $x-$coordinate (AC), must be equal to the distance to the line $4x = 3y$, thus

$$x_0 = \frac{|4x_0 - 3y_0|}{5} \Rightarrow x_0 = \frac{|4x_0 - 3(x_0^2 - 27)|}{5} = \frac{3(2x_0^2 - 27) - 4x_0}{5} \Rightarrow 6x_0^2 - 9x_0 - 81 = 0 \Rightarrow x_0 = \frac{9}{2}\ (x_0 > 0)$$

Hence, $m + n = 9 + 2 = \boxed{11.}$ □

Problem 5.3.10 (Problem 10)**.** (*5 points*) Let N be a positive integer whose digits add up to 23. What is the greatest possible product the digits of N can have?

Solution. First, digits 0 and 1 would not be among the digits of N.

A digit of 4 can be replaced by two digits of 2 having the same sum and same product.

Any digit k larger then or equal to 5 can be replace by a pair of 2 and $k - 2$, where $2(k - 2) = 2k - 4 > k$.

Therefore N has a digits of 2 and b digits of 3, where a and b are non-negative integers and the product of them is $2^a 3^b$, where $2a + 3b = 23$.

Now, $2 + 2 + 2 = 3 + 3$, and $2 \cdot 2 \cdot 2 < 3 \cdot 3$, thus a can be 0, 1 or 2. Only $a = 1$ gives $b = 7$ integer value.

Thus $N = 2 \cdot 3^7 = \boxed{4374.}$ □

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Problem 5.3.11 (Problem 11)**.** (*5 points*) Let a, b, and c be non-zero real numbers such that

$$\frac{ab}{a+b} = 3, \frac{bc}{b+c} = 4, \frac{ca}{c+a} = 5.$$

There are relatively prime positive integers m and n so that

$$\frac{abc}{ab+bc+ca} = \frac{m}{n}.$$

Find $m+n$.

Solution.

$$\frac{ab}{a+b} = 3 \Rightarrow \frac{a+b}{ab} = \frac{1}{3} \Rightarrow \frac{1}{a} + \frac{1}{b} = \frac{1}{3}$$
$$\text{Similarly } \frac{1}{b} + \frac{1}{c} = \frac{1}{4}, \ \frac{1}{c} + \frac{1}{a} = \frac{1}{5}$$
$$\Rightarrow \frac{ab+bc+ca}{abc} = \frac{1}{a} + \frac{1}{b} + \frac{1}{c} = \frac{1}{2}\left(\frac{1}{3} + \frac{1}{4} + \frac{1}{5}\right) = \frac{47}{120}$$

Hence, $m+n = 47+120 = \boxed{167.}$ □

Problem 5.3.12 (Problem 12)**.** (*5 points*) How many positive integer solutions are there to $w+x+y+z = 20$ where $w+x \geq 5$ and $y+z \geq 5$?

Solution. Let $k = w+x$, then $y+z = 20-k$. For a value of $k \geq 2$, there are $k-1$ ways to assign positive value to w and x so that their sum is k.

Similarly with $20-k \geq 2$, there are $19-k$ ways to assign positive value to w and x so that their sum is $20-k$.

Hence, the number of ways is:

$$\sum_{k=5}^{15}(k-1)(19-k) = \sum_{k=1}^{11}(k+3)(15-k) = \sum_{k=1}^{11}(45+12k-k^2) = 11 \cdot 45 + 12\frac{11 \cdot 12}{2} - \frac{11 \cdot 12 \cdot 23}{6} = \boxed{781.}$$

□

Problem 5.3.13 (Problem 13)**.** (*5 points*) Find the number of three-digit numbers such that its first two digits are each divisible by its third digit.

Solution. It is obvious that the third digit cannot be 0. There are five cases:

3rd digit	1st digit	2nd digit	# of ways
1	1,2,3,4,5,6,7,8,9	0,1,2,3,4,5,6,7,8,9	90
2	2,4,6,8	0,2,4,6,8	20
3	3,6,9	0,3,6,9	12
4	4,8	0,4,8	6
5,6,7,8,9	same as 3rd	0 or same as 3rd	10

Hence, the number of ways is $90+20+12+6+10 = \boxed{138.}$ □

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Problem 5.3.14 (Problem 14)**.** (*5 points*) Find the remainder when $2^{5^9} + 5^{9^2} + 9^{2^5}$ is divided by 11.

Solution. By Fermat's Little Theorem: $\gcd(n, p) = 1$, then $n^{p-1} \equiv 1 \pmod{p}$, so:

$$2^{10} \equiv 5^{10} \equiv 9^{10} \equiv 1 \pmod{11}.$$

It is easy to see remainders of $5^9, 9^2$, and 2^5 modulo 10 are 5, 1, and 2. Thus:

$$2^{5^9} + 5^{9^2} + 9^{2^5} \equiv 2^5 + 5^1 + 9^2 = 32 + 5 + 81 \equiv \boxed{8} \pmod{11}$$

□

Problem 5.3.15 (Problem 15)**.** (*5 points*) Square $ABCD$ has side length 68. Let E be the midpoint of segment CD, and let F be the point on segment AB a distance 17 from point A. Point G is on segment EF so that EF is perpendicular to segment GD. The length of segment BG can be written as $m\sqrt{n}$, where m and n be are positive integers, and n is not divisible by the square of any prime. Find $m + n$.

Solution. Let vector $\overrightarrow{BC} = u$, and $\overrightarrow{BA} = v$. Then $\overrightarrow{EF} = \frac{1}{4}v - u$. Note that $\overrightarrow{EG}$ is the projection of $\overrightarrow{ED} = \frac{1}{2}v$ onto $\overrightarrow{EF}$. This projection is:

$$\left(\frac{\overrightarrow{ED} \cdot \overrightarrow{EF}}{\overrightarrow{EF} \cdot \overrightarrow{EF}}\right)\overrightarrow{EF} = \frac{\frac{1}{2}v \cdot \left(\frac{1}{4}v - u\right)}{\left(\frac{1}{4}v - u\right) \cdot \left(\frac{1}{4}v - u\right)}\left(\frac{1}{4}v - u\right) = \frac{\frac{1}{8}}{\frac{1}{16} + 1}\left(\frac{1}{4}v - u\right) = \frac{1}{34}v - \frac{2}{17}u$$

Then

$$\overrightarrow{BG} = u + \frac{1}{2}v + \overrightarrow{EG} = \frac{15}{17}u + \frac{9}{17}v$$

The length of this vector is

$$\frac{68}{17}\sqrt{15^2 + 9^2} = 12\sqrt{34} \Rightarrow m + n = 12 + 34 = \boxed{46.}$$

□

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Problem 5.3.16 (Problem 16)**.** (*5 points*) Each time you click a toggle switch, the switch either turns from *off* to *on* or from on to *off*. Suppose that you start with three toggle switches with one of them *on* and two of them *off*. On each move you randomly select one of the three switches and click it. Let m and n be relatively prime positive integers so that $\frac{m}{n}$ is the probability that after four such clicks, one switch will be *on* and two of them will be *off*. Find $m+n$.

Solution. Without loss of generality assume that at the beginning the first of the three toggle switches is *on*, and the second and third are *off*.

There are $3^4 = 81$ equally likely ways to select a sequence of four toggle switches to click. After four clicks, there will either be one or three switches in the *on* position.

To get three toggle switches in the *on* position, one much click the first switch an even number of times and the second and third switches an odd number of times each. This can be done by clicking the first switch twice and the other switches once each, or by clicking either the second and third switches three times and the other of the two switches one time. The number of ways to do one of these is:

$$\binom{4}{2,1,1} + \binom{4}{0,1,3} + \binom{4}{0,3,1} = \frac{4!}{2!1!1!} + \frac{4!}{0!1!3!} + \frac{4!}{0!3!1!} = 12 + 4 + 4 = 20.$$

It follows that the desired probability is $\frac{81-20}{81} = \frac{61}{81}$.

Thus the desired sum $61 + 81 = \boxed{142.}$ □

Problem 5.3.17 (Problem 17)**.** (*5 points*) The diagram below shows circles radius 1 and 2 externally tangent to each other and internally tangent to a circle radius 3. There are relatively prime positive integers m and n so that a circle radius $\frac{m}{n}$ is internally tangent to the circle radius 3 and externally tangent to the other two circles as shown. Find $m+n$.

Solution. Let A, B, C, and D be the centres of the circles radius 3, 2, 1 and $r = \frac{m}{n}$.

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By the Law of Cosines:

$$\begin{aligned}
&\triangle ABD: \ 1^2 + (2+r)^2 - 2 \cdot 1 \cdot (2+r)\cos(\angle ABD) = (3-r)^2 \\
&\triangle CBD: \ 3^2 + (2+r)^2 - 2 \cdot 3 \cdot (2+r)\cos(\angle ABD) = (1+r)^2 \\
&\Rightarrow 3(3-r)^2 - (1+r)^2 = -6 + 2(2+r)^2 \Rightarrow r = \frac{6}{7}.
\end{aligned}$$

Thus $m + n = 6 + 7 = \boxed{13.}$ □

Problem 5.3.18 (Problem 18)**.** (*5 points*) Find the greatest seven-digit integer divisible by 132 whose digits, in order, are $2, 0, x, y, 1, 2, z$ where x, y, and z are single digits.

Solution. [Solution 1] Let n be the greatest seven-digit integer divisible by 132, whose digits, in order, are $2, 0, x, y, 1, 2, z$ where x, y, and z are single digits.

$$\begin{aligned}
&3 \mid 132 \Rightarrow 5 + x + y + z \equiv 0 \pmod 3 \\
&11 \mid 132 \Rightarrow 1 + x - y + z \equiv 0 \pmod{11} \\
&4 \mid 132 \Rightarrow z \equiv 0 \pmod 4
\end{aligned}$$

Thus, $z \in \{0, 4, 8\}$. n would be greatest if $x = 9$, in this case $y \equiv 1 - z \pmod 3$, and $y \equiv z - 1 \pmod{11}$.

$z = 0$ means $y \equiv 10 \pmod{11}$, which is impossible.

$z = 8$ means $y \equiv 1 - 8 \equiv 2 \pmod 3$, and $y \equiv 7 \pmod{11}$, which is impossible.

$z = 4$ means $y \equiv 1 - 4 \equiv 0 \pmod 3$, $y \equiv 4 - 1 = 3 \pmod{11}$, thus $y = 3$.

Hence, the number is $\boxed{2093124.}$ □

Solution. [Solution 2] We show a coding solution. The problem is equivalent to find the largest multiple of 132 in the format $\overline{20xy12z}$.

```
for x in range(9, -1, -1):
    for y in range(9, -1, -1):
        for z in range(9, -1, -1):
            i = 2000000 + x * 10000 + y * 1000  + 120 + z
            if i % 132 == 0:
                print(i)
                exit(0)
```

The answer is $\boxed{2093124.}$ □

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Problem 5.3.19 (Problem 19)**.** (*5 points*) There are positive integers m and n so that $x = m + \sqrt{n}$ is a solution to the equation

$$x^2 - 10x + 1 = \sqrt{x}(x+1).$$

Find $m + n$.

Solution. It is easy to see that $x = 0$ is not a solution. Divide both side of the equation by x, we have

$$x - 10 + \frac{1}{x} = \sqrt{x} + \frac{1}{\sqrt{x}}.$$

Let $y = \sqrt{x} + \frac{1}{\sqrt{x}} > 0$, then $y^2 = x + \frac{1}{x} + 2$, thus

$$y^2 - 12 = y \Rightarrow (y+3)(y-4) = 0 \Rightarrow y = 4 \Rightarrow \sqrt{x} + \frac{1}{\sqrt{x}} = 4 \Rightarrow x - 4\sqrt{x} + 1 = 0$$
$$\Rightarrow \sqrt{x} = 2 \pm 3 \Rightarrow x = (2+\sqrt{3})^2 = 7 + \sqrt{48}.$$

Thus $m + n = 7 + 48 = \boxed{55.}$ □

Problem 5.3.20 (Problem 20)**.** (*5 points*) Find the largest prime that divides $1 \cdot 2 \cdot 3 + 2 \cdot 3 \cdot 4 + \ldots + 44 \cdot 45 \cdot 46$.

Solution. Note that $(k-1)k(k+1) = (k^2-1)k = k^3 - k$, thus the given sum is equivalent to

$$\sum_{k=2}^{45} \left(k^3 - k\right) = \sum_{k=1}^{45} k^3 - \sum_{k=1}^{45} k = \left(\frac{45 \cdot 46}{2}\right)^2 - \frac{45 \cdot 46}{2} = 45 \cdot 23\,(45 \cdot 23 - 1) = 2 \cdot 3^2 \cdot 5 \cdot 11 \cdot 23 \cdot 47.$$

Thus the largest prime factor is $\boxed{47}$. □

Problem 5.3.21 (Problem 21)**.** (*5 points*) A paper cup has a base that is a circle with radius r, a top that is a circle with radius $2r$, and sides that connect the two circles with straight line segments as shown below. This cup has height h and volume V. A second cup that is exactly the same shape as the first is held upright inside the first cup so that its base is a distance of $\frac{h}{2}$ from the base of the first cup. The volume of liquid that will fit inside the first cup and outside the second cup can be written as $\frac{m}{n} \cdot V$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. The volume between the cups does not change if the sides of each cup are extended so that the cups form a circular cones with radius $2r$ and height $2h$.

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The volume of the first cone is:

$$\frac{1}{3}\pi(2r)^2(2h) = \frac{8}{3}\pi r^2 h.$$

The part of the second cone inside the first is a cone that is $\frac{3}{4}$ the height of the first cone, so the volume that it takes up within the first cone is:

$$\left(\frac{3}{4}\right)^3 \frac{8}{3}\pi r^2 h = \frac{9}{8}\pi r^2 h$$

Thus the volume inside the first cup and outside of the second cup is

$$\left(\frac{8}{3} - \frac{9}{8}\right)\pi r^2 h = \frac{37}{24}\pi r^2 h$$

Thus, the volume of the first cup is

$$\left(1 - \left(\frac{1}{2}\right)^3\right)\frac{4}{3}\pi r^2(2h) = \frac{7}{3}\pi r^2 h$$

The desired fraction is:

$$\frac{\frac{37}{24}}{\frac{7}{3}} = \frac{37}{56} \Rightarrow m + n = 37 + 56 = \boxed{93}.$$

□

Problem 5.3.22 (Problem 22)**.** (*5 points*) You have some white one-by-one tiles and some black and white two-by-one tiles as shown below. There are four different color patterns that can be generated when using these tiles to cover a three-by-one rectangle by laying these tiles side by side (WWW, BWW, WBW, WWB). How many different color patterns can be generated when using these tiles to cover a ten-by-one rectangle?

Solution. Let A_j be the number of colour patterns one can obtain by laying these tiles together to tile a $j \times 1$ rectangle. It is easy to see that $A_1 = 1$, $A_2 = 3$, and $A_3 = 4$.

For $j > 2$, categorize the colouring patterns by the position of the first black square among the j square.

If the colouring patter begins with a black square in its first position, the pattern must have a 2×1 tile followed by one of the A_{j-2} patterns of length $j - 2$.

Similarly if the colouring patter begins with a white square in the first position, and a black square in the second position, the first two squares be followed by any of the A_{j-2} patterns of length $j - 2$.

If the first black square appears in the kth position, where $k > 2$, it can be followed by any of the A_{j-k}, pattern of length $j - k$. Note that if the first black square appears in the last position, it constitutes a pattern. Finally, there is one pattern consisting of all white square. Thus:

$$A_j = A_{j-2} + A_{j-2} + A_{j-3} + A_{j-4} + \ldots + A_1 + 1 + 1.$$

Below is the number of patterns for each of $j \times 1$ rectangles, where $j = 1, 2, \ldots, 10$.

1	2	3	4	5	6	7	8	9	10
1	3	4	9	14	28	47	89	155	286

The answer is $\boxed{286}$. □

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Problem 5.3.23 (Problem 23)**.** (*5 points*) A bag contains 8 green candies and 4 red candies. You randomly select one candy at a time to eat. If you eat five candies, there are relatively prime positive integers m and n so that $\frac{m}{n}$ is the probability that you do not eat a green candy after you eat a red candy. Find $m+n$.

Solution. The five candies can be eaten in order

$$GRRRR,\ GGRRR,\ GGGRR,\ GGGGR,\ GGGGG.$$

The probability of eating the candies in these orders are, respectively:

$$\begin{cases} GRRRR: & \frac{8}{12}\cdot\frac{4}{11}\cdot\frac{3}{10}\cdot\frac{2}{9}\cdot\frac{1}{8} \\ GGRRR: & \frac{8}{12}\cdot\frac{7}{11}\cdot\frac{4}{10}\cdot\frac{3}{9}\cdot\frac{2}{8} \\ GGGRR: & \frac{8}{12}\cdot\frac{7}{11}\cdot\frac{6}{10}\cdot\frac{4}{9}\cdot\frac{3}{8} \\ GGGGR: & \frac{8}{12}\cdot\frac{7}{11}\cdot\frac{6}{10}\cdot\frac{5}{9}\cdot\frac{4}{8} \\ GGGGG: & \frac{8}{12}\cdot\frac{7}{11}\cdot\frac{6}{10}\cdot\frac{5}{9}\cdot\frac{4}{8} \end{cases}$$

Their sum is

$$\frac{8\cdot4\cdot3\cdot2\cdot1+8\cdot7\cdot4\cdot3\cdot2+8\cdot7\cdot6\cdot4\cdot3+8\cdot7\cdot6\cdot5\cdot4\cdot(2)}{12\cdot11\cdot10\cdot9\cdot8}=\frac{1}{5}.$$

Thus $m+n=1+5=\boxed{6.}$ □

Problem 5.3.24 (Problem 24)**.** (*5 points*) Let $A=1,3,5,7,9$ and $B=2,4,6,8,10$. Let f be a randomly chosen function from the set $A\cup B$ into itself. There are relatively prime positive integers m and n such that $\frac{m}{n}$ is the probability that f is a one-to-one function on $A\cup B$ given that it maps A one-to-one into $A\cup B$ and it maps B one-to-one into $A\cup B$. Find $m+n$.

Solution. A one-to-one function f that maps $A\cup B$ into itself is just a permutation of the set $A\cup B$. Thus there are 10! such functions.

The number of one-to-one functions that map A into $A\cup B$ is the number of ways to map each element of A to a distinct element of $A\cup B$, or $10\cdot9\cdot8\cdot7\cdot6$. That is also the number of one-to-one functions that map B into $A\cup B$. Thus the desired probability isosceles

$$\frac{10!}{(10\cdot9\cdot8\cdot7\cdot6)^2}=\frac{5\cdot4\cdot3\cdot2\cdot1}{10\cdot9\cdot8\cdot7\cdot6}=\frac{1}{252}.$$

The answer is $m+n=1+252=\boxed{253.}$ □

Problem 5.3.25 (Problem 25)**.** (*5 points*) The diagram below shows four regular hexagons each with side length 1 meter attached to the sides of a square. This figure is drawn onto a thin sheet of metal and cut out. The hexagons are then bent upward along the sides of the square so that A_1 meets A_2, B_1 meets B_2, C_1 meets C_2, and D_1 meets D_2. The resulting dish is set on a table with the square lying flat on the table. If this dish is filled with water, the water will rise to the height of the corner where the A_1 and A_2 meet. There are relatively prime positive integers m and n so that the number of cubic meters of water the dish will hold is $\sqrt{\frac{m}{n}}$. Find $m+n$.

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Solution. Let the point where A_1 and A_2 meet be labeled A, and the point where B_1 and B_2 meet be labeled B. Let the center of the square be labeled F. Let the corner of the square nearest point A be labeled H, the corner of nearest point B be labeled G, and the corner diagonally opposite G be labeled E as shown below.

Let J be the projection of the point A in the plane of the square. Because $\angle AHE = 120°$, the Law of Cosines gives that

$$AE = \sqrt{AH^2 + HE^2 - 2(AH)(HE)\cos(120°)} = \sqrt{1+1+1} = \sqrt{3}.$$

Since $EF = HF = \sqrt{2}2$, the Pythagorean Theorem gives that

$$AF = \sqrt{AE^2 - EF^2} = \sqrt{3 - \frac{1}{2}} = \sqrt{\frac{5}{2}}.$$

The Law of Cosines then gives

$$\cos(\angle AHF) = \frac{AF^2 - AH^2 - HF^2}{-2(AH)(HF)} = \frac{\frac{5}{2} - 1 - \frac{1}{2}}{-\sqrt{2}} = -\frac{1}{\sqrt{2}}.$$

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Therefore $\angle AHF = 135°$, $\angle AHJ = 45°$. Thus $AJ = \frac{1}{\sqrt{2}}$ is the height of A from the plane of the square. Since the diameter of a regular hexagon is twice the length of one of its sides, it follows that $AB = 2$.

If the vertical edges of the dish AH and BG are extended, they will meet at a point K as shown in the diagram. Note that K is the vertex of a downward pointing square pyramid with base having side length 2 and with height $\sqrt{2}$.

The volume of this pyramid is given by $\frac{1}{3}$ the area of its base times its height $\frac{1}{3} \cdot 4 \cdot \sqrt{2}$. The lower half of the pyramid is another square pyramid with base having side length 1 and with height $\frac{\sqrt{2}}{2}$ so its volume is $\frac{1}{3} \cdot 1 \cdot \sqrt{2}$.

The desired volume is

$$\frac{4}{3} \cdot \sqrt{2} - \frac{1}{3} \cdot \frac{\sqrt{2}}{2} = \frac{7\sqrt{2}}{2} = \sqrt{\frac{49}{18}}.$$

Thus $m + n = 49 + 18 = \boxed{67.}$ □

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5.4 High School - Test

High school students: grade 9 (US, CA), grade 10 (FR, UK, VN) and above.

You have **30 minutes** to complete the test. You have to **submit only the answers**. No solution is required.

Note that you have to **follow the instructions by the COs** *for submitting the answers.*

- **Intermediate (I) level: Problems 1-10**
- **Advanced (A) level: Problems 8-17**
- **Olympiad (O) level: Problems 16-25**

If you submit solution based on coding, please make sure that your submission is compliant. Read the introduction chapter for more information.

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Problem 5.4.1 (Problem 1)**.** (*5 points*) Find the least positive integer n so that both n and $n+1$ have prime factorizations with exactly three (not necessarily distinct) prime factors.

Solution. One of n and $n+1$ is an odd number. The smallest integer with four prime factors is $3^3 = 27$. And $28 = 2^2 \cdot 7$ has the desired property. The answer is $\boxed{27.}$ □

Problem 5.4.2 (Problem 2)**.** (*5 points*) Two convex polygons have a total of 33 sides and 279 diagonals. Find the number of diagonals in the polygon with the greater number of sides.

Solution. A convex polygon has n sides then it has $\frac{n(n-1)}{2} - n = \frac{n^2-3n}{2}$ diagonals.

Now

$$279 = \frac{n^2-3n}{2} + \frac{(33-n)^2 - 3(33-n)}{2} = n^2 - 33n + 495 \Rightarrow n^2 - 33n + 216 = 0 \Rightarrow n = 9 \text{ or } n = 24$$

The number of diagonals of the polygon with 24 sides is $\frac{24^2-3\cdot 24}{2} = \boxed{252.}$ □

Problem 5.4.3 (Problem 3)**.** (*5 points*) In the tribe of Zimmer, being able to hike long distances and knowing the roads through the forest are both extremely important, so a boy who reaches the age of manhood is not designated as a man by the tribe until he completes an interesting rite of passage. The man must go on a sequence of hikes. The first hike is a 5 kilometer hike down the main road. The second hike is a $5\frac{1}{4}$ kilometer hike down a secondary road. Each hike goes down a different road and is a quarter kilometer longer than the previous hike. The rite of passage is completed at the end of the hike where the cumulative distance walked by the man on all his hikes exceeds **500** kilometers. So in the tribe of Zimmer, how many roads must a man walk down, before you call him a man?

Solution. The total distance a man walked in the n hikes is

$$5 + 5\frac{1}{4} + 5\frac{1}{2} + \cdots + \frac{19+n}{4} = \sum_{k=1}^{n} \frac{19+k}{4} = \frac{1}{4}\left(19n + \frac{n(n+1)}{2}\right) = \frac{n(n+39)}{8}$$

The smallest n for $n^2 + 39n > 8 \cdot 500$ is $n = \boxed{47.}$ □

Problem 5.4.4 (Problem 4)**.** (*5 points*) Find the value of x that satisfies $\log_2(\log_4 x) = \log_4(\log_2 x)$.

Solution. Note that

$$\log_4 x = \frac{\log_2 x}{\log_2 4} \Rightarrow \begin{cases} \log_2(\log_4 x) = \log_2\left(\frac{\log_2 x}{\log_2 4}\right) = \log_2\left(\frac{\log_2 x}{2}\right) \\ \log_4(\log_2 x) = \frac{\log_2(\log_2 x)}{\log_2 4} = \frac{\log_2(\log_2 x)}{2} \end{cases}$$

$$\Rightarrow \log_2\left(\frac{\log_2 x}{2}\right) = \frac{\log_2(\log_2 x)}{2} \Rightarrow 2\log_2\left(\frac{\log_2 x}{2}\right) = \log_2(\log_2 x) \Rightarrow \log_2\left(\frac{\log_2 x}{2}\right)^2 = \log_2(\log_2 x)$$

Thus $\Rightarrow \left(\frac{\log_2 x}{2}\right)^2 = log_2 x$. Since $\log_2 x > 0$, $\log_2 x = 4 \Rightarrow x = \boxed{16.}$ □

Problem 5.4.5 (Problem 5)**.** (*5 points*) Consider a sequence of twelve squares that have side lengths $3, 6, 9, 12, \ldots, 33, 36$. Ten copies of a single square each with area A have the same total area as the total area of the twelve squares of the sequence. Find A.

Solution. It is easy to see that the total area of twelve squares is:

$$3 \cdot 3 + 6 \cdot 6 + \cdots + 36 \cdot 36 = 9(1^2 + 2^2 + \cdots + 12^2) = 9 \cdot \frac{12 \cdot 13 \cdot 25}{6} = 10 \cdot 585 = 10 \cdot A$$

Hence, the area $A = \boxed{585.}$ □

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Problem 5.4.6 (Problem 6)**.** (*5 points*) Define $f(x) = 2x + 3$and suppose that $g(x+2) = f(f(x-1) \cdot f(x+1) + f(x))$. Find $g(5)$.

Solution.

$$g(5) = g(3+2) = f(f(3-1) \cdot f(3+1) + f(3)) = f(f(2)f(4) + f(3)) = f(7 \cdot 11 + 9) = f(86) = \boxed{175.}$$

□

Problem 5.4.7 (Problem 7)**.** (*5 points*) Ted flips seven fair coins. There are relatively prime positive integers m and n so that $\frac{m}{n}$ is the probability that Ted flips at least one head given that he flips at least three tails. Find $m + n$.

Solution. The total number of possibilities of flipping k tails with seven flips is $\binom{7}{k}$, thus the probability that Ted flips at least three tails is

$$\frac{\binom{7}{3} + \binom{7}{4} + \binom{7}{5} + \binom{7}{6}}{\binom{7}{3} + \binom{7}{4} + \binom{7}{5} + \binom{7}{6} + \binom{7}{7}} = \frac{98}{99}.$$

The answer is $m + n = 98 + 99 = \boxed{197.}$ □

Problem 5.4.8 (Problem 8)**.** (*5 points*) Find the least n for which $n!(n+1)!(2n+1)! - 1$ ends in thirty-five digits that are all 9's.

Solution. If $n!(n+1)!(2n+1)! - 1$ ends in thirty-five digits that are all 9's then $n!(n+1)!(2n+1)!$ ends in thirty-five digits that are all 0's.

Let's try to find if the least $n < 100$. The number of trailing zeros in $n!$ is the number of factors of 5 in $n!$, which is $\left\lfloor \frac{n}{5} \right\rfloor + \left\lfloor \frac{n}{25} \right\rfloor$.

So we are trying to find an n such that the following sum is at least 35:

$$S(n) = \left\lfloor \frac{n}{5} \right\rfloor + \left\lfloor \frac{n}{25} \right\rfloor + \left\lfloor \frac{n+1}{5} \right\rfloor + \left\lfloor \frac{n+1}{25} \right\rfloor + \left\lfloor \frac{2n+1}{5} \right\rfloor + \left\lfloor \frac{2n+1}{25} \right\rfloor + \left\lfloor \frac{2n+1}{125} \right\rfloor$$

For example $S(25) = 5 + 1 + 5 + 1 + 10 + 2 = 24$, $S(27) = 6 + 6 + 11 + 2 = 25$. By continuing doing so $S(38) = 7 + 1 + 7 + 1 + 15 + 3 = 34$. $S(39) = 7 + 1 + 8 + 1 + 15 + 3 = 35$. Hence, the answer is $\boxed{39.}$ □

Problem 5.4.9 (Problem 9)**.** (*5 points*) A circle in the first quadrant with center on the curve $y = 2x^2 - 27$ is tangent to the $y-$axis and the line $4x = 3y$. The radius of the circle is $\frac{m}{n}$ where m and n are relatively prime positive integers. Find $m - n$.

Solution. The distance from a point $A(x_0, y_0)$ to the line $4x = 3y$ is given by the normal form for the equation of the line $(4)x + (-3)y + 0 = 0$,

$$\frac{|4x_0 + (-3)y_0 + 0|}{\sqrt{(4^2 + (-3)^2)}} = \frac{|4x_0 - 3y_0|}{5}.$$

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If point A, in the first quadrant, is on the curve $y = 2x^2 - 27$ at the same distance from the $y-$axis and the line $4x = 3y$, then the distance to the $y-$axis, or its $x-$coordinate (AC), must be equal to the distance to the line $4x = 3y$, thus

$$x_0 = \frac{|4x_0 - 3y_0|}{5} \Rightarrow x_0 = \frac{|4x_0 - 3(x_0^2 - 27)|}{5} = \frac{3(2x_0^2 - 27) - 4x_0}{5} \Rightarrow 6x_0^2 - 9x_0 - 81 = 0 \Rightarrow x_0 = \frac{9}{2}\ (x_0 > 0)$$

Hence, $m + n = 9 - 2 = \boxed{7.}$ □

Problem 5.4.10 (Problem 10)**.** (*5 points*) Among positive integers whose digits add up to 2024, N is the number whose product of digits is the greatest possible. Find the number of divisors of N.

Solution. First, digits 0 and 1 would not be among the digits of N.

A digit of 4 can be replaced by two digits of 2 having the same sum and same product.

Any digit k larger then or equal to 5 can be replace by a pair of 2 and $k - 2$, where $2(k - 2) = 2k - 4 > k$.

Therefore N has a digits of 2 and b digits of 3, where a and b are non-negative integers and the product of them is $2^a 3^b$, where $2a + 3b = 2024$.

Now, $2 + 2 + 2 = 3 + 3$, and $2 \cdot 2 \cdot 2 < 3 \cdot 3$, thus a can be 0, 1 or 2. Only $a = 1$ gives $b = 674$ integer value.

Thus $N = 2 \cdot 3^{674}$, and the number of divisors of N is $(1 + 1)(674 + 1) = \boxed{1350.}$ □

Problem 5.4.11 (Problem 11)**.** (*5 points*) Let a, b, and c be non-zero real numbers such that

$$\frac{ab}{a+b} = 3, \frac{bc}{b+c} = 4, \frac{ca}{c+a} = 5.$$

There are relatively prime positive integers m and n so that

$$\frac{abc}{ab + bc + ca} = \frac{m}{n}.$$

Find $n - m$.

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Solution.

$$\frac{ab}{a+b} = 3 \Rightarrow \frac{a+b}{ab} = \frac{1}{3} \Rightarrow \frac{1}{a} + \frac{1}{b} = \frac{1}{3}$$

Similarly $\frac{1}{b} + \frac{1}{c} = \frac{1}{4}$, $\frac{1}{c} + \frac{1}{a} = \frac{1}{5}$

$$\Rightarrow \frac{ab+bc+ca}{abc} = \frac{1}{a} + \frac{1}{b} + \frac{1}{c} = \frac{1}{2}\left(\frac{1}{3} + \frac{1}{4} + \frac{1}{5}\right) = \frac{47}{120}$$

Hence, $n - m = 120 - 47 = \boxed{73.}$ □

Problem 5.4.12 (Problem 12)**.** (*5 points*) How many positive integer solutions are there to $w+x+y+z = 21$ where $w + x \geq 5$ and $y + z \geq 5$?

Solution. Let $k = w + x$, then $y + z = 21 - k$. For a value of $k \geq 2$, there are $k - 1$ ways to assign positive value to w and x so that their sum is k.

Similarly with $21 - k \geq 2$, there are $20 - k$ ways to assign positive value to w and x so that their sum is $21 - k$.

Hence, the number of ways is:

$$\sum_{k=5}^{16}(k-1)(20-k) = \sum_{k=1}^{12}(k+3)(16-k) = \sum_{k=1}^{12}(48+13k-k^2) = 12 \cdot 48 + 13\frac{12 \cdot 13}{2} - \frac{12 \cdot 13 \cdot 25}{6} = \boxed{940.}$$

□

Problem 5.4.13 (Problem 13)**.** (*5 points*) Find the number of three-digit numbers such that the hundreds digit is divisible by the tens digit and the tens digit is divisible by the unit digit.

Solution. It is clear that the unit digit cannot be 0. Similarly the tens digit cannot be 0. We show a coding solution.

```
count = 0
for i in range(100, 1000):
    u = i % 10
    t = (i // 10) % 10
    h = i // 100
    print(h,t,u)
    if u != 0 and t != 0 and h % t == 0 and t % u == 0:
        count +=1
print(count)
```

The answer is $\boxed{44.}$ □

Problem 5.4.14 (Problem 14)**.** (*5 points*) Find the remainder when $2^{5^9} + 5^{9^2} + 9^{2^5}$ is divided by 13.

Solution. By Fermat's Little Theorem: $\gcd(n, p) = 1$, then $n^{p-1} \equiv 1 \pmod{p}$, so:

$$2^{12} \equiv 5^{12} \equiv 9^{12} \equiv 1 \pmod{13}.$$

$$5^9 = 5 \cdot (5^2)^4 = 5 \cdot (25)^4 \equiv 5 \cdot 1^4 = 5 \pmod{12} \Rightarrow 2^{5^9} \equiv 2^5 = 32 \equiv 6 \pmod{13}$$

$$9^2 = 81 \equiv 9 \pmod{12} \Rightarrow 5^{9^2} \equiv 5^9 = 5 \cdot (5^2)^4 \equiv 5 \cdot (-1)^4 \equiv 5 \pmod{13}$$

$$2^5 = 32 \equiv 8 \pmod{12} \Rightarrow 9^{2^5} \equiv 9^8 \equiv 4^8 = 4^2 \cdot (4^3)^2 \equiv 3 \pmod{13}$$

Thus $2^{5^9} + 5^{9^2} + 9^{2^5} \equiv 6 + 5 + 3 \equiv \boxed{1} \pmod{13}$. □

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Problem 5.4.15 (Problem 15)**.** (*5 points*) Square $ABCD$ has side length 68. Let E be the midpoint of segment CD, and let F be the point on segment AB a distance 17 from point A. Point G is on segment EF so that EF is perpendicular to segment GD. The length of segment BG can be written as $m\sqrt{n}$, where m and n be are positive integers, and n is not divisible by the square of any prime. Find $n - m$.

Solution. Let vector $\overrightarrow{BC} = u$, and $\overrightarrow{BA} = v$. Then $\overrightarrow{EF} = \frac{1}{4}v - u$. Note that $\overrightarrow{EG}$ is the projection of $\overrightarrow{ED} = \frac{1}{2}v$ onto $\overrightarrow{EF}$. This projection is:

$$\left(\frac{\overrightarrow{ED}\cdot\overrightarrow{EF}}{\overrightarrow{EF}\cdot\overrightarrow{EF}}\right)\overrightarrow{EF} = \frac{\frac{1}{2}v\cdot\left(\frac{1}{4}v-u\right)}{\left(\frac{1}{4}v-u\right)\cdot\left(\frac{1}{4}v-u\right)}\left(\frac{1}{4}v-u\right) = \frac{\frac{1}{8}}{\frac{1}{16}+1}\left(\frac{1}{4}v-u\right) = \frac{1}{34}v - \frac{2}{17}u$$

Then

$$\overrightarrow{BG} = u + \frac{1}{2}v + \overrightarrow{EG} = \frac{15}{17}u + \frac{9}{17}v$$

The length of this vector is

$$\frac{68}{17}\sqrt{15^2+9^2} = 12\sqrt{34} \Rightarrow n - m = 34 - 12 = \boxed{22.}$$

□

Problem 5.4.16 (Problem 16)**.** (*5 points*) Each time you click a toggle switch, the switch either turns from *off* to *on* or from on to *off*. Suppose that you start with three toggle switches with one of them *on* and two of them *off*. On each move you randomly select one of the three switches and click it. Let m and n be relatively prime positive integers so that $\frac{m}{n}$ is the probability that after four such clicks, one switch will be *on* and two of them will be *off*. Find $n - m$.

Solution. Without loss of generality assume that at the beginning the first of the three toggle switches is *on*, and the second and third are *off*.

There are $3^4 = 81$ equally likely ways to select a sequence of four toggle switches to click. After four clicks, there will either be one or three switches in the *on* position.

To get three toggle switches in the *on* position, one much click the first switch an even number of times and the second and third switches an odd number of times each. This can be done by clicking the first switch

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twice and the other switches once each, or by clicking either the second and third switches three times and the other of the two switches one time. The number of ways to do one of these is:

$$\binom{4}{2,1,1} + \binom{4}{0,1,3} + \binom{4}{0,3,1} = \frac{4!}{2!1!1!} + \frac{4!}{0!1!3!} + \frac{4!}{0!3!1!} = 12 + 4 + 4 = 20.$$

It follows that the desired probability is $\frac{81-20}{81} = \frac{61}{81}$. Thus the desired difference is $81 - 61 = \boxed{20.}$ □

Problem 5.4.17 (Problem 17)**.** (*5 points*) The diagram below shows circles radius 1 and 2 externally tangent to each other and internally tangent to a circle radius 3. There are relatively prime positive integers m and n so that a circle radius $\frac{m}{n}$ is internally tangent to the circle radius 3 and externally tangent to the other two circles as shown. Find the product mn.

Solution. Let A, B, C, and D be the centres of the circles radius 3, 2, 1 and $r = \frac{m}{n}$.

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By the Law of Cosines:

$$\begin{aligned}
&\triangle ABD: \ 1^2 + (2+r)^2 - 2\cdot 1\cdot(2+r)\cos(\angle ABD) = (3-r)^2 \\
&\triangle CBD: \ 3^2 + (2+r)^2 - 2\cdot 3\cdot(2+r)\cos(\angle ABD) = (1+r)^2 \\
&\Rightarrow 3(3-r)^2 - (1+r)^2 = -6 + 2(2+r)^2 \Rightarrow r = \frac{6}{7}.
\end{aligned}$$

Thus $mn = 6\cdot 7 = \boxed{42.}$ □

Problem 5.4.18 (Problem 18)**.** (*5 points*) Find the greatest seven-digit integer divisible by 132 whose digits, in order, are $x, 0, y, 2, 1, 2, z$ where x, y, and z are single digits.

Solution. We show a coding solution. The problem is equivalent to find the largest multiple of 132 in the format $\overline{x0y212z}$.

```
for x in range(9, -1, -1):
for y in range(9, -1, -1):
    for z in range(9, -1, -1):
        i = x * 1000000 + y * 10000 +  2 * 1000 +  120 + z
        if i % 132 == 0:
            print(i)
            exit(0)
```

The answer is $\boxed{9082128.}$ □

Problem 5.4.19 (Problem 19)**.** (*5 points*) There are positive integers m and n so that $x = m + \sqrt{n}$ is a solution to the equation

$$x^2 - 28x + 1 = \sqrt{x}(x+1).$$

Find $m + n$.

Solution. It is easy to see that $x = 0$ is not a solution. Divide both side of the equation by x, we have

$$x - 28 + \frac{1}{x} = \sqrt{x} + \frac{1}{\sqrt{x}}.$$

Let $y = \sqrt{x} + \frac{1}{\sqrt{x}} > 0$, then $y^2 = x + \frac{1}{x} + 2$, thus

$$\begin{aligned}
&y^2 - 30 = y \Rightarrow (y+5)(y-6) = 0 \Rightarrow y = 6 \Rightarrow \sqrt{x} + \frac{1}{\sqrt{x}} = 6 \Rightarrow x - 6\sqrt{x} + 1 = 0 \\
&\Rightarrow \sqrt{x} = 3 \pm 2\sqrt{2} \Rightarrow x = (3+2\sqrt{2})^2 = 17 + 12\sqrt{2} = 17 + \sqrt{288}
\end{aligned}$$

Thus $m + n = 17 + 288 = \boxed{305.}$ □

Problem 5.4.20 (Problem 20)**.** (*5 points*) Find the largest prime that divides $1\cdot 2\cdot 3 + 2\cdot 3\cdot 4 + \ldots + 2023\cdot 2024\cdot 2025$.

Solution. Note that $(k-1)k(k+1) = (k^2-1)k = k^3 - k$, thus the given sum is equivalent to

$$\begin{aligned}
&\sum_{k=2}^{n}(k-1)k(k+1) = \sum_{k=2}^{n}\left(k^3 - k\right) = \sum_{k=1}^{n}k^3 - \sum_{k=1}^{n}k = \left(\frac{n(n+1)}{2}\right)^2 - \frac{n(n+1)}{2} \\
&= \frac{n(n+1)}{2}\left(\frac{n(n+1)}{2} - 1\right) = \frac{(n-1)n(n+1)(n+2)}{4}
\end{aligned}$$

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For $n = 2024$,

$$\frac{(n-1)n(n+1)(n+2)}{4} = \frac{(2024-1)(2024)(2024+1)(2024+2)}{4} = 2^2 \cdot 3^4 \cdot 5^2 \cdot 7 \cdot 11 \cdot 17^2 \cdot 23 \cdot 1013.$$

Thus the largest prime factor is $\boxed{1013}$. □

Problem 5.4.21 (Problem 21)**.** (*5 points*) A paper cup has a base that is a circle with radius r, a top that is a circle with radius $2r$, and sides that connect the two circles with straight line segments as shown below. This cup has height h and volume V. A second cup that is exactly the same shape as the first is held upright inside the first cup so that its base is a distance of $\frac{h}{2}$ from the base of the first cup. The volume of liquid that will fit inside the first cup and outside the second cup can be written as $\frac{m}{n} \cdot V$, where m and n are relatively prime positive integers. Find $n - m$.

Solution. The volume between the cups does not change if the sides of each cup are extended so that the cups form a circular cones with radius $2r$ and height $2h$.

The volume of the first cone is:

$$\frac{1}{3}\pi(2r)^2(2h) = \frac{8}{3}\pi r^2 h.$$

The part of the second cone inside the first is a cone that is $\frac{3}{4}$ the height of the first cone, so the volume that it takes up within the first cone is:

$$\left(\frac{3}{4}\right)^3 \frac{8}{3}\pi r^2 h = \frac{9}{8}\pi r^2 h$$

Thus the volume inside the first cup and outside of the second cup is

$$\left(\frac{8}{3} - \frac{9}{8}\right)\pi r^2 h = \frac{37}{24}\pi r^2 h$$

Thus, the volume of the first cup is

$$\left(1 - \left(\frac{1}{2}\right)^3\right)\frac{4}{3}\pi r^2(2h) = \frac{7}{3}\pi r^2 h$$

The desired fraction is:

$$\frac{\frac{37}{24}}{\frac{7}{3}} = \frac{37}{56} \Rightarrow n - m = 56 - 37 = \boxed{19}.$$

□

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Problem 5.4.22 (Problem 22)**.** (*5 points*) You have some white one-by-one tiles and some black and white two-by-one tiles as shown below. There are four different color patterns that can be generated when using these tiles to cover a three-by-one rectangle by laying these tiles side by side (WWW, BWW, WBW, WWB). How many different color patterns can be generated when using these tiles to cover a eight-by-one rectangle?

Solution. Let A_j be the number of colour patterns one can obtain by laying these tiles together to tile a $j \times 1$ rectangle. It is easy to see that $A_1 = 1$, $A_2 = 3$, and $A_3 = 4$.

For $j > 2$, categorize the colouring patterns by the position of the first black square among the j square.

If the colouring patter begins with a black square in its first position, the pattern must have a 2×1 tile followed by one of the A_{j-2} patterns of length $j - 2$.

Similarly if the colouring patter begins with a white square in the first position, and a black square in the second position, the first two squares be followed by any of the A_{j-2} patterns of length $j - 2$.

If the first black square appears in the kth position, where $k > 2$, it can be followed by any of the A_{j-k}, pattern of length $j - k$. Note that if the first black square appears in the last position, it constitutes a pattern. Finally, there is one pattern consisting of all white square. Thus:

$$A_j = A_{j-2} + A_{j-2} + A_{j-3} + A_{j-4} + \ldots + A_1 + 1 + 1.$$

Below is the number of patterns for each of $j \times 1$ rectangles, where $j = 1, 2, \ldots, 10$.

1	2	3	4	5	6	7	8	9	10
1	3	4	9	14	28	47	89	155	286

The answer is $\boxed{89}$. □

Problem 5.4.23 (Problem 23)**.** (*5 points*) A bag contains 7 green candies and 4 red candies. You randomly select one candy at a time to eat. If you eat five candies, there are relatively prime positive integers m and n so that $\frac{m}{n}$ is the probability that you do not eat a green candy after you eat a red candy. Find $m + n$.

Solution. The five candies can be eaten in order

$$GRRRR,\ GGRRR,\ GGGRR,\ GGGGR,\ GGGGG.$$

The probability of eating the candies in these orders are, respectively:

$$\begin{cases} GRRRR: & \frac{7}{11} \cdot \frac{4}{10} \cdot \frac{3}{9} \cdot \frac{2}{8} \cdot \frac{1}{7} \\ GGRRR: & \frac{7}{11} \cdot \frac{6}{10} \cdot \frac{4}{9} \cdot \frac{3}{8} \cdot \frac{2}{7} \\ GGGRR: & \frac{7}{11} \cdot \frac{6}{10} \cdot \frac{5}{9} \cdot \frac{4}{8} \cdot \frac{3}{7} \\ GGGGR: & \frac{7}{11} \cdot \frac{6}{10} \cdot \frac{5}{9} \cdot \frac{4}{8} \cdot \frac{4}{7} \\ GGGGG: & \frac{7}{11} \cdot \frac{6}{10} \cdot \frac{5}{9} \cdot \frac{4}{8} \cdot \frac{3}{7} \end{cases}$$

Their sum is

$$\frac{7 \cdot 4 \cdot 3 \cdot 2 \cdot 1 + 7 \cdot 6 \cdot 4 \cdot 3 \cdot 2 + 7 \cdot 6 \cdot 5 \cdot 4 \cdot 3 + 7 \cdot 6 \cdot 5 \cdot 4 \cdot 4 + 7 \cdot 6 \cdot 5 \cdot 4 \cdot 3}{11 \cdot 10 \cdot 9 \cdot 8 \cdot 7} = \frac{19}{110}.$$

Thus $m + n = 19 + 110 = \boxed{129.}$ □

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Problem 5.4.24 (Problem 24)**.** (*5 points*) Let $A = 1, 3, 5, 7$ and $B = 2, 4, 6, 8$. Let f be a randomly chosen function from the set $A \cup B$ into itself. There are relatively prime positive integers m and n such that $\frac{m}{n}$ is the probability that f is a one-to-one function on $A \cup B$ given that it maps A one-to-one into $A \cup B$ and it maps B one-to-one into $A \cup B$. Find $m + n$.

Solution. A one-to-one function f that maps $A \cup B$ into itself is just a permutation of the set $A \cup B$. Thus there are 8! such functions.

The number of one-to-one functions that map A into $A \cup B$ is the number of ways to map each element of A to a distinct element of $A \cup B$, or $8 \cdot 7 \cdot 6 \cdot 5$ That is also the number of one-to-one functions that map B into $A \cup B$. Thus the desired probability isosceles

$$\frac{8!}{(8 \cdot 7 \cdot 6 \cdot 5)^2} = \frac{4 \cdot 3 \cdot 2 \cdot 1}{8 \cdot 7 \cdot 6 \cdot 5} = \frac{1}{70}.$$

The answer is $m + n = 1 + 70 = \boxed{71.}$ □

Problem 5.4.25 (Problem 25)**.** (*5 points*) The diagram below shows four regular hexagons each with side length 1 meter attached to the sides of a square. This figure is drawn onto a thin sheet of metal and cut out. The hexagons are then bent upward along the sides of the square so that A_1 meets A_2, B_1 meets B_2, C_1 meets C_2, and D_1 meets D_2. The resulting dish is set on a table with the square lying flat on the table. If this dish is filled with water, the water will rise to the height of the corner where the A_1 and A_2 meet.

Let the point where A_1 and A_2 meet be labeled A, the point B_1 and B_2 meet be labeled B, the point C_1 and C_2 meet be labeled C, and the point D_1 and D_2 meet be labeled D. Let the center of the square be labeled F. Let the corner of the square nearest point A be labeled H, the corner of nearest point B be labeled G, and the corner diagonally opposite G be labeled E as shown below.

Let J be the projection of the point A in the plane of the square. If the vertical edges of the dish AH and BG are extended, they will meet at a point K as shown in the diagram. Note that K is the vertex of a downward pointing square pyramid.

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Find the measure of $\angle AHF$ in degrees.

Solution. Because $\angle AHE = 120°$, the Law of Cosines gives that

$$AE = \sqrt{AH^2 + HE^2 - 2(AH)(HE)\cos(120°)} = \sqrt{1+1+1} = \sqrt{3}.$$

Since $EF = HF = \frac{1}{\sqrt{2}}$, the Pythagorean Theorem gives that

$$AF = \sqrt{AE^2 - EF^2} = \sqrt{3 - \frac{1}{2}} = \sqrt{\frac{5}{2}}.$$

The Law of Cosines then gives

$$\cos(\angle AHF) = \frac{AF^2 - AH^2 - HF^2}{-2(AH)(HF)} = \frac{\frac{5}{2} - 1 - \frac{1}{2}}{-\sqrt{2}} = -\frac{1}{\sqrt{2}}.$$

Therefore $\angle AHF = \boxed{135°.}$ $\square$

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Chapter 6

Session 4

6.1 Middle School - Test 4

You have **60 minutes** to complete the test. You have to **submit only the answers**. No solution is required.

Note that you have to **follow the instructions by the COs** *for submitting the answers.*

- **Intermediate (I) level: Problems 1-10**
- **Advanced (A) level: Problems 11-20**

If you submit solution based on coding, please make sure that your submission is compliant. Read the introduction chapter for more information.

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Problem 6.1.1. (*1 point*) There are relatively prime positive integers m and n so that

$$\frac{\frac{1}{2}}{\frac{\frac{1}{3}}{\frac{1}{4}+\frac{1}{4}+\frac{1}{4}}+\frac{\frac{1}{3}}{\frac{1}{4}+\frac{1}{4}+\frac{1}{4}}}=\frac{m}{n}.$$

Find $2m+n$.

Solution.

$$\frac{1}{4}+\frac{1}{4}+\frac{1}{4}=\frac{3}{4},\ \frac{\frac{1}{3}}{\frac{1}{4}+\frac{1}{4}+\frac{1}{4}}=\frac{\frac{1}{3}}{\frac{3}{4}}=\frac{1}{3}\cdot\frac{4}{3}=\frac{4}{9}$$

Thus the given fraction is

$$\frac{\frac{1}{2}}{2\cdot\frac{4}{9}}=\frac{1}{2}\cdot\frac{9}{4}=\frac{9}{16}\Rightarrow 2m+n=2\cdot 9+16=\boxed{34.}$$

□

Problem 6.1.2. (*1 point*) The diagram below shows a 12-sided figure made up of three congruent squares. The figure has total perimeter 60. Find its area.

Solution. If the total perimeter is 60, each square has a perimeter of 20, thus each square has a side length of 5. Thus the entire area is $3\cdot 25=\boxed{75.}$ □

Problem 6.1.3. (*1 point*) Find the sum of all two-digit integers which are both prime and are 1 more than a multiple of 10.

Solution. It is easy to see that these primes are $11, 31, 41, 61, 71$, and their sum $11+31+41+61+71=\boxed{215.}$ □

Problem 6.1.4. (*1 point*) Jerry buys a bottle of 150 pills. Using a standard 12 hour clock, he sees that the clock reads exactly 12 when he takes the first pill. If he takes one pill every five hours, what hour will the clock read when he takes the last pill in the bottle?

Solution. Jerry will take the last pill 5×149 hours after he takes the first pill. Since $5\times 149 =\equiv 1 \pmod{12}$, the clock will read 1 hour pass 12, or $\boxed{1}$ when Jerry takes the last pill. □

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Problem 6.1.5. (*1 point*) Given that $\frac{6}{11} - \frac{10}{19} = \frac{9}{19} - \frac{n}{11}$, find n.

Solution.

$$\frac{6}{11} - \frac{10}{19} = \frac{9}{19} - \frac{n}{11} \Rightarrow \frac{6}{11} = \frac{10}{19} + \frac{9}{19} - \frac{n}{11} = 1 - \frac{n}{11}$$
$$\Rightarrow \frac{n+6}{11} = 1 \Rightarrow n = \boxed{5.}$$

□

Problem 6.1.6. (*1 point*) The following addition problem is not correct if the numbers are interpreted as base 10 numbers. In what number base is the problem correct?

$$\begin{array}{r} 66 \\ 87 \\ 85 \\ +\,48 \\ \hline 132 \end{array}$$

Solution. Let the number base for this problem be b. The ones column in the problem adds to $6+7+5+8 = 26 \equiv 2 \pmod{b}$. Thus b is a divisor of 24. Since the problem includes the digit 8, so $b > 8$. Therefore $b = 12$ or $b = 24$. It is easy to check that $b = \boxed{24.}$ □

Problem 6.1.7. (*1 point*) When 12^{18} is divided by 18^{12}, the result is $\left(\frac{m}{n}\right)^3$, where m and n are relatively prime positive integers. Find mn.

Solution.

$$\frac{12^{18}}{18^{12}} = \frac{4^{18}3^{18}}{2^{12}9^{12}} = \frac{2^{36}3^{18}}{2^{12}3^{24}} = \frac{2^{24}}{3^6} = \left(\frac{256}{9}\right)^3$$

Thus $mn = 256 \cdot 9 = \boxed{2304.}$ □

Problem 6.1.8. (*1 point*) A square measuring 15 by 15 is partitioned into five rows of five congruent squares as shown below. The small squares are alternately colored black and white as shown. Find the total area of the part colored black.

Solution. Each of the small square has side length $\frac{15}{5} = 3$, so each has an area of $3^2 = 9$. There are 13 shaded squares, Thus the shaded area is $9 \cdot 13 = \boxed{117.}$ □

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Problem 6.1.9. (*1 point*) A jar contains one quarter red jelly beans and three quarters blue jelly beans. If Chris removes three quarters of the red jelly beans and one quarter of the blue jelly beans, what percent of the jelly beans remaining in the jar will be blue?

Solution. At the start $\frac{1}{4}$ of the jelly beans are red, and $\frac{3}{4}$ of them are removed, so at the end, the number od red jelly bean will be:

$$\frac{1}{4} - \frac{3}{4} \cdot \frac{1}{4} = \frac{1}{16} \text{ of the original number of jelly beans.}$$

Similarly, at the end, the number of blue jelly beans will be

$$\frac{3}{4} - \frac{1}{4} \cdot \frac{3}{4} = \frac{9}{16} \text{ of the original number of jelly beans.}$$

Therefore the fraction of blue jelly beans is $\boxed{90\%.}$ □

Problem 6.1.10. (*1 point*) Five rays $\overrightarrow{OA}, \overrightarrow{OB}, \overrightarrow{OC}, \overrightarrow{OD}$, and $\overrightarrow{OE}$ radiate in a clockwise order from O forming four non-overlapping angles such that $\angle EOD = 2\angle COB$, $\angle COB = 2\angle BOA$, while $\angle DOC = 3\angle BOA$. If E, O, A are collinear with O between A and E, what is the degree measure of $\angle DOB$?

Solution. Let $x = \angle BOA$, then

$$\angle COB = 2x, \angle DOC = 3x, \angle EOD = 4x \Rightarrow x + 2x + 3x + 4x = 10x = 180^\circ \Rightarrow x = 18^\circ.$$

Thus $\angle DOB = \angle DOC + \angle COB = 3x + 2x = 5x = \boxed{90^\circ}$. □

Problem 6.1.11. (*1 point*) How many numbers are there that appear both in the arithmetic sequence $10, 16, 22, 28, \ldots 1000$ and the arithmetic sequence $10, 21, 32, 43, \ldots 1000$?

Solution. The first sequence includes every sixth integer from 10 up to 1000. The second sequence includes every eleventh integer from 10 up to 1000. The number contained in both sequences are the every sixty-sixth number from 10 to 1000, that inscribed $10, 76, 142, \ldots, 1000$. There are $\frac{1000-10}{66} + 1 = \boxed{16}$ such numbers. □

Problem 6.1.12. (*1 point*) When Troy writes his digits, his 0, 1, and 8 look the same right-side-up and upside-down as seen in the figure below. His 6 and 9 look like upside-down images of each other. None of his other digits look like digits when they are inverted. How many different five-digit numbers (which do not begin with the digit zero) can Troy write which read the same right-side-up and upside-down?

Solution. Each of the digits that Troy writes in a five-digit number must be one of the five: 0,1,8,6,9.

In addition, the numbers in positions 4 and 5 must be the up-side-down versions of the digits be written in position 2 and 1, respectively. Also, the digit in position 3 must be 0, 1, or 8 since it must look the same right-side-up and up-side-down. Finally, the digit in the first position cannot be 0 since no five-digit number can begin with a digit 0.

Thus, there are 4 possible choices for the first digit, 5 choices for the second digit, three choices for the third digit, and the last two digits are determined by the choices of the first two.

Hence, there are $4 \cdot 5 \cdot 3 = \boxed{60}$ choices. □

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Problem 6.1.13. (*1 point*) The diagram shows two equilateral triangles with side length 4 mounted on two adjacent sides of a square also with side length 4. The distance between the two vertices marked A and B can be written as $\sqrt{m}+\sqrt{n}$ for two positive integers m and n. Find mn.

Solution. Let the center of the square be the point C. The distance from A to C is given by the height of the equilateral triangle $4\cdot\frac{\sqrt{3}}{2}$ plus half the length of the side of the square, 2; or $\sqrt{12}+2$. Triangle ACB is an isosceles right triangle, so its hypotenuse AB has a length of $\sqrt{2}(\sqrt{12}+2)=\sqrt{24}+\sqrt{8}$.

Hence, $mn = 24\cdot 8 = \boxed{192.}$ □

Problem 6.1.14. (*1 point*) The five-digit number 12110 is divisible by the sum of its digits $1+2+1+1+0=5$. Find the greatest five-digit number which is divisible by the sum of its digits.

Solution. Let n be such a number. We will try strategy by descend from 99999 to find the first number satisfies the required conditions.

If $n=\overline{9999a}$, then $36+a \mid n \Rightarrow 36+a \mid n-(36+a)=99954$. But $99954=2\cdot 3^4\cdot 617$. Since $36\le 36+a\le 45$, it is easy to verify that there is no such a so that $36+a \mid 99954$.

If $n=\overline{9998a}$, then $35+a \mid n \Rightarrow 35+a \mid n-(35+a)=99945=3^2\cdot 5\cdot 2221$. By the same method as above case, there is no such a.

If $n=\overline{9997a}$, then $34+a \mid n \Rightarrow 34+a \mid n-(34+a)=99936=2^5\cdot 3^2\cdot 347$. It is easy to test that for $a=2, 36=2^2\cdot 3^2 \mid 99936$ is the only solution.

Thus $n=\boxed{99972.}$ □

Problem 6.1.15. (*1 point*) In the diagram below, AB and CD are parallel, $\angle BXY=45^\circ$, $\angle DZY=25^\circ$, and $XY=YZ$. What is the degree measure of $\angle YZX$?

> **Remark.** The diagram mentioned in the text was missing. It is shown as below.

Solution. By drawing line through Y parallel to AB, it is easy to see that $\angle XYZ=\angle YXB+\angle YZD=70^\circ$. $\triangle XYZ$ is isosceles at Y, so $\angle YZX=\frac{1}{2}(180^\circ-70)=\boxed{55^\circ.}$ □

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Problem 6.1.16. (*1 point*) Let a and b be nonzero real numbers such that

$$\begin{cases} \frac{1}{3a} + \frac{1}{b} = 2011 \\ \frac{1}{a} + \frac{1}{3b} = 1 \end{cases}$$

What is the quotient when $2a + 2b$ is divided by $3ab$?

Solution.

$$\begin{cases} \frac{1}{3a} + \frac{1}{b} = 2011 \\ \frac{1}{a} + \frac{1}{3b} = 1 \end{cases} \Rightarrow \frac{3a+b}{3ab} = 2011, \frac{a+3b}{3ab} = 1 \Rightarrow \frac{4a+4b}{3ab} = 2012 \Rightarrow \frac{2a+2b}{3ab} = \frac{2012}{2} = \boxed{1006.}$$

□

Problem 6.1.17. (*1 point*) Find the number of ordered quadruples (a, b, c, d) where each of a, b, c, and d are (not necessarily distinct) elements of $\{1, 2, 3, 4, 5, 6, 7\}$ and $3abc + 4abd + 5bcd$ is even. For example, $(2, 2, 5, 1)$ and $(3, 1, 4, 6)$ satisfy the conditions.

Solution. The given sum is even exactly when the products abc and bcd are either both even or both odd. This happens either when the product bc is even and or when bc is odd and a and d are either both odd or both even.

Of the $7 \cdot 7 = 49$ ways to assign values to b and c, $4 \cdot 4 = 16$ ways result in bc being odd, and $49 - 16 = 33$ ways result in bc being even. Similarly, there are 49 ways to assign value to a and d, of these $4 \cdot 4 = 16$ ways result in both a and d being odd, and $3 \cdot 3$ in both a and d being even.

It follows that the total number of ways to assign value to a, b, c, and d so that $3abc + 4abd + 5bcd$ is even is

$$33 \cdot 49 + 16 \cdot (16 + 9) = \boxed{2017.}$$

□

Problem 6.1.18. (*1 point*) Find the positive integer n so that n^2 is the least perfect square exceeding $8 + 16 + 24 + \cdots + 8040$.

Solution.

$$8 + 16 + 24 + \cdots + 8040 = 8\left(\sum_{i=1}^{1005} i\right) = 8 \cdot \frac{1005 \cdot 1006}{2} = 2010 \cdot 2012 = 2011^2 - 1$$

The least perfect square exceeding $2011^2 - 1$ is 2011^2, thus $n = \boxed{2011.}$ □

Problem 6.1.19. (*1 point*) How many ordered pairs of sets (A, B) have the properties:

$$\begin{cases} A \subseteq \{1, 2, 3, 4, 5, 6\} \\ B \subseteq \{2, 3, 4, 5, 6, 7, 8\} \\ |A \cap B| = 3 \text{ (A and B has exactly 3 elements.)} \end{cases}$$

Solution. The sets $\{1, 2, 3, 4, 5, 6\}$ and $\{2, 3, 4, 5, 6, 7, 8\}$ have five elements in common, so there are $\binom{5}{3} = 10$ ways to select three elements that the sets A and B have in common.

Having selected the three shared elements, there are two choices of what to do with the element 1 which can either be in or out of set A Similarly, there are two choices for each of the element 7 and 8 which can be in or out of set B. Of the element in $\{2, 3, 4, 5, 6\}$, three of the elements have been chosen to appear in both A and B, but there are three choices of what to do with each of the other two elements which can be placed either in the set A, in the set B, or left out of both sets.

It follows that the number of ways to choose the sets A and B is $10 \cdot 2 \cdot 2 \cdot 2 \cdot 3 \cdot 3 = \boxed{720.}$ □

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Problem 6.1.20. (*1 point*) Let V be the set of vertices of a regular 25 sided polygon with center at point C. How many triangles have vertices in V and contain the point C in the interior of the triangle?

Solution. The number of triangles with vertices among the 25 vertices is $\binom{25}{3} = 2300$. The triangles that do not contain the center C are exactly the triangles that are obtuse.

Number the vertices of the regular 25 sided polygon in order from 1 to 25. A triangle will have an obtuse angle at the point number 11 if one of its other two vertices is numbered with a number less than 11, one is numbered with a number greater than 11, and the difference between these two number does not exceed 11. Thus one of these vertices could be numbered k for $1 \leq k \leq 10$ while the other could be numbered m with $12 \leq m \leq k + 11$.

That is, for each choice of k, there are k choice for m. It follows that the number of triangles with an obtuse angle at vertex 11 is

$$1 + 2 + 3 + \ldots + 10 = \frac{10 \cdot 11}{2} = 55.$$

An obtuse triangle could have its obtuse angle at any of the 25 vertices, thus there are $25 \cdot 55$ obtuse triangles. Hence the number of triangles that contain point C is $2300 - 25 \cdot 55 = \boxed{925.}$ $\square$

6.2 High School - Test 4

You have **90 minutes** to complete the test. You have to **submit only the answers**. No solution is required.

Note that you have to **follow the instructions by the COs** *for submitting the answers.*

- **Intermediate (I) level: Problems 1-10**
- **Advanced (A) level: Problems 11-20**
- **Olympiad (O) level: Problems 21-30**

If you submit solution based on coding, please make sure that your submission is compliant. Read the introduction chapter for more information.

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Problem 6.2.1. (*1 point*) The ratio of 3 to the positive number n is the same as the ratio of n to 192. Find n.

Solution.

$$\frac{3}{n} = \frac{n}{192} \Rightarrow n^2 = 3 \cdot 193 = 3 \cdot 3 \cdot 64 \Rightarrow n = 3 \cdot 8 = \boxed{24.}$$

□

Problem 6.2.2. (*1 point*) The target below is made up of concentric circles with diameters 3, 6, 9, 12, and 15. The area of the dark region is $n\pi$. Find n.

Solution. The area of a circle with radius r is πr^2. The area of the shaded region is

$$\pi\left[\left(\frac{15}{2}\right)^2 - \left(\frac{12}{2}\right)^2 + \left(\frac{9}{2}\right)^2 - \left(\frac{6}{2}\right)^2 + \left(\frac{3}{2}\right)^2\right] = \pi\boxed{\frac{135}{4}.}$$

□

Problem 6.2.3. (*1 point*) Shirley went to the store planning to buy 160 balloons for 10 dollars. When she arrived, she was surprised to find that the balloons were on sale for 20 percent less than expected. How many balloons could Shirley buy for her 10 dollars?

Solution. Shirley will spend 10 dollars to buy balloons selling at the price $\frac{10(1-0.20)}{160}$. This will let her to purchase for \$10:

$$\frac{10}{\frac{10(1-0.20)}{160}} = \boxed{200.}$$

□

Problem 6.2.4. (*1 point*) Five non-overlapping equilateral triangles meet at a common vertex so that the angles between adjacent triangles are all congruent. What is the degree measure of the angle between two adjacent triangles?

Solution. There are 10 angles that meet at the center point of the diagram. The angles within the five triangles are all $60°$, thus the other five angles have the total measures of $360° - 5 \cdot 60° = 60°$. Thus each of them is $\frac{60°}{5} = \boxed{12°.}$ □

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Problem 6.2.5. (*1 point*) Let $a_1 = 2$, and for $n \geq 1$, let $a_{n+1} = 2a_n + 1$. Find the smallest value of an $a_n > 100$ that is not a prime number.

Solution. Let just compute the terms

$$a_2 = 2 \cdot 2 + 1 = 5, a_3 = 2 \cdot 5 + 1 = 11, a_4 = 2 \cdot 11 + 1 = 23, a_5 = 2 \cdot 23 + 1 = 47$$
$$a_6 = 2 \cdot 47 + 1 = 95, a_6 = 2 \cdot 95 + 1 = 191 \text{ (prime)}, a_7 = 2 \cdot 191 + 1 = 382 \text{ (prime)}, a_8 = 767 = 13 \cdot 59$$

So the smallest value of an $a_n > 100$ that is not a prime number, is $\boxed{767.}$ □

Problem 6.2.6. (*1 point*) Working alone, the expert can paint a car in one day, the amateur can paint a car in two days, and the beginner can paint a car in three days. If the three painters work together at these speeds to paint three cars, it will take them $\frac{m}{n}$ days where m and n are relatively prime positive integers. Find mn.

Solution. The expert paints car at the rate of 1 per day, the amateur at $\frac{1}{2}$ per day, and the beginner at $\frac{1}{3}$ per day. When working together, they paint $1 + \frac{1}{2} + \frac{1}{3}$ cars per day. To paint three cars, they need:

$$\frac{3}{1 + \frac{1}{2} + \frac{1}{3}} = \frac{18}{11}.$$

Thus $mn = 18 \times 11 = \boxed{198.}$ □

Problem 6.2.7. (*1 point*) Find the prime number p such that $73p + 1$ is a perfect square.

Solution. Let $n^2 = 73p + 1$, then $73p = (n-1)(n+1)$. Since 73 and p are both primes, so

$$\begin{cases} 73 = n - 1, p = n + 1 \Rightarrow p = 75 \text{ not a prime} \\ 73 = n + 1, p = n - 1 \Rightarrow p = \boxed{71} \end{cases}$$

□

Problem 6.2.8. (*1 point*) When 126 is added to its reversal, 621, the sum is $126 + 621 = 747$. Find the greatest integer which when added to its reversal yields 1110.

Solution. Assume that the answer is a three-digit number $\overline{abc}$, then according to the given conditions:

$$(100a + 10b + c) + (100c + 10b + a) = 1110 \Rightarrow 101(a + c) + 20b = 1110 \Rightarrow 101(a + c) = 10(111 - 2b).$$

Note that 101 is a prime number, so $101 = 111 - 2b \Rightarrow b = 5$, then $a + c = 10$. The largest number is $\boxed{951.}$ □

Problem 6.2.9. (*1 point*) There are integers m and n so that $9 + \sqrt{11}$ is the root of the polynomial $x^2 + mx + n$. Find mn.

Solution. From the quadratic formula $x^2 + mx + n$, its root $9 + \sqrt{11}$ should be in the format

$$\frac{-m + \sqrt{m^2 - 4n}}{2} \Rightarrow m = -18, n = 70.$$

Thus $mn = (-18) \cdot 70 = \boxed{-1260.}$ □

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Problem 6.2.10. (*1 point*) The diagram shows a large circular dart board with four smaller shaded circles each internally tangent to the larger circle. Two of the internal circles have half the radius of the large circle, and are, therefore, tangent to each other. The other two smaller circles are tangent to these circles. If a dart is thrown so that it sticks to a point randomly chosen on the dart board, then the probability that the dart sticks to a point in the shaded area is $\frac{m}{n}$ where m and n are relatively prime positive integers. Find mn.

Remark. The diagram mentioned in the text of the problem was missing. It is now shown as below.

Solution. WLOG, assume that the dart board has radius 2. Then the larger shaded circles have radius 1, and the smaller shaded circles have radius r. The Pythagorean Theorem can be used ot relate the distance between the centers of a larger and a smaller shaded circle to the distance of these two circles to the center of the dartboard:

$$1^2 + (2-r)^2 = (1+r)^2 \Rightarrow r = \frac{2}{3}$$

The probability that the dart sticks to a point in the shaded area is the ratio of the shaded area to the area of the dart board:

$$\frac{2\pi 1^2 + 2\pi\left(\frac{2}{3}\right)^2}{\pi 2^2} = \frac{13}{18}.$$

Hence, $mn = 13 \cdot 18 = \boxed{234.}$ □

Problem 6.2.11. (*1 point*) Six distinct positive integers are randomly chosen between 1 and 2023, inclusive. The probability that some pair of the six chosen integers has a difference that is a multiple of 5 is n percent. Find n.

Solution. There are only 5 different possible remainders when a number is divided by 5. If six numbers are selected, then by thee Pigeonhole Principle, at least two of the selected numbers have the same remainder when divided by 5. The difference of these two numbers will be an integer divisible by 5. Thus the probability is $\boxed{100}$ percent. □

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Problem 6.2.12. (*1 point*) Find the area of the region in the coordinate plane satisfying the three conditions

$$\begin{cases} x \leq 2y \\ y \leq 2x \\ x + y \leq 30 \end{cases}$$

Solution. Let B be the point where lines $x = 2y$ and $x + y = 30$ meet:

$$\begin{cases} x = 2y \\ x + y = 30 \end{cases} \Rightarrow x = 20, y = 10 \Rightarrow B(20, 10)$$

Let C be the point where lines $y = 2x$ and $x + y = 30$ meet:

$$\begin{cases} y = 2x \\ x + y = 30 \end{cases} \Rightarrow x = 10, y = 20 \Rightarrow C(10, 20)$$

It is obvious that $A(0, 0)$ is where lines $x = 2y$ and $y = 2x$. It is easy to see that ABC is a isosceles triangle.

The length of the base BC is $\sqrt{(20-10)^2 + (10-20)^2} = 10\sqrt{2}$. The midpoint M of BC is $M(\frac{20+10}{2}, \frac{10+20}{2})$ or $M(15, 15)$. The length of the altitude AM is $\sqrt{(0-15)^2 + (0-15)^2} = 15\sqrt{2}$.

Thus the area of $\triangle ABC$, where $x \leq 2y, y \leq 2x$, and $x + y \leq 30$ is $\frac{1}{2}(10\sqrt{2})(15\sqrt{2}) = \boxed{150}$. □

Problem 6.2.13. (*1 point*) Let S be the set of all 10-term arithmetic progressions that include the numbers 4 and 10. For example,

$$(-2, 1, 4, 7, 10, 13, 16, 19, 22, 25) \text{ and } (10, 8\frac{1}{2}, 7, 5\frac{1}{2}, 4, 2\frac{1}{2}, 1, -\frac{1}{2}, -2, -3\frac{1}{2})$$

are both members of S. Find the sum of all values of a_{10} for each $(a_1, a_2, a_3, a_4, a_5, a_6, a_7, a_8, a_9, a_{10}) \in S$, that is

$$\sum_{(a_1,a_2,a_3,a_4,a_5,a_6,a_7,a_8,a_9,a_{10}) \in S} a_{10}.$$

Solution. An arithmetic progression containing the terms 4 and 10 is completely determine by the position in the progression of the 4 and the 10.

For each $(a1, a2, a3, a4, a5, a6, a7, a8, a9, a10) \in S$ there is exactly one $(b1, b2, b3, b4, b5, b6, b7, b8, b9, b10) \in S$ where the positions of the 4 and the 10 are reversed.

Then

$$(a_1 + b_1, a_2 + b_2, a_3 + b_3, a_3 + b_4, a_5 + b_5, a_6 + b_6, a_7 + b_7, a_8 + b_8, a_9 + b_9, a_{10} + b_{10})$$

is also an arithmetic progression, but since two of its terms are $4 + 10 = 10 + 4 = 14$, so it is a constant progression with all terms equal to 14. Therefore $a_{10} + b_{10} = 14$. It follows that the mean of all tenth terms of the progressions in S is $\frac{1}{2}14 = 7$, and the requested sums of all tenth terms is 7 times the number of elements in S.

Since an element of S is completely determined by the positions of the 4 and the 10, we just need to count those. There are 10 possible position for the 4 and 9 possible position for the 10, thus there are $10 \cdot 9 = 90$ sequences. Hence the requested sum is $7 \cdot 90 = \boxed{630.}$ □

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Problem 6.2.14. (*1 point*) The lengths of the three sides of a right triangle form a geometric sequence. The sine of the smallest of the angles in the triangle is $\frac{m+\sqrt{n}}{k}$, where m, n, and k are integers, and k is not divisible by the square of any prime. Find $(m+n)k$.

Solution. There are real number $a > 0$ and $r > 1$ so that the sides of the triangle have lengths a, ar, ar^2. By the Pythagorean Theorem,

$$a^2 + (ar)^2 = (ar^2)^2 \Rightarrow 1 + r^2 = r^4 \Rightarrow r^2 = \frac{1+\sqrt{5}}{2}.$$

The sine of the smallest angle is

$$\frac{a^2}{ar^2} = \frac{1}{r^2} = \frac{2}{1+\sqrt{5}} = \frac{-1+\sqrt{5}}{2}.$$

Thus $(m+n)k = (-1+5)2 = \boxed{8.}$ □

Problem 6.2.15. (*1 point*) A pyramid has a base which is an equilateral triangle with side length 300 centimeters. The vertex of the pyramid is 100 centimeters above the center of the triangular base. A mouse starts at a corner of the base of the pyramid and walks up the edge of the pyramid toward the vertex at the top. When the mouse has walked a distance of 148 centimeters, how many centimeters above the base of the pyramid is the mouse?

Solution. An equilateral triangle with side length a has an altitude $\frac{a\sqrt{3}}{2}$, and the distance from a vertex to the center (the centroid, incenter, and circumcenter are all at the same point in an equilateral triangle) is two-thirds the altitude or $\frac{a}{\sqrt{3}}$.

Thus, for the base of the pyramid, the distance from a vertex to the center is $100\sqrt{3}$ centimeters. By the Pythagorean Theorem, the length of an edge of the pyramid going from the corner of the base to the top vertex inscribed

$$\sqrt{(100\sqrt{3})^2 + 100^2} = 200.$$

Thus. the edge is twice as long as the height of the pyramid. It follows by similar triangles that the mouse walks a distance equal to twice the height that the mouse is from the base of the pyramid. When the mouse has walked 148 centimeters, it is at a height of $\frac{1}{2}(148) = \boxed{74}$ centimeters above the base. □

Problem 6.2.16. (*1 point*) Evaluate $1^3 - 2^3 + 3^3 - 4^3 + 5^3 - \cdots + 99^3$.

Solution.

$$1^3 - 2^3 + 3^3 - 4^3 + \cdots + 99^3 = \sum_{k=1}^{99} (-1)^{k+1} k^3 = \sum_{k=1}^{99} k^3 - 2\sum_{k=1}^{49} (2k)^3 = \left(\frac{99 \cdot 100}{2}\right)^2 - 16\left(\frac{49 \cdot 50}{2}\right)^2 = \boxed{492\ 500}$$

□

Problem 6.2.17. (*1 point*) In how many distinguishable rearrangements of the letters ABBCCDEEF does the A precede both C's, the F appears between the 2 C's, and the D appears after the F?

Solution. The conditions in the problem indicate that the letters $ACFC$ must appear in that order.

Into this sequence of four letters, there are two positions into which the D letter can be placed, either before or after the right-most C. Thus, we obtain a sequence of five letters.

Into this sequence of five letters we need insert four positions for the four letters B, B, E, and E. By star-and-bar counting method, there are $\binom{5+4}{4} = 126$ ways to find four places.

Finally, there are $\frac{4!}{2!2!} = 6$ ways to put the four letters B, B, E, and E into these four positions.

Hence the number of ways is $2 \cdot 126 \cdot 6 = \boxed{1512.}$ □

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Problem 6.2.18. (*1 point*) Let a be a positive real number such that $\dfrac{a^2}{a^4-a^2+1}=\dfrac{4}{37}$. Then $\dfrac{a^2}{a^4-a^2+1}=\dfrac{m}{n}$, where m and n are relatively prime positive integers. Find mn.

> **Remark.** The second expression is incorrect. It should be $\dfrac{a^3}{a^6-a^3+1}=\dfrac{m}{n}$,

Solution. Let $x=a+\frac{1}{a}>0$, then $x^2=a^2+\frac{1}{a^2}+2$,

$$\frac{4}{37}=\frac{a^2}{a^4-a^2+1}=\frac{1}{a^2-1+\frac{1}{a^2}}=\frac{1}{x^2-3}\Rightarrow x^2=\frac{37}{4}+3=\frac{49}{4}\Rightarrow x=\frac{7}{2}$$

$$\Rightarrow\left(a^2+\frac{1}{a^2}\right)\left(a+\frac{1}{a}\right)=a^3+\frac{1}{a^3}+a+\frac{1}{a}\Rightarrow a^3+\frac{1}{a^3}=(x^2-2)(x)-x=\left(\frac{7}{2}\right)^3-3\cdot\frac{7}{2}=\frac{259}{8}$$

$$\Rightarrow\frac{a^3}{a^6-a^3+1}=\frac{1}{a^3-1+\frac{1}{a^3}}=\frac{8}{251}\Rightarrow mn=8\cdot 251=\boxed{2008.}$$

□

Problem 6.2.19. (*1 point*) The diagrams below shows a 2 by 2 grid made up of four 1 by 1 squares. Shown are two paths along the grid from the lower left corner to the upper right corner of the grid, one with length 4 and one with length 6. A path may not intersect itself by moving to a point where the path has already been. Find the sum of the lengths of all the paths from the lower left corner to the upper right corner of the grid.

Solution. By alternately colouring the corners of the squares black and white and noticing that each edge of a square connects a black corner to a white corner, it is seen that any path from the lower left corner to the upper right corner of the grid must be of even length.

Because a path from the lower left corner of the grid to the upper right corner of the grid must move right along at least to sides of the 1×1 squares, such a path must have a length at least 4. Since there are only 9 corner of he 1×1 squares in the grid, a a path cannot cross any corner twice, a path must have length at most 8. Thus, a path from the lower left corner of the grid to the upper right corner of the grid can have length 4, 6, or 8.

A path of length 4 consists of movements along two horizontal edges and two vertical edges of 1×1 squares. The number of ways to arrange two horizontal moves and two vertical moves in a sequence of four moves in $\binom{4}{2}=6$, so there are 6 paths of length 4. There are 4 paths of length 6, a fact easily verified by considering that a path of length 6 is determined by the first two edges of the path. There are only 2 paths of length 8, a fact easily verified by noticing that a path of length 9 must reach each of the corners which can be done only by including either all horizontal edges or all vertical edges of the 1×1 squares.

Thus, the sum of the lengths of all the paths is $6\cdot 4+4\cdot 6+2\cdot 8=\boxed{64.}$ □

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Problem 6.2.20. (*1 point*) Points A and B are the endpoints of a diameter of a circle with center C. Points D and E lie on the same diameter so that C bisects segment DE. Let F be a randomly chosen point within the circle. The probability that $\triangle DEF$ has a perimeter less than the length of the diameter of the circle is $\frac{17}{128}$. There are relatively prime positive integers m and n so that the ratio of DE to AB is $\frac{m}{n}$. Find mn.

Solution. WLOG, assume that the circle has radius 1 so its diameter is 2. Assume that point D and E are each a distance x from C.

If $\triangle DEF$ has a perimeter less than 2, then

$$DF + FE + 2x < 2 \Rightarrow DF + FE < 2 - 2x.$$

It follows that point F lies inside an ellipse with foci D and E where the sum of distances from a point on the ellipse to the points D and E is the constant $2 - 2x$. It follows that the endpoints of the major axis of the ellipse are each a distance $1 - x$ from C.

Let G be an endpoint of the minor axis of the ellipse. Then $DG + GE = 2 - 2x$ and $DG = EG$, so $DG = 1 - x$. Since $\triangle CDG$ is a right triangle with hypotenuse $DG = 1 - x$ and leg $CD = x$, then the leg

$$CG = \sqrt{(1-x)^2 - x^2} = \sqrt{1 - 2x}.$$

The semiminor axis of the ellipse, therefore has length $\sqrt{1-2x}$, while the semimajor axis of the ellipse has length $1 - x$.

It follows that the area of the ellipse is $\pi(1-x)\sqrt{1-2x}$. The area of the circle is π, therefore the probability that $\triangle DEF$ has a perimeter less than the length of the diameter of the circle inscribed satisfy that

$$\frac{17}{128} = \frac{\pi(1-x)\sqrt{1-2x}}{\pi} \Rightarrow 2x^3 - 5x^2 + 4x - 1 = \frac{289}{16384}$$
$$\Rightarrow 2^{15}x^3 - 52^{14}x^2 + 2^{16}x - 16095 = 0$$

Since it is given by the problem that x is a rational root of the above equations, thus there exists m positive integer such that $x = \frac{m}{2^5}$. By substitution

$$m^3 - 80m^2 - 2^{11}m - 16095 = 0 \Rightarrow m \mid 16095 = 3 \cdot 5 \cdot 29 \cdot 37$$
$$\text{By testing } m = 15 \Rightarrow x = \frac{15}{32}$$

Hence $mn = 15 \cdot 32 = \boxed{480.}$ $\square$

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Problem 6.2.21. (*1 point*) Let a be the sum of the numbers:

$$99 \times 0.9,\ 999 \times 0.9, 9999 \times 0.9 \ldots, 999 \cdots 9 \times 0.9$$

where the final number in the list is 0.9 times a number written as a string of 100 digits all equal to 9. Find the sum of the digits in the number a.

Solution. Note that the list contains 99 numbers. Their sum is:

$$\begin{aligned}
a &= 0.9(99 + 999 + \cdots + 999\ldots9) = 0.9((100-1) + (1000-1) + \cdots + (100\ldots0-1)) \\
&= 0.9((1-1) + (10-1) + (100-1) + (1000-1) + \cdots + (100\ldots0-1)) - 0.9((1-1) + (10-1)) \\
&= 0.9\left(\sum_{n=0}^{100}(10^n - 1)\right) - 0.9(9) = 0.9\left(\sum_{n=0}^{100} 10^n\right) - 0.9(101) - 0.9(9) \\
&= 0.9\left(\frac{10^{101}-1}{10-1}\right) - 0.9(110) = 0.1(10^{101}-1) - 99 = 0.1(10^{101} - 991)
\end{aligned}$$

Note that the sum of digits of $10a$ and a is the same, so we just need to consider $10^{101} - 991$, this number has $101 - 3 = 98$ digits of 9, followed by 0, 0, and 9. Thus, their sum is $98 \cdot 9 + 0 + 0 + 9 = \boxed{891.}$ □

Problem 6.2.22. (*1 point*) A disk with radius 10 and a disk with radius 8 are drawn so that the distance between their centers is 3. Two congruent small circles lie in the intersection of the two disks so that they are tangent to each other and to each of the larger circles as shown. The radii of the smaller circles are both $\frac{m}{n}$ where m and n are relatively prime positive integers. Find mn.

Solution. Let A be the center of the circle with radius 10, and B be the center of the circle with radius 8. The two small circles are tangent to each other and the line AB at point C. Let D be the center of one of the small circles. E and F be the point where that small circle is tangent to the circles centered at A and B, respectively.

Both triangles ACD and BCD are right triangle with the right angles at C. Let r be the radius of a small circle. Since $AE = 10$, $AC = \sqrt{(10-r)^2 - r^2}$. Similarly $BC = \sqrt{(8-r)^2 - r^2}$. Furthermore

$$\begin{aligned}
&AC = AB + BC \Rightarrow \sqrt{(10-r)^2 - r^2} = 3 + \sqrt{(8-r)^2 - r^2} \\
&\Rightarrow 27 - 4r = 6\sqrt{(8-r)^2 - r^2} \Rightarrow 16r^2 + 360r - 1575 = 0 \Rightarrow r = \frac{15}{4}
\end{aligned}$$

Hence $mn = 15 \cdot 4 = \boxed{60.}$ □

Problem 6.2.23. (*1 point*) Let x be a real number in the interval $\left(0, \frac{\pi}{2}\right)$ such that

$$\frac{1}{\sin x \cos x} + 2\cot 2x = \frac{1}{3}.$$

Evaluate

$$\frac{1}{\sin x \cos x} - 2\cot 2x = \frac{1}{2}.$$

Remark. The given expression is incorrect. The correct expression is:

$$\frac{1}{\sin x \cos x} - 2\cot 2x.$$

Solution. Note that

$$\frac{1}{\sin x \cos x} + 2\cot 2x = \frac{2}{\sin 2x} + 2\cot 2x, \left(\frac{2}{\sin 2x} + 2\cot 2x\right)\left(\frac{2}{\sin 2x} - \frac{2\cos 2x}{\sin 2x}\right) = \frac{4}{\sin^2 2x} - \frac{4\cos^2 2x}{\sin^2 2x}$$
$$= \frac{4}{\sin^2 2x}(1 - \cos^2 2x) = 4 \Rightarrow \frac{2}{\sin 2x} - \frac{2\cos 2x}{\sin 2x} = \frac{4}{\frac{2}{\sin 2x} + 2\cot 2x} = \boxed{12.}$$

□

Problem 6.2.24. (*1 point*) The diagram below shows a regular hexagon with an inscribed square where two sides of the square are parallel to two sides of the hexagon. There are positive integers m, n, and p such that the ratio of the area of the hexagon to the area of the square can be written as $\frac{m+\sqrt{n}}{p}$ where m and p are relatively prime. Find $(m+n)p$.

Remark. The diagram associated with the problem was missing.

Solution. Label the vertices of the hexagon as shown. Let G and H be the points where one side of the square touches the hexagon. Let J be the point on the side of the square closest to vertex E. Let the distance from E to J be x.

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WLOG, assume that the hexagon has side length 1. Since $\angle DEF = 120°$, $DE = 1$, the distance from D to F is twice the height of a $30-60-90$ triangle with hypotenuse 1, or $2 \cdot 1 \cdot \sin(60°) = \sqrt{3}$. So the hexagon is made up of a rectangles measuring 1 by $\sqrt{3}$ and four $30-60-90$ triangle with legs measuring $\frac{1}{2}$ and $\frac{\sqrt{3}}{2}$. Thus the area of the hexagon is $\sqrt{3} + 4 \cdot \frac{\sqrt{3}}{8} = \frac{3\sqrt{3}}{2}$.

The width of the hexagon is 2, so the width of the square is $2 - 2x$. The height of the square is the length GH, which is $2x\sqrt{3}$. Therefore $2 - 2x = 2x\sqrt{3}$, so $x = \frac{1}{1+\sqrt{3}}$. The area of the square is

$$(2x\sqrt{3})^2 = \left(\frac{2\sqrt{3}}{1+\sqrt{3}}.\right) = \frac{4 \cdot 3}{4 + 2\sqrt{3}} = \frac{6}{2+\sqrt{3}}.$$

The ratio of the area is

$$\left(\frac{3\sqrt{3}2}{\frac{6}{2+\sqrt{3}}}\right) = \frac{3+\sqrt{12}}{4}.$$

Hence $(m+n)p = (3+12)4 = \boxed{60.}$ □

Problem 6.2.25. (*1 point*) Let x_1, x_2, and x_3 be the three roots of the polynomial $x^3 + 3x + 1$. There are relatively prime positive integers m and n so that

$$\frac{m}{n} = \frac{x_1^2}{(5x_2+1)(5x_3+1)} + \frac{x_2^2}{(5x_3+1)(5x_1+1)} + \frac{x_3^2}{(5x_1+1)(5x_2+1)}.$$

Find mn.

Solution. First, note that $x^3 + 3x + 1 = (x - x_1)(x - x_2)(x - x_3)$. By Viete's Theorem:

$$x_1 + x_2 + x_3 = 0, x_1x_2 + x_2x_3 + x_3x_1 = 3, x_1x_2x_3 = -1$$
$$\Rightarrow 0 = (x_1 + x_2 + x_3)^2 = x_1^2 + x_2^2 + x_3^2 + 2(x_1x_2 + x_2x_3 + x_3x_1) \Rightarrow x_1^2 + x_2^2 + x_3^2 = -6$$
$$\Rightarrow x_1^3 + x_2^3 + x_3^3 = (-3x_1 - 1) + (-3x_2 - 1) + (-3x_3 - 1) = -3(x_1 + x_2 + x_3) - 3 = -3$$

Now

$$\frac{x_1^2}{(5x_2+1)(5x_3+1)} + \frac{x_2^2}{(5x_3+1)(5x_1+1)} + \frac{x_3^2}{(5x_1+1)(5x_2+1)} = \frac{x_1^2(5x_1+1) + x_2^2(5x_2+1) + x_2^2(5x_2+1)}{(5x_1+1)(5x_2+1)(5x_3+1)}$$
$$= \frac{5(x_1^3 + x_2^3 + x_3^3) + (x_1^2 + x_2^2 + x_3^2)}{125(x_1x_2x_3) + 25(x_1x_2 + x_2x_3 + x_3x_1) + 5(x_1 + x_2 + x_3) + 1} = \frac{5(-3) + (-6)}{125(-1) + 25(3) + 5(0) + 1} = \frac{3}{7}$$

Hence $mn = 3 \cdot 7 = \boxed{21.}$ □

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Problem 6.2.26. (*1 point*) Square ABCD has side length 4. Points E and F are the midpoints of sides AB and CD, respectively. Eight 1 by 2 rectangles are placed inside the square so that no two of the eight rectangles overlap (see diagram). If the arrangement of eight rectangles is chosen randomly, then there are relatively prime positive integers m and n so that $\frac{m}{n}$ is the probability that none of the rectangles crosses the line segment EF (as in the arrangement on the right). Find mn.

Solution. First, count the number of ways to place the rectangles so that none of them cross the segment EEF. In these arrangements four 1×2 rectangles cover the 2×4 rectangle $AEFD$, and four 1×2 rectangles cover teh 2×4 rectangle $EBCF$. Four 1×2 rectangles can cover a 2×4 rectangle in five ways, as shown below.

Thus, there are $5 \cdot 5 = 25$ ways to cover the 4×4 rectangle without crossing the segment EF.

Now, count the number of ways to cover the 4×4 rectangle while crossing the segment EF. The segment EF can be crossed by either two 1×2 rectangles or by four 1×2 rectangles. Below show the possible arrangements:

For the first three figures from the left, there is 1 way for each to cross EF with 4 rectangles. For the last two figures, there are 4 ways to cross with 2 rectangles. Thus, all together there are $1 + 1 + 4 + 4 = 11$ ways to cover the 4×4 rectangle while crossing the segment EF.

It follows that the probability that none of the rectangles crosses the line segment EF is $\frac{25}{11+25} = \frac{25}{36}$.

Hence $mn = 25 \cdot 36 = \boxed{900.}$ □

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Problem 6.2.27. (*1 point*) Find the smallest prime number that does not divide

$$9 + 9^1 + 9^2 + \ldots + 9^{2064}$$

> **Remark.** The given expression is incorrect, it should have been as follow
>
> $$9^1 + 9^2 + \ldots + 9^{2064}.$$

Solution. Let $n = 9^1 + 9^2 + \ldots + 9^{2064}$.

First, $2 \mid n$ because n is a sum of even number of odd terms, thus n is even.

Second, $3 \mid n$, because each of the terms in the sum if divisible by 9.

Third, 2064 is even, so $n = 9(1+9) + 9^3(1+9) + \ldots + 9^{2063}(1+9)$, so $5 \mid 10 = 1 + 9 \mid n$.

Forth, $3 \mid 2064$, so $n = 9(1+9+9^2)+9^4(1+9+9^2)+\ldots+9^{2062}(1+9+9^2)$, and since $1+9+9^2 = 91 = 7\cdot 13$, so $7 \mid n$ and $13 \mid n$.

Fifth, by Fermat's Little Theorem, $2^{10} \equiv 1 \pmod{11}$,

$$9 + 9^1 + 9^2 + \ldots + 9^{2064} = 9 \cdot \frac{9^{2064} - 1}{9 - 1} \Rightarrow n \equiv 9^{2064} - 1 \pmod{11}$$
$$9^{2064} \mid (-2)^{2064} \mid (2^{10})^{206} \cdot 2^4 \mid 5 \pmod{11} \Rightarrow 9^{2064} - 1 \equiv 4 \pmod{11}$$

Thus, $\boxed{11}$ is the smallest prime number that does not divide n. □

Problem 6.2.28. (*1 point*) Pictured below is part of a large circle with radius 30. There is a chain of three circles with radius 3, each internally tangent to the large circle and each tangent to its neighbors in the chain. There are two circles with radius 2 each tangent to two of the radius 3 circles. The distance between the centers of the two circles with radius 2 can be written as $d\frac{a\sqrt{b}-c}{d}$ where a, b, c, and d are positive integers, c and d are relatively prime, and b is not divisible by the square of any prime. Find $(a + b + c)d$.

Solution. Let G be the center of the circle with radius 30. A, B, and C be the centers of the circles with radius 3, and D, E be the centers of the circles with radius 2 as shown in the diagram. Also shown in the diagram are radii of the circle with radius 30 passing through point F where the circles with centers A, D, B, and E.

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Line GD also passes through point F where the circles centered at A and B are tangent because point D is equally distant from points A and B. Thus GD is tangent to the circle centered at B, so $\triangle FDB$ is right with $FB = 3$, and $BD = 2 + 3 = 5$, thus $FD = 4$.

Also $GB = 30 - 3 = 27$, so it follows that $GF = \sqrt{GB^2 - BF^2} = \sqrt{27^2 - 3^2} = \sqrt{720} = 12\sqrt{5}$. Then $GD = GF - FD = 12\sqrt{5} - 4$. Now since $\triangle GAB$ is similar to $\triangle GDE$, it follows that

$$\frac{DE}{GD} = \frac{AB}{GA} \Rightarrow DE = \frac{6}{27} \cdot (12\sqrt{5} - 4) = \frac{24\sqrt{5} - 8}{9}.$$

Thus $(a + b + c)d = (24 + 5 + 8)9 = \boxed{333.}$ □

Problem 6.2.29. (*1 point*) Let S be a randomly selected four-element subset of $\{1, 2, 3, 4, 5, 6, 7, 8\}$. Let m and n be relatively prime positive integers so that the expected value of the maximum element in S is $\frac{m}{n}$. Find mn.

Solution. If S has a maximum element k, then it has three other elements less than k. Thus, the number of four-element subsets S with maximum element $k > 3$ is $\binom{k-1}{3}$. The expected value of the maximum element is

$$E = \frac{4\binom{3}{3} + 5\binom{4}{3} + 6\binom{5}{3} + 7\binom{6}{3} + 8\binom{7}{3}}{\binom{8}{4}}.$$

Since

$$k\binom{k-1}{3} = \frac{k(k-1)!}{3!(k-4)!} = 4 \cdot \frac{k!}{4!(k-4)!} = 4\binom{k}{k-4}, \ textthus\ E = 4 \cdot \frac{\binom{4}{4} + \binom{5}{4} + \binom{6}{4} + \binom{7}{4} + \binom{8}{4}}{\binom{8}{4}}.$$

Now, each term of the sum $\binom{4}{4} + \binom{5}{4} + \binom{6}{4} + \binom{7}{4} + \binom{8}{4}$ is the number of ways counting the number of subsets of size 5 from the set $\{1, 2, 3, 4, 5, 6, 7, 8, 9\}$ with maximum element 5, 6, 7, 8, and 9. Therefore the sum is the number of ways selecting a subset of size 5 from the set $\{1, 2, 3, 4, 5, 6, 7, 8, 9\}$, or $\binom{9}{5}$.

Thus

$$E = 4 \cdot \frac{\binom{9}{5}}{\binom{8}{4}} = \frac{36}{5}.$$

Hence $mn = 36 \cdot 5 = \boxed{180}$. □

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Problem 6.2.30. (*1 point*) Four congruent spheres are stacked so that each is tangent to the other three. A larger sphere, R, contains the four congruent spheres so that all four are internally tangent to R. A smaller sphere, S, sits in the space between the four congruent spheres so that all four are externally tangent to S. The ratio of the surface area of R to the surface area of S can be written $m + \sqrt{n}$ where m and n are positive integers. Find $m + n$.

Solution. The center of the four congruent spheres are at the vertices of a regular tetrahedron. Without loss of generality, three of those vertices are located in three-dimensional coordinate space at $(2, 0, 0)$, $(-1, \sqrt{3}, 0)$, and $(-1, -\sqrt{3}, 0)$. Note that the distance between any two of these points is $2\sqrt{3}$. The fourth vertex can be located at $(0, 0, \sqrt{2}$ which is a distance $2\sqrt{3}$ from each of the other three vertices. Each of the four congruent spheres then has radius $\sqrt{3}$.

The center of both spheres R and S is equidistant from these three vertices and is located at $(0, 0, h)$ where the square of its distance from $(2, 0, 0)$ is $2^2 + h^2 = 4 + h^2$, and its distance squared from $(0, 0, 2\sqrt{2})$ is $(2\sqrt{2} - h)^2 = 8 - 4h\sqrt{2} + h^2$. Equating these two squared distances and solving for h yields $h = \frac{1}{\sqrt{2}}$.

The radius of S is the distance from $\left(0, 0, \frac{1}{\sqrt{2}}\right)$ to $(0, 0, 2\sqrt{2})$ minus the radius of one of the congruent spheres. Thus S has a radius $2\sqrt{2} - \frac{1}{\sqrt{2}} - \sqrt{3} = \frac{3}{\sqrt{2}} - \sqrt{3}$. The radius of R is the distance from $\left(0, 0, \frac{1}{\sqrt{2}}\right)$ to $(0, 0, 2\sqrt{2})$ plus the radius of one of the congruent spheres. THus R has a radius $2\sqrt{2} - \frac{1}{\sqrt{2}} + \sqrt{3} = \frac{3}{\sqrt{2}} + \sqrt{3}$.

The ratio of surface areas is the square of the ratio of these radii or

$$\left(\frac{\frac{3}{\sqrt{2}} + \sqrt{3}}{\frac{3}{\sqrt{2}} - \sqrt{3}}\right)^2 = (5 + 2\sqrt{6})^2 = 49 + 20\sqrt{6} = 49 + \sqrt{2400}.$$

Hence, $m + n = 49 + 2400 = \boxed{2449.}$ $\square$

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6.3 IC Test for Level 1

- All test lasts for **60 minutes**.
- The test consists of 4 **show-you-work** problems. For each of 4 show-you-work problems, you have to provide a complete solution in details. If your solution uses any diagram, please submit them too.
- Paper-based book, calculators are allowed. Computers are allowed for solving problem with coding. No searching on Internet for ideas, hints, or solutions are allowed. No help from anyone is allowed. Be honest.
- Grading:
  1. For a *show-you-work problem* the total number of points can be earned is 10**.** For a complete solution for each question of a show-you-work problem, you earn all available points for that question. If your solution for that question is not correct, you may earn some but not all available points for that question. The actual number of points to be awarded is based on the discretion of the grading COs.
- Students, if not able to join the contest at the official designated time, are eligible to write at an earlier time. They must contact the COs in time for arrangement. They must not discuss any of the received contest problems with anyone until the official contest time passed.
- Qualification: The minimum number of points **to pass the level test is** $\boxed{25.}$

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Problem 6.3.1. A bag containing some widgets weighs 77 kg. When 2 of the widgets are removed, the weight of the bag of widgets drops to 69 kg. The bag weighs 1 kg when empty. How many widgets are left in the bag?

Solution. Let w be the weight of one widget. Since the weight of the bag of widgets drops 8 kg when 2 widgets are removed, we have $2w = 8$. Dividing by 2 gives $w = 4$, so each widget weighs 4 kg. Since the bag weighs 1 kg, the total weight of the widgets in the final bag is $77 - 1 = 76$ kg. Suppose there are n widgets in the bag. Each widget weighs 4 kg and all of them together weigh 76 kg, so we must have $4n = 76$. Dividing both sides of this equation by 4 gives $n = 19$ widgets. The number of widgets left in the bag after removing 2 of them is $19 - 2 = \boxed{17.}$ □

Problem 6.3.2. The angle $\angle B$ in $\triangle ABC$ is $60°$. If an exterior angle at A is $170°$, what is $\angle C$?

Solution. We know that an exterior angle of a triangle is equal to the sum of its remote interior angles. Since the angles remote to the exterior angle at A are $\angle B$ and $\angle C$, we have $170° = \angle B + \angle C = 60° + \angle C$. Therefore, $\angle C = \boxed{110°}$. □

Problem 6.3.3. Each week, between 60 and 80 students show up for an archery class run by Betty and Wilma. Usually the students break up into groups of equal size for target practice. However, this week, Betty noticed that she could not break the students up into multiple groups of equal size. Wilma noticed that if Betty and Wilma joined the students in practicing, they still could not break the archers up into groups of equal size. How many students showed up to the archery class this week?

Solution. Let n be the number of students at class. Betty noticed that n has no divisors between 1 and itself, so n is prime. Wilma noticed that $n + 2$ is prime. This means we are looking for the smaller of two primes that differ by 2 that are between 60 and 80. The primes in that range are 61, 67, 71, 73, and 79. Since 71 and 73 differ by 2, $n = \boxed{71}$. □

Problem 6.3.4. In how many ways can I place 6 different beads on a bracelet if rotating or flipping the bracelet does not change the order of the beads?

Solution. There are 5! ways to arrange 6 beads in a line. Since there are 6 rotations in a circle for each of these arrangements, we must divide by 6, and since there are two matching reflections for each arrangement, we must divide by 2. So there are $\dfrac{6!}{6 \times 2} = \boxed{60}$ ways. □

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6.4 IC Test for Level 2

- All test lasts for **60 minutes**.
- The test consists of 4 **show-you-work** problems. For each of 4 show-you-work problems, you have to provide a complete solution in details. If your solution uses any diagram, please submit them too.
- Paper-based book, calculators are allowed. Computers are allowed for solving problem with coding. No searching on Internet for ideas, hints, or solutions are allowed. No help from anyone is allowed. Be honest.
- Grading:
  1. For a *show-you-work problem* the total number of points can be earned is 10**.** For a complete solution for each question of a show-you-work problem, you earn all available points for that question. If your solution for that question is not correct, you may earn some but not all available points for that question. The actual number of points to be awarded is based on the discretion of the grading COs.
- Students, if not able to join the contest at the official designated time, are eligible to write at an earlier time. They must contact the COs in time for arrangement. They must not discuss any of the received contest problems with anyone until the official contest time passed.
- Qualification: The minimum number of points **to pass the level test is** $\boxed{25.}$

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Problem 6.4.1. For what value of the constant c does the system of equations below have no solutions (x, y)?

$$\begin{cases} 3x - 7y = -2.3 \\ 6x = cy + 9.3 \end{cases}$$

Solution. We collect all the x and y terms on the left and put the constants on the right:

$$\begin{cases} 3x - 7y = -2.3 \\ 6x = cy + 9.3 \end{cases}$$

We multiply the first equation by -2 to set up eliminating the x terms:

$$\begin{cases} -6x + 14y = 4.6 \\ 6x = cy + 9.3 \end{cases}$$

If we add these equations, we eliminate x. If $c = \boxed{14}$, we eliminate y, as well, and are left with $0 = 13.9$. So, when $c = 14$, we have no solutions to this system. If c is not equal to 14, then when we add the equations above, we will eliminate x but not y. We will therefore have a linear equation we can solve for y, and we can then use this value for y to solve for x. So, if c is any value besides 14, then the system of equations has one solution. □

Problem 6.4.2. Points P and Q are on $\overline{AB}$ and $\overline{AC}$, respectively, such that $\overline{PQ} \parallel \overline{BC}$. Given $AB = 36$, $PB = 27$, and $AC = 54$, find QA.

Solution. Since $\overline{PQ} \parallel \overline{BC}$, we have $\angle APQ = \angle ABC$ and $\angle AQP = \angle ACB$. Therefore, $\triangle APQ \sim \triangle ABC$ by AA Similarity. Since $AB = 36$, $PB = 27$, and $AP = AB - PB$, we have $AP = 9$. Our similarity gives us

$$AQ/AC = AP/AB = 9/36 = 1/4.$$

So, $AQ = AC/4 = \boxed{27/2}$. □

Problem 6.4.3. What is the smallest number of marbles that could either be divided up into bags of 12 marbles or into bags of 18 marbles or into bags of 30 marbles with no marbles leftover in each case?

Solution. Let x be this smallest number of marbles that can be broken up into bags of 12 or bags of 18 or bags of 30. This means x must be a multiple of 12, 18 and 30. The smallest such number is $\text{lcm}[12, 18, 30] = 180$, so $x = \boxed{180}$. □

Problem 6.4.4. The student council has 7 boys and 5 girls as class representatives. Two committees, each consisting of 2 boys and 2 girls, are to be created. If no student can serve on both committees, how many different pairs of committees are possible?

Solution. To make the first committee, we choose 2 boys in $\binom{7}{2} = 21$ ways and 2 girls in $\binom{5}{2} = 10$ ways, for a total of $21 \times 10 = 210$ possible committees. Then to make the second committee, we choose 2 more boys in $\binom{5}{2} = 10$ ways and 2 more girls in $\binom{3}{2} = 3$ ways, for a total of $10 \times 3 = 30$ possible committees. So the number of ways to form two committees like this is $210 \times 30 = 6300$.

But this counts each pair of committees twice (in other words, there is no "first" committee or "second" committee), so we must divide by 2 to get the final answer of $6300/2 = \boxed{3150}$ pairs of committees. □

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6.5 IC Test for Level 3

- All test lasts for **60 minutes**.
- The test consists of 4 **show-you-work** problems. For each of 4 show-you-work problems, you have to provide a complete solution in details. If your solution uses any diagram, please submit them too.
- Paper-based book, calculators are allowed. Computers are allowed for solving problem with coding. No searching on Internet for ideas, hints, or solutions are allowed. No help from anyone is allowed. Be honest.
- Grading:
  1. For a *show-you-work problem* the total number of points can be earned is 10**.** For a complete solution for each question of a show-you-work problem, you earn all available points for that question. If your solution for that question is not correct, you may earn some but not all available points for that question. The actual number of points to be awarded is based on the discretion of the grading COs.
- Students, if not able to join the contest at the official designated time, are eligible to write at an earlier time. They must contact the COs in time for arrangement. They must not discuss any of the received contest problems with anyone until the official contest time passed.
- Qualification: The minimum number of points **to pass the level test is** $\boxed{25.}$

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Problem 6.5.1. Alice began peeling a pile of 52 potatoes at the rate of 3 potatoes per minute. Four minutes later Bob joined him and peeled at the rate of 5 potatoes per minute. When they finished, how many potatoes had Bob peeled?

Solution. After 4 minutes, Alice has peeled $3(4) = 12$ potatoes, so there are 40 left. Together, Alice and Bob peel $3 + 5 = 8$ potatoes each minute. So, it takes them $40/8 = 5$ minutes to peel the rest of the potatoes. In those 5 minutes, Bob peels $5(5) = \boxed{25}$ of the potatoes. □

Problem 6.5.2. In triangle ABC, let M be the midpoint of $\overline{BC}$. Prove that if $MA = MB = MC$, then $\angle BAC = 90°$.

Solution. Both $\triangle AMB$ and $\triangle AMC$ are isosceles:

$$\angle MBA = \angle MAB, \angle MCA = \angle MAC \Rightarrow \angle BAC = \angle MAB + \angle MAC = \angle MBA + \angle MCA$$
$$\angle MBA = \angle B, \angle MCA = \angle C \Rightarrow \angle BAC = \angle B + \angle C = 180° - \angle BAC$$

Thus $\angle BAC = 90°$. □

Problem 6.5.3. How many of the divisors of 10800 are perfect squares?

Solution. The perfect square divisors of $10800 = 2^4 \cdot 3^3 \cdot 5^2$ are in the form $2^{2a} \cdot 3^{2b} \cdot 5^{2c}$, where $0 \le a \le 2$, $0 \le b \le 1$, and $0 \le c \le 1$. This gives $3 \cdot 2 \cdot 2 = \boxed{12}$ choices for the exponents to the primes that make up the prime factorizations of the perfect square divisors of 10800. □

Problem 6.5.4. Clara is a house painter. She has been given a contract to paint any 3 of the houses that she wants on a street that contains 7 houses. Clara has 4 different colors of paint, in unlimited supply. She can use only one color on any given house, but for each house, she gets to pick which color to use. In how many different ways can Clara fulfill her contract?

Solution. First, she has to choose which 3 of the 7 houses she's going to paint. Since it doesn't matter in what order she paints the houses, the number of ways she can choose the houses is given by $\binom{7}{3}$.

Second, for each of the 3 houses, Clara has to choose one of her 4 colors to use. The choice of color for each house is independent of her choice for the other houses, so to get the total number of ways that Clara can choose colors, we multiply the choices for each individual house. Thus there are 4^3 ways to choose colors once the houses have been chosen.

Since for each of the $\binom{7}{3}$ ways to choose the houses, Clara has 4^3 ways to choose the colors, the total number of choices that she has is $\binom{7}{3} \cdot 4^3 = \boxed{2240.}$ □

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6.6 IC Test for Level 4

- All test lasts for **60 minutes**.
- The test consists of 4 **show-you-work** problems. For each of 4 show-you-work problems, you have to provide a complete solution in details. If your solution uses any diagram, please submit them too.
- Paper-based book, calculators are allowed. Computers are allowed for solving problem with coding. No searching on Internet for ideas, hints, or solutions are allowed. No help from anyone is allowed. Be honest.
- Grading:
  1. For a *show-you-work problem* the total number of points can be earned is 10**.** For a complete solution for each question of a show-you-work problem, you earn all available points for that question. If your solution for that question is not correct, you may earn some but not all available points for that question. The actual number of points to be awarded is based on the discretion of the grading COs.
- Students, if not able to join the contest at the official designated time, are eligible to write at an earlier time. They must contact the COs in time for arrangement. They must not discuss any of the received contest problems with anyone until the official contest time passed.
- Qualification: The minimum number of points **to pass the level test is** $\boxed{25.}$

Problem 6.6.1. Find the equation, in standard form, of the line that passes through $(4, 1)$ and has slope $-\frac{2}{3}$. Graph the equation.

Solution. We start with a point-slope form of the line through $(4, 1)$ with slope $-2/3$, and then convert this equation to standard form:

$$y - 1 = -\frac{2}{3}(x - 4) \Rightarrow 3(y - 1) = -2(x - 4) \Rightarrow 2x + 3y = 11$$

The graph of the line is shown below.

□

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Problem 6.6.2. $\triangle XYZ$ is an equilateral triangle with side length 12. M is the midpoint of side $\overline{YZ}$ and N is the midpoint of $\overline{XZ}$. $\overline{YN}$ and $\overline{XM}$ meet at E. Find the inradius of $\triangle XYZ$.

Solution. The semiperimeter of triangle XYZ is $s = (12 + 12 + 12)/2 = 18$. Therefore, the inradius is $A/s = 36\sqrt{3}/18 = \boxed{2\sqrt{3}}$. We also might note that EM is the inradius, and $EM = XM/3 = \boxed{2\sqrt{3}}$. □

Problem 6.6.3. Find all ordered pairs of positive integers (x, y) where

$$\frac{1}{2x} + \frac{1}{3y} = \frac{1}{12}.$$

Solution. It's easier to work without fractions, so we multiply both sides of the equation by $12xy$ to get

$$6y + 4x = xy.$$

Now we reorganize the equation in order to apply Simon's Favorite Factoring Trick:

$$xy - 4x - 6y \Rightarrow xy - 4x - 6y + 24 = 24 \Rightarrow (x - 6)(y - 4) = 24$$

Since $(6 - 3) \mid 24$, we get the possible values of x by solving for equations made by equating $x - 3$ with various divisors of 24, which are

$$-24, -12, -8, -6, -4, -3, -2, -1, 1, 2, 3, 4, 6, 8, 12, 24$$

Noting that $x \geq 1, y \geq 1$, meaning $x - 6 \geq -5, y - 4 \geq -3$, thus $x - 6, y - 4$ can only be positive.

$$\begin{cases} x - 6 = 1, y - 4 = 24 \Rightarrow (x, y) = (7, 28) \\ x - 6 = 2, y - 4 = 12 \Rightarrow (x, y) = (8, 16) \\ x - 6 = 3, y - 4 = 8 \Rightarrow (x, y) = (9, 12) \\ x - 6 = 4, y - 4 = 6 \Rightarrow (x, y) = (10, 10) \\ x - 6 = 6, y - 4 = 4 \Rightarrow (x, y) = (12, 8) \\ x - 6 = 8, y - 4 = 3 \Rightarrow (x, y) = (14, 7) \\ x - 6 = 12, y - 4 = 2 \Rightarrow (x, y) = (18, 6) \\ x - 6 = 24, y - 4 = 1 \Rightarrow (x, y) = (30, 5) \end{cases}$$

□

Problem 6.6.4. The box A holds 7 red balls and 5 green balls; boxes B and C each hold 2 red balls and 4 green balls. A box is selected at random and then a ball is randomly selected from that box. What is the probability that the ball selected is green?

Solution. The probability to select box A is $\frac{1}{3}$. For A, the probability to select a green ball is $\frac{5}{12}$.

The probability to select box B is $\frac{1}{3}$. For B, the probability to select a green ball is $\frac{4}{6}$.

The probability to select box C is $\frac{1}{3}$. For C, the probability to select a green ball is $\frac{4}{6}$.

Thus the probability that the ball selected is green is:

$$\frac{1}{3} \cdot \frac{5}{12} + \frac{1}{3} \cdot \frac{4}{6} + \frac{1}{3} \cdot \frac{4}{6} = \boxed{\frac{7}{12}.}$$

□

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6.7 IC Test for Level 5

- All test lasts for **60 minutes**.
- The test consists of 4 **show-you-work** problems. For each of 4 show-you-work problems, you have to provide a complete solution in details. If your solution uses any diagram, please submit them too.
- Paper-based book, calculators are allowed. Computers are allowed for solving problem with coding. No searching on Internet for ideas, hints, or solutions are allowed. No help from anyone is allowed. Be honest.
- Grading:
  1. For a *show-you-work problem* the total number of points can be earned is 10**.** For a complete solution for each question of a show-you-work problem, you earn all available points for that question. If your solution for that question is not correct, you may earn some but not all available points for that question. The actual number of points to be awarded is based on the discretion of the grading COs.
- Students, if not able to join the contest at the official designated time, are eligible to write at an earlier time. They must contact the COs in time for arrangement. They must not discuss any of the received contest problems with anyone until the official contest time passed.
- Qualification: The minimum number of points **to pass the level test is** $\boxed{25.}$

Problem 6.7.1. Let $x = 2001^{1002} - 2001^{-1002}$ and $y = 2001^{1002} + 2001^{-1002}$. Find $x^2 - y^2$.

Solution. We could square those expressions for x and y, but it's much more convenient to factor $x^2 - y^2$ as $(x+y)(x-y)$. Since $x + y = 2(2001^{1002})$ and $x - y = -2(2001^{-1002})$, we have

$$x^2 - y^2 = (x+y)(x-y) = 2(2001^{1002}) \cdot (-2)(2001^{-1002}) = [2 \cdot (-2)](2001^{1002} \cdot 2001^{-1002}) = \boxed{-4.}$$

□

Problem 6.7.2. The bases of a trapezoid are $2x$ and $4x$. The height is $2x$. If the area is 54, what is x?

Solution. In terms of x, the area of the trapezoid is $(2x + 4x)(2x)/2 = 6x^2$. Since we are given that the area is 48, we have $6x^2 = 54$, so $x = \boxed{3}$. □

Problem 6.7.3. Determine which of the following are multiples of 12.

$$717_8,\ 212021_3,\ 14202_5,\ 6234_7,\ C10B_{13}$$

Solution. Since $12 = 3 \cdot 4$, a multiple of 12 must be a multiple of 4. However,

$$717_8 = 7 \cdot 8^2 + 1 \cdot 8^1 + 7 \cdot 8^0 = 8(7 \cdot 8^1 + 1 \cdot 8^0) + 7$$

is not a multiple of 4 because the first two digit bundles are multiples of 4 and the last is not. Therefore, 717_8 is not a multiple of 12 either.

$$212021_3 = 2 \cdot 3^5 + 1 \cdot 3^4 + 2 \cdot 3^3 + 0 \cdot 3^2 + 2 \cdot 3^1 + 1 \cdot 3^0$$

All of the base-3 digit bundles except the last are multiples of 3, so 212021_3 is not a multiple of 3. Since a multiple of 12 is a multiple of 3, 212021_3 is not a multiple of 12.

n order for an integer to be a multiple of 12, it must be even. However,

$$14202_5 = 1 \cdot 5^4 + 4 \cdot 5^3 + 2 \cdot 5^2 + 0 \cdot 5^1 + 2 \cdot 5^0$$

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is a sum of one odd integer and four even ones (including $0 \cdot 5^1 = 0$), so 14202_5 is odd and therefore not a multiple of 12.

$$6234_7 = 6 \cdot 7^3 + 2 \cdot 7^2 + 3 \cdot 7^1 + 4 \cdot 7^0$$

is the sum of three even integers and one odd integer, so it is itself odd and not a multiple of 12.

A base-13 integer is a multiple of 12 only if the sum of its digits is a multiple of 12.

$$C_{13} + 1_{13} + 0_{13} + B_{13} = 12 + 1 + 0 + 11 = 24.$$

Since $12 \mid 24$, $C10B_{13}$ is a multiple of 12. □

Problem 6.7.4. Given that a and b are real numbers such that $-4 \le a \le -1$ and $-2 \le b \le 4$, and values for a and b are chosen at random, what is the probability that the product ab is positive?

Solution. $ab > 0$ if $a < 0, b < 0$ or $a > 0, b > 0$. Since $-4 \le a \le -1$ so $a < 0$, thus $-2 \le b < 0$. In the diagram below, point (a, b) can only be chosen from the shaded area.

Hence, the probability is the ratio of the shaded area to the area of the whole rectangle of $\frac{6}{18} = \boxed{\frac{1}{3}.}$

□

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6.8 IC Test for Level 6

- All test lasts for **60 minutes**.
- The test consists of 4 **show-you-work** problems. For each of 4 show-you-work problems, you have to provide a complete solution in details. If your solution uses any diagram, please submit them too.
- Paper-based book, calculators are allowed. Computers are allowed for solving problem with coding. No searching on Internet for ideas, hints, or solutions are allowed. No help from anyone is allowed. Be honest.
- Grading:
  1. For a *show-you-work problem* the total number of points can be earned is 10**.** For a complete solution for each question of a show-you-work problem, you earn all available points for that question. If your solution for that question is not correct, you may earn some but not all available points for that question. The actual number of points to be awarded is based on the discretion of the grading COs.
- Students, if not able to join the contest at the official designated time, are eligible to write at an earlier time. They must contact the COs in time for arrangement. They must not discuss any of the received contest problems with anyone until the official contest time passed.
- Qualification: The minimum number of points **to pass the level test is** $\boxed{25.}$

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Problem 6.8.1. Graph the equation $x^2 + 2x + y^2 - 4y - 11 = 0$.

Solution. We start by completing the squares in both x and y, which gives

$$x^2 + 2x + 1 + y^2 - 4y + 4 - 11 = 1 + 4 \Rightarrow (x+1)^2 + (y-2)^2 = 16.$$

The graph of this equation is a circle with center $(-1, 2)$ and radius $\sqrt{16} = 4$, as shown below.

□

Problem 6.8.2. $A_1A_2A_3A_4A_5$ is a pentagon. Prove that $A_1A_3 > A_2A_4$.

> **Remark.** There is typo in the text. The correct inequality should be $A_1A_3 > A_1A_2$.

Solution. For $n > 4$, we consider the exterior angles of the polygon, each of which measures $360°/5 < 360°/4 = 90°$, so the exterior angles are acute. Since each interior angle is supplementary to each exterior angle, we know that each interior angle is obtuse. Specifically, $\angle A_1A_2A_3$ is obtuse, so it is the largest angle in $\triangle A_1A_2A_3$. Therefore, $\overline{A_1A_3}$, which is opposite the obtuse angle in $\triangle A_1A_2A_3$, is the longest side of $\triangle A_1A_2A_3$. Thus, $A_1A_3 > A_1A_2$. □

Problem 6.8.3. Find the units digit of $3^{2024} - 2^{2024}$.

Solution. The units digit of powers of 2 and 3 both repeat in cycles four long. Since $2024 \div 4$ has a remainder of 0, the units digit of $3^{2024} - 2^{2024}$ is the same as $3^4 - 2^4 = 65$ or $\boxed{5}$. □

Problem 6.8.4. The numbers on a standard six-sided die are arranged such that numbers on opposite faces always add to 7. The die is rolled, and the product of the numbers appearing on the four lateral faces of the die is calculated (ignoring the numbers on the top and bottom). What is the expected value of this product?

Solution. The products of opposite faces are $1 \times 6 = 6$, $2 \times 5 = 10$, and $3 \times 4 = 12$. Therefore, after rolling the die, the outcomes $6 \times 10 = 60$, $6 \times 12 = 72$, and $10 \times 12 = 120$ are equally likely. So the expected value is just the average of these outcomes, namely $(60 + 72 + 120)/3 = \boxed{84}$. □

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Chapter 7

Session 5

7.1 IC Test for Level 1

- All test lasts for **60 minutes**.
- The test consists of 4 **show-you-work** problems. For each of 4 show-you-work problems, you have to provide a complete solution in details. If your solution uses any diagram, please submit them too.
- Paper-based book, calculators are allowed. Computers are allowed for solving problem with coding. No searching on Internet for ideas, hints, or solutions are allowed. No help from anyone is allowed. Be honest.
- Grading:
  1. For a *show-you-work problem* the total number of points can be earned is 10**.** For a complete solution for each question of a show-you-work problem, you earn all available points for that question. If your solution for that question is not correct, you may earn some but not all available points for that question. The actual number of points to be awarded is based on the discretion of the grading COs.
- Students, if not able to join the contest at the official designated time, are eligible to write at an earlier time. They must contact the COs in time for arrangement. They must not discuss any of the received contest problems with anyone until the official contest time passed.
- Qualification: The minimum number of points **to pass the level test is** $\boxed{25.}$

Problem 7.1.1. Stan has an equal positive number of quarters, dimes, and nickels in his bag. The total amount of money Stan has in his bag is a whole number of dollars. What is the smallest amount of money Stan could have?

Solution. Let x be the number of each coin Stan has in his bag. Therefore, the quarters are together worth $0.25x$, the dimes are worth $0.10x$, and the nickels are worth $0.05x$. Combining these, the total value of the money in the bag is $0.25x + 0.10x + 0.05x = 0.40x$. In order for this to be a whole number of dollars, the expression $0.40x$ must equal a whole number. Trying $x = 1$, 2, 3, and 4 fails to make this expression a whole number, but for $x = 5$, we have $0.40(5) = 2$. So, the smallest amount of money Stan could have is $\boxed{\$2}$. $\square$

Problem 7.1.2. Lines $\overleftrightarrow{PQ}$ and $\overleftrightarrow{RS}$ are parallel, and $\overleftrightarrow{TV} \perp \overleftrightarrow{PQ}$. If $\overleftrightarrow{TV}$ intersects $\overleftrightarrow{PQ}$ at X and $\overleftrightarrow{RS}$ at Y, find $\angle RYX$.

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Solution. We begin by drawing the diagram described below. From this diagram we can see that $\angle RYX$ and $\angle PXY$ are same-side interior angles.

Since $\angle PXY = 90°$, $\angle RYX = 180 - \angle PXY = \boxed{90°}$. □

Problem 7.1.3. Find all two-digit prime numbers whose digits sum is 9.

Solution. All two-digit numbers whose digits sum to 9 are composite:

$$18 = 2 \cdot 9, 27 = 3 \cdot 9, 364 \cdot 9, 45 = 5 \cdot 9, 54 = 6 \cdot 9, 63 = 7 \cdot 9, 72 = 8 \cdot 9, 81 = 9 \cdot 9, 90 = 9 \cdot 10.$$

Hence, there are $\boxed{\text{no such numbers.}}$ □

Problem 7.1.4. In how many ways can 8 people sit around a round table if 3 of the people - Pierre, Rosa, and Thomas - all want to sit together?

Solution. First choose three consecutive seats for Pierre, Rosa, and Thomas. It doesn't matter which three consecutive seats that we choose, since any three such seats can be rotated to any other such seats.

Once the three seats are chosen, there are 3! ways to seat the three friends there. The other five seats are for the other five people, so there are 5! ways to seat them there. The answer is $3! \times 5! = \boxed{720}$. □

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7.2 IC Test for Level 2

- All test lasts for **60 minutes**.
- The test consists of 4 **show-you-work** problems. For each of 4 show-you-work problems, you have to provide a complete solution in details. If your solution uses any diagram, please submit them too.
- Paper-based book, calculators are allowed. Computers are allowed for solving problem with coding. No searching on Internet for ideas, hints, or solutions are allowed. No help from anyone is allowed. Be honest.
- Grading:
  1. For a *show-you-work problem* the total number of points can be earned is 10**.** For a complete solution for each question of a show-you-work problem, you earn all available points for that question. If your solution for that question is not correct, you may earn some but not all available points for that question. The actual number of points to be awarded is based on the discretion of the grading COs.
- Students, if not able to join the contest at the official designated time, are eligible to write at an earlier time. They must contact the COs in time for arrangement. They must not discuss any of the received contest problems with anyone until the official contest time passed.
- Qualification: The minimum number of points **to pass the level test is** $\boxed{25.}$

Problem 7.2.1. The product of two nonzero numbers is equal to twice the sum. Find the sum of their reciprocals.

Solution. Let the numbers be x and y. We are given $xy = 2(x+y)$. We wish to evaluate $\frac{1}{x} + \frac{1}{y}$. We'd like to turn the equation $xy = 2(x+y)$ into something with x and y in denominators. We start by dividing both sides by x, which gives

$$\frac{xy}{x} = \frac{2(x+y)}{x} \quad \Rightarrow \quad y = 2 + \frac{2y}{x}.$$

So, that puts x in a denominator. Let's divide by y:

$$\frac{y}{y} = \frac{2}{y} + \frac{2y/x}{y} \Rightarrow 1 = \frac{2}{y} + \frac{2y}{xy} \Rightarrow 1 = \frac{2}{y} + \frac{2}{x}.$$

Dividing this equation by 2 tells us $\frac{1}{y} + \frac{1}{x} = \boxed{\frac{1}{2}}$. □

Problem 7.2.2. The length of a given rectangle is 2 less than 4 times the width of the rectangle. Its perimeter is 51. What is its area?

Solution. Let the width of the rectangle be w, so the length is $4w - 2$. In terms of w, the perimeter then is $2(w) + 2(4w-2) = 10w - 4$. Since the perimeter of the rectangle is given as 51, we have $10w - 4 = 51$, so $w = 5.5$. Therefore, the length is $4w - 2 = 20$, so the area is $(5.5)(20) = \boxed{110}$. □

Problem 7.2.3. There are 25 primes less than 100. Is their sum even or odd?

Solution. Of the 25 primes less than 100, only 1 is even. The other 24 are odd and their sum is therefore even. Adding the even prime, 2, the sum of all 25 primes is $\boxed{\text{even}}$. □

Problem 7.2.4. In how many ways can we choose 3 distinct letters of the alphabet, without regard to order, if we must choose 1 vowel (A, E, I, O, or U) and 2 consonants?

Solution. We have 5 options for the choice of the vowel, and we must make 2 choices out of the remaining 21 letters, for a total of $\binom{21}{2} = 210$ choices for the consonants. This gives a total of $5 \times 210 = \boxed{1050}$. □

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7.3 IC Test for Level 3

- All test lasts for **60 minutes**.
- The test consists of 4 **show-you-work** problems. For each of 4 show-you-work problems, you have to provide a complete solution in details. If your solution uses any diagram, please submit them too.
- Paper-based book, calculators are allowed. Computers are allowed for solving problem with coding. No searching on Internet for ideas, hints, or solutions are allowed. No help from anyone is allowed. Be honest.
- Grading:
  1. For a *show-you-work problem* the total number of points can be earned is 10**.** For a complete solution for each question of a show-you-work problem, you earn all available points for that question. If your solution for that question is not correct, you may earn some but not all available points for that question. The actual number of points to be awarded is based on the discretion of the grading COs.
- Students, if not able to join the contest at the official designated time, are eligible to write at an earlier time. They must contact the COs in time for arrangement. They must not discuss any of the received contest problems with anyone until the official contest time passed.
- Qualification: The minimum number of points **to pass the level test is** $\boxed{25.}$

Problem 7.3.1. The tail of a 1-mile long train exits a tunnel exactly 3 minutes after the front of the train entered the tunnel. If the train is moving 60 miles per hour, how long is the tunnel?

Solution. Because the train is moving 60 miles per hour, the front of the train moves 1 mile every minute. Therefore, in the three minutes since the front of the train entered the tunnel, the front of the train has moved three miles. At the end of these three minutes, we know the front of the train is 1 mile beyond the end of the tunnel, because the train is one mile long and its tail is just leaving the tunnel. So, the front of the train has moved 3 miles from the beginning of the tunnel and is now 1 mile beyond the end of the tunnel. This tells us that the tunnel is $3 - 1 = \boxed{2 \text{ miles}}$ long. □

Problem 7.3.2. In the diagram below, $\overline{AP} \parallel \overline{BQ} \parallel \overline{CR}$. Prove that

$$\frac{1}{CR} = \frac{1}{AP} + \frac{1}{BQ}.$$

Solution. Since $\overline{AP} \parallel \overline{RC}$, we have $\angle P = \angle CRB$ and $\angle PAB = \angle RCB$, so $\triangle BRC \sim \triangle BPA$. Therefore, $BC/BA = CR/PA$. Similarly, $\overline{BQ} \parallel \overline{CR}$ gives us $\triangle QBA \sim \triangle RCA$, so $AC/BA = CR/BQ$. Adding these two equations gives us

$$\frac{CR}{AP} + \frac{CR}{BQ} = \frac{BC}{BA} + \frac{AC}{BA} = \frac{BC + AC}{BA} = \frac{BA}{BA} = 1.$$

Dividing both sides of this by CR gives $\frac{1}{AP} + \frac{1}{BQ} = \frac{1}{CR}$, as desired. □

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Problem 7.3.3. Find the GCD of 7! and $(5!)^2$.

Solution.

$$7! = 7 \cdot 6 \cdot 5 \cdot 4 \cdot 3 \cdot 2 \cdot 1 = 2^4 \cdot 3^2 \cdot 5^1 \cdot 7^1$$
$$(5!)^2 = (5 \cdot 4 \cdot 3 \cdot 2 \cdot 1)^2 = 2^6 \cdot 3^2 \cdot 5^2$$
$$\Rightarrow \gcd(7!, (5!)^2) = 2^4 \cdot 3^2 \cdot 5^1 = \boxed{720}$$

□

Problem 7.3.4. How many pairs of diagonals of a regular decagon (10-sided polygon) are parallel?

Solution. Fix a vertex A of the 10-gon $ABCDEFGHIJ$ (with the vertices in that order). There are 4 diagonals that have their endpoints equidistant from vertex A (and equidistant from the vertex F opposite A), namely BJ, CI, DH and EG. These 4 are parallel to each other. There are 5 such sets of 4 parallel diagonals, since the vertices of the 10-gon can be paired into 5 sets. In each set, there are $\binom{4}{2} = 6$ pairs of parallel diagonals, so this gives a total of 30 pairs of parallel diagonals.

Now fix a side AB of the 10-gon. There are 3 diagonals that are parallel to this side AB (and to the side FG opposite AB), namely CJ, DI, and EH. We again have 5 such sets of 3 diagonals. In each set, there are $\binom{3}{2} = 3$ pairs of parallel diagonals, so the total for this case is 15 pairs. The final answer is $30 + 15 = \boxed{45}$. □

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7.4 IC Test for Level 4

- All test lasts for **60 minutes**.
- The test consists of 4 **show-you-work** problems. For each of 4 show-you-work problems, you have to provide a complete solution in details. If your solution uses any diagram, please submit them too.
- Paper-based book, calculators are allowed. Computers are allowed for solving problem with coding. No searching on Internet for ideas, hints, or solutions are allowed. No help from anyone is allowed. Be honest.
- Grading:
  1. For a *show-you-work problem* the total number of points can be earned is 10**.** For a complete solution for each question of a show-you-work problem, you earn all available points for that question. If your solution for that question is not correct, you may earn some but not all available points for that question. The actual number of points to be awarded is based on the discretion of the grading COs.
- Students, if not able to join the contest at the official designated time, are eligible to write at an earlier time. They must contact the COs in time for arrangement. They must not discuss any of the received contest problems with anyone until the official contest time passed.
- Qualification: The minimum number of points **to pass the level test is** $\boxed{25.}$

Problem 7.4.1. A line passing through the points $(2a+4, 3a^2)$ and $(3a+4, 5a^2)$ has slope $a+3$, where a is nonzero. Find the value of a.

Solution. The slope between the given points is

$$\frac{5a^2-3a^2}{(3a+4)-(2a+4)} = \frac{2a^2}{a} = 2a,$$

so we have $2a = a+3$. Solving this equation gives us $a = \boxed{3}$. □

Problem 7.4.2. Points T and U are on a circle centred at K such that K is 2 units from the segment $\overline{TU}$. If $TU = 14$, what is the radius of the circle?

Solution. Let M be the midpoint of $\overline{TU}$. Since $\overline{TU}$ is a chord of $\odot K$, the perpendicular bisector of $\overline{TU}$ goes through K. Since both M and K are on this perpendicular bisector, we have $\overline{MK} \perp \overline{TU}$. We are given $MK = 2$, and $TM = TU/2 = 7$, so the Pythagorean Theorem gives us $TK = \sqrt{TM^2 + KM^2} = \boxed{\sqrt{53}}$. □

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Problem 7.4.3. Let $n = ABC$ be a positive 3-digit integer that is equal to the sum $AB + BA + AC + CA + BC + CB$ of six positive 2-digit integers. Find the largest possible value for n.

Solution. We begin by rewriting part of the given equation chain in terms of the digits A, B, and C:

$$100A + 10B + C = (10A + B) + (10B + A) + (10A + C) + (10C + A) + (10B + C) + (10C + B)$$
$$\Rightarrow 100A + 10B + C = 22A + 22B + 22C \Rightarrow 26A = 4B + 7C.$$

Our goal is to find the largest possible value of n, which means we need to find the largest possible value of A. From the equation above, the largest possible value of $4B + 7C$ is $4(9) + 7(9) = 99$. This means $26A \leq 99$ and since A is an integer, $A \leq 3$. Now we plug $A = 3$ in to see if we can find a solution:

$$26 \cdot 3 = 78 = 4B + 7C.$$

Since we want the largest possible n and hopefully we already know the digit A, we begin hunting for a solution from the largest possible value of B. When $B = 9$, $C = 6$ and we have a solution:

$$ABC = 396 = 39 + 93 + 36 + 63 + 96 + 69,$$

so $\boxed{396}$ is the largest possible value of n. □

Problem 7.4.4. Six green balls and four red balls are in a bag. A ball is taken from the bag, its color recorded. It is NOT placed back in the bag. A second ball is taken and its color recorded. What is the probability the two balls are the same color?

Solution. We could have either two greens or two reds. The probability of drawing two greens is is $\frac{6}{10} \times \frac{5}{9} = \frac{1}{3}$. The probability of drawing two reds is $\frac{4}{10} \times \frac{3}{9} = \frac{2}{15}$. So the answer is $\frac{1}{3} + \frac{2}{15} = \boxed{\frac{7}{15}}$. □

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7.5 IC Test for Level 5

- All test lasts for **60 minutes**.
- The test consists of 4 **show-you-work** problems. For each of 4 show-you-work problems, you have to provide a complete solution in details. If your solution uses any diagram, please submit them too.
- Paper-based book, calculators are allowed. Computers are allowed for solving problem with coding. No searching on Internet for ideas, hints, or solutions are allowed. No help from anyone is allowed. Be honest.
- Grading:
  1. For a *show-you-work problem* the total number of points can be earned is 10**.** For a complete solution for each question of a show-you-work problem, you earn all available points for that question. If your solution for that question is not correct, you may earn some but not all available points for that question. The actual number of points to be awarded is based on the discretion of the grading COs.
- Students, if not able to join the contest at the official designated time, are eligible to write at an earlier time. They must contact the COs in time for arrangement. They must not discuss any of the received contest problems with anyone until the official contest time passed.
- Qualification: The minimum number of points **to pass the level test is** $\boxed{25.}$

Problem 7.5.1. Alice and Bobby took the same algebra test. The problem asked them to find the solutions to a quadratic equation. Alice misread the constant term. She correctly found that the roots to her incorrect quadratic were -4 and 7. Bobby misread the linear term. He correctly found that the roots to his incorrect quadratic were -4 and 10. What are the roots of the correct quadratic?

Solution. Alice has the correct quadratic and linear terms, so the sum of her roots will match the sum of the roots of the correct quadratic. The sum of her roots is 3, so the sum of the roots of the correct equation is also 3.

Similarly, Bobby has the correct quadratic and constant terms, so he has the right product of roots, which equals $(-4)(10) = -40$.

Since the correct quadratic has roots which add to 3 and multiply to -40, the roots of the correct quadratic are the roots of $x^2 - 3x - 40 = 0$. Since $x^2 - 3x - 40 = (x-8)(x+5)$, the correct roots are $\boxed{x = 8 \text{ and } x = -5}$. □

Problem 7.5.2. If A, B, C, D are midpoints of the sides of square $EFGH$, what is the ratio of the area of triangle ABC to the area of square $EFGH$?

Solution. Since $FA = AE = ED = FB$, $\triangle DEA$ and $\triangle AFB$ are 45-45-90 right triangles. Therefore,

$$\angle DAB = 180^\circ - \angle EAD - \angle FAB = 90^\circ,\ AD = AB = AE\sqrt{2} = EF\sqrt{2}/2.$$

Similarly, we can show that all sides of $ABCD$ equal $EF\sqrt{2}/2$ and all angles of $ABCD$ equal 90°. Since $\triangle ABC$ is a 45-45-90 right triangle (since $ABCD$ is a square), we have

$$[ABC] = (AB)(BC)/2 = EF^2/4 = [EFGH]/4.$$

Therefore, $[ABC]/[EFGH] = \boxed{1/4}$. □

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Problem 7.5.3. What is the smallest integer $b > 3$ for which the base-b number 23_b is a perfect square?

Solution. Since $23_b = 2b + 3$ and $b > 3$, 23_b can be any odd integer greater than $2(3) + 3 = 9$. We are looking for the next smallest odd perfect square, which is $5^2 = 25$. Since $2b + 3 = 25$, $b = \boxed{11}$ is our answer. □

Problem 7.5.4. There are 11 students in Ms. McGinn's Chemistry class, including the Baker triplets: Annika, Billy, and Catherine. The teacher calls all 11 students in random order one at a time to her desk to tell each student his or her final grade.

The first time he calls a student to his desk, Billy is in the bathroom and therefore can't be called up, but he's back in time for the rest of the students to be called. What is the probability that Billy is the first of the triplets to be called to the desk?

Solution. Billy can only be called before his sisters if one of the other 8 students in the class is called first (while Billy is out of the room). This occurs with probability $\frac{8}{10} = \frac{4}{5}$. Now when Billy comes back, each one of the siblings is just as likely to be called to the desk first as either of the others, the probability of him being called before his sisters, provided a non-Baker student is called first, is $\frac{1}{3}$. So the probability of Billy being the first of the triplets to be called to the desk is $\dfrac{4}{5} \times \dfrac{1}{3} = \boxed{\dfrac{4}{15}}$. □

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7.6 IC Test for Level 6

- All test lasts for **60 minutes**.
- The test consists of 4 **show-you-work** problems. For each of 4 show-you-work problems, you have to provide a complete solution in details. If your solution uses any diagram, please submit them too.
- Paper-based book, calculators are allowed. Computers are allowed for solving problem with coding. No searching on Internet for ideas, hints, or solutions are allowed. No help from anyone is allowed. Be honest.
- Grading:
  1. For a *show-you-work problem* the total number of points can be earned is 10**.** For a complete solution for each question of a show-you-work problem, you earn all available points for that question. If your solution for that question is not correct, you may earn some but not all available points for that question. The actual number of points to be awarded is based on the discretion of the grading COs.
- Students, if not able to join the contest at the official designated time, are eligible to write at an earlier time. They must contact the COs in time for arrangement. They must not discuss any of the received contest problems with anyone until the official contest time passed.
- Qualification: The minimum number of points **to pass the level test is** $\boxed{25.}$

Problem 7.6.1. If $x^2 - 5x + 6 < 0$ and $P = x^2 + 5x + 6$, then what are the possible values of P?

Solution. First, we solve the inequality to determine what the possible values of x are. We factor the quadratic to find $(x-2)(x-3) < 0$. The product $(x-2)(x-3)$ is negative only when one factor is negative and the other is positive, which occurs when $2 < x < 3$.

Next, we find the possible values of P when x is in this range. When $x = 2$, we have $P = 2^2 + 5 \cdot 2 + 6 = 20$. When $x = 3$, we have $P = 9 + 15 + 6 = 30$. To see that this information tells us that $\boxed{20 < P < 30}$, we consider the graph of $y = x^2 + 5x + 6$. This graph is an upward-opening parabola whose vertex has x-coordinate $-5/2$. Therefore, the portion of this graph from $x = 2$ to $x = 3$ is entirely on the right of the vertex. So, the graph goes upward the whole time from $(2, 20)$ to $(3, 30)$. So, for any value of y between 20 and 30, there is some value of x between 2 and 3 such that $y = x^2 + 5x + 6$. Finally, we exclude 20 and 30 from the possibilities for P because we cannot have $x = 2$ or $x = 3$. □

Problem 7.6.2. $A_1A_2A_3A_4A_5$ is a pentagon. Prove that $A_1A_3 > A_1A_2$.

Solution. We consider the exterior angles of the pentagon, each of which measures $360°/5 < 360°/4 = 90°$, so the exterior angles are acute. Since each interior angle is supplementary to each exterior angle, we know that each interior angle is obtuse. Specifically, $\angle A_1A_2A_3$ is obtuse, so it is the largest angle in $\triangle A_1A_2A_3$. Therefore, $\overline{A_1A_3}$, which is opposite the obtuse angle in $\triangle A_1A_2A_3$, is the longest side of $\triangle A_1A_2A_3$. Thus, $A_1A_3 > A_1A_2$. □

Problem 7.6.3. Find the units digit of each of the following within the indicated number base.

$$314_5 + 2423_5,\ 513_9 \cdot 7121_9,\ (17_{12})^6$$

Solution.

$$314_5 + 2423_5 = 324\boxed{2}_5$$
$$513_9 \cdot 7121_9 = 406617\boxed{3}_9$$
$$(17_{12})^6 = 1390976\boxed{1}_{12}$$

□

Problem 7.6.4. Two fair eight-sided dice have their faces numbered from 1 to 8. What is the expected value of the sum of the rolls of both dice?

Solution. The expected value of one roll is the average of all the outcomes, or $E = \frac{1}{8}(1 + 2 + \cdots + 8) = 4.5$. To find the expected value of a double roll, we can simply add the expected values of the individual rolls, giving $4.5 + 4.5 = \boxed{9}$. $\square$

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7.7 IC Test for Level 7

- All test lasts for **60 minutes**.
- The test consists of 4 **show-you-work** problems. For each of 4 show-you-work problems, you have to provide a complete solution in details. If your solution uses any diagram, please submit them too.
- Paper-based book, calculators are allowed. Computers are allowed for solving problem with coding. No searching on Internet for ideas, hints, or solutions are allowed. No help from anyone is allowed. Be honest.
- Grading:
  1. For a *show-you-work problem* the total number of points can be earned is 10**.** For a complete solution for each question of a show-you-work problem, you earn all available points for that question. If your solution for that question is not correct, you may earn some but not all available points for that question. The actual number of points to be awarded is based on the discretion of the grading COs.
- Students, if not able to join the contest at the official designated time, are eligible to write at an earlier time. They must contact the COs in time for arrangement. They must not discuss any of the received contest problems with anyone until the official contest time passed.
- Qualification: The minimum number of points **to pass the level test is** $\boxed{25.}$

Problem 7.7.1. How many square units are in the area of the triangle whose vertices are the x- and y-intercepts of the curve $y = (x-3)^2(x+2)$?

Solution. The x-intercepts are the points on the graph where $y = 0$. Solving $(x-3)^2(x+2) = 0$ gives $x = 3$ and $x = -2$ as solutions. So, the x-intercepts of the graph are $(3, 0)$ and $(-2, 0)$. The y-intercept is the point where $x = 0$. When $x = 0$, we have $y = (0-3)^2(0+2) = 18$. Therefore, the y-intercept is $(0, 18)$. Because the y-intercept is 18 units above the x-axis and our two x-intercepts are both on the x-axis, the height of our triangle is 18 units. The two x-intercepts are 5 units apart, so the length of the base of the triangle is 5.

The area of a triangle is half the product of a side of the triangle and the height of the triangle drawn to that side. So, the area of our triangle in this problem is $(5)(18)/2 = \boxed{45}$ square units. □

Problem 7.7.2. A and B are two points on a circle with center O, and C lies outside the circle, on ray $\overrightarrow{AB}$. Given that $AB = 24$, $BC = 28$, and $OA = 15$, find OC.

Solution. The power of point C is $(CB)(CA) = 28(52)$. Since C is outside the circle, the power of point C equals $CO^2 - r^2$. Therefore, we have

$$CO^2 = 28(52) + 15^2 = 1681 = 41^2,$$

so $CO = \boxed{41}$.

(We can also solve this problem by letting M be the midpoint of $\overline{AB}$ and considering right triangles $\triangle OAM$ and $\triangle OCM$.) □

Problem 7.7.3. What is the 4037th digit following the decimal point in the expansion of $\dfrac{1}{17}$?

Solution. First, we find the repeating decimal expansion of our fraction: $\dfrac{1}{17} = 0.\overline{0588235294117647}$. We want the 4037th digit of a 16-digit block of digits. The remainder from $4037 \div 16$ is 5, so our answer is the 5th digit of the block, which is $\boxed{2}$. □

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Problem 7.7.4. Prove that

$$\binom{n}{0}\binom{n}{1}+\binom{n}{1}\binom{n}{2}+\binom{n}{2}\binom{n}{3}+\cdots+\binom{n}{n-1}\binom{n}{n}=\binom{2n}{n-1}.$$

Solution. We can rewrite the sum as

$$\binom{n}{0}\binom{n}{n-1}+\binom{n}{1}\binom{n}{n-2}+\cdots+\binom{n}{n-1}\binom{n}{0}.$$

The general term is of the form $\binom{n}{k}\binom{n}{n-1-k}$.

We can use a committee-forming argument: think of choosing of committee of size $n-1$ from a group of $2n$ people, n of whom are men and n of whom are women. There are $\binom{2n}{n-1}$ ways to do this.

But if the committee has k men and $n-1-k$ women, there are $\binom{n}{k}\binom{n}{n-1-k}$ ways to choose it. So the left side of the desired equation sums the number of ways to choose committees by gender makeup, and the right side just counts the number of committees without regard to gender. $\square$

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7.8 IC Test for Level 10

- All test lasts for **60 minutes**.
- The test consists of 4 **show-you-work** problems. For each of 4 show-you-work problems, you have to provide a complete solution in details. If your solution uses any diagram, please submit them too.
- Paper-based book, calculators are allowed. Computers are allowed for solving problem with coding. No searching on Internet for ideas, hints, or solutions are allowed. No help from anyone is allowed. Be honest.
- Grading:
  1. For a *show-you-work problem* the total number of points can be earned is 10**.** For a complete solution for each question of a show-you-work problem, you earn all available points for that question. If your solution for that question is not correct, you may earn some but not all available points for that question. The actual number of points to be awarded is based on the discretion of the grading COs.
- Students, if not able to join the contest at the official designated time, are eligible to write at an earlier time. They must contact the COs in time for arrangement. They must not discuss any of the received contest problems with anyone until the official contest time passed.
- Qualification: The minimum number of points **to pass the level test is** $\boxed{25.}$

Problem 7.8.1. How many different triples of numbers (a, b, c) satisfy the equation

$$a^2 + bc = b^2 + ac,$$

if a, b, and c are integers from 1 to 5, inclusive? (The numbers a, b, and c are not necessarily different.)

Solution. We can't factor either side as the equation is now, but if we subtract a^2 and ac from both sides, we'll have

$$bc - ac = b^2 - a^2 \quad \Rightarrow \quad c(b-a) = (b+a)(b-a).$$

Now, we can subtract $c(b-a)$ from both sides and factor more:

$$(b+a)(b-a) - c(b-a) = 0 \quad \Rightarrow \quad (b+a-c)(b-a) = 0.$$

Therefore, we must have either $b - a = 0$ or $b + a - c = 0$. From $b - a = 0$, we have $b = a$, and no restriction on c. Therefore, we have 5 choices for the value that a and b both have, and 5 choices for c. So, there are $5 \cdot 5 = 25$ solutions with $a = b$.

Turning to $b + a - c = 0$, we have $c = a + b$. We can count these solutions quickly with a little casework.

$c = 2$. Then $a = b = 1$, and we have already counted this solution in the $a = b$ case.

$c = 3$. We have two such solutions, $(a, b, c) = (2, 1, 3)$ and $(1, 2, 3)$.

$c = 4$. We have two new solutions, $(a, b, c) = (3, 1, 4)$ and $(1, 3, 4)$. (We already counted $(2, 2, 4)$ in the $a = b$ case.)

$c = 5$. We have four new solutions, $(a, b, c) = (4, 1, 5)$, $(3, 2, 5)$, $(2, 3, 5)$, and $(1, 4, 5)$.

Combining our solutions with $a = b$ with the new solutions we found with $a + b = c$, we have a total of $25 + 2 + 2 + 4 = \boxed{33}$ solutions. □

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Problem 7.8.2. In $\triangle XYZ$, we have $\angle X = 20^\circ$ and $XY = XZ$. Prove that $XY < 3YZ$.

Solution. We draw $\triangle XAY$ and $\triangle XBZ$ such that each is congruent to $\triangle XYZ$. Therefore, $XA = XY = XZ = XB$.

Moreover,

$$\angle AXY = \angle YXZ = \angle ZXB = 20^\circ \Rightarrow \angle AXB = 60^\circ.$$

Since we also have $XA = XB$, we know that $\triangle XAB$ is equilateral. So, we have $AB = XA = XY$. From $\triangle AYB$, we have $AY + YB > AB$.

From $\triangle YZB$ we have $YZ + ZB > YB$. Combining these gives

$$AY + YZ + ZB > AY + YB > AB.$$

Since $AB = XY$ and $AY = ZB = YZ$, this inequality is equivalent to the desired $3YZ > XY$. □

Problem 7.8.3. How many four-digit integers either leave a remainder of 2 when divided by 7, or a remainder of 4 when divided by 5, but not both?

Solution. Let A be the number of four-digit integers that leave a remainder of 2 when divided by 7. Let B be the number of four-digit integers that leave a remainder of 4 when divided by 5. Let C be the number of four-digit integers that both leave a remainder of 2 when divided by 7 and a remainder of 4 when divided by 5. Our goal is to compute $(A - C) + (B - C)$

To calculate A, we note that we are looking for integers x such that

$$1000 \leq 7x + 2 < 10000 \Rightarrow 143 \leq x \leq 1428 \Rightarrow A = 1428 - 143 + 1 = 1286.$$

To tabulate B, we note that we are looking for integers y such that

$$1000 \leq 5y + 4 < 10000 \Rightarrow 200 \leq y \leq 1999 \Rightarrow B = 1999 - 200 + 1 = 1800.$$

In tabulating C, we first determine that we are looking for integers z such that

$$1000 \leq 35z + 9 < 10000 \Rightarrow 9 \leq z \leq 285 \Rightarrow C = 285 - 29 + 1 = 257.$$

Now we compute our answer: $(A - C) + (B - C) = (1286 - 257) + (1800 - 257) = \boxed{2572}$. □

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Problem 7.8.4. In how many ways can we distribute 16 chocolate donuts, 13 glazed donuts, and 15 jelly donuts among 4 people if each person insists on receiving at least 2 of each variety of donut?

Solution. First, give 2 of each kind of donuts to each person, so we have 8 chocolate, 5 glazed, and 7 jelly left to distribute. Each distribution is independent of the other two.

The chocolates can be distributed in $\binom{8+4-1}{4-1} = \binom{11}{3} = 165$ ways.

The glazed can be distributed in $\binom{5+4-1}{4-1} = \binom{8}{3} = 56$ ways.

The jellies can be distributed in $\binom{7+4-1}{4-1} = \binom{10}{3} = 120$ ways.

Therefore there are a total of $165 \times 56 \times 120 = \boxed{1\ 108\ 800}$ ways to distribute the donuts. $\square$

7.9 Middle School - Test 5

You have **60 minutes** to complete the test. You have to **submit only the answers**. No solution is required.

Note that you have to **follow the instructions by the COs** *for submitting the answers.*

- **Intermediate (I) level: Problems 1-10**
- **Advanced (A) level: Problems 11-20**

If you submit solution based on coding, please make sure that your submission is compliant. Read the introduction chapter for more information.

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Problem 7.9.1. (*1 point*) The diagram shows a polygon made by removing six 2×2 squares from the sides of an 8×12 rectangle. Find the perimeter of this polygon.

Solution. The square removed from the lower right corner of the rectangle does not change the perimeter, but when each of the other five squares is removed, the perimeter is increased by 4. Thus, the perimeter of the polygon is $2 \cdot 8 + 2 \cdot 12 + 5 \cdot 4 = \boxed{60.}$ □

Problem 7.9.2. (*1 point*) ohn, Paul, George, and Ringo baked a circular pie. Each cut a piece that was a sector of the circle. John took one-third of the whole pie. Paul took one-fourth of the whole pie. George took one-fifth of the whole pie. Ringo took one-sixth of the whole pie. At the end the pie had one sector remaining. Find the measure in degrees of the angle formed by this remaining sector.

Solution. The total number of degrees removed from the four out of the 360 degree circle as

$$360\left(\frac{1}{3}+\frac{1}{4}+\frac{1}{5}+\frac{1}{6}\right) = 120 + 90 + 72 + 60 = 342$$

Thus the number of degrees remaining is $360 - 342 = \boxed{18.}$ □

Problem 7.9.3. (*1 point*) There were 891 people voting at precinct 91. There were 20 percent more female voters than male voters. How many female voters were there?

Solution. Let m, f be the number of male and female voters, then:

$$m + f = 891,\ m + 0.2m = f \Rightarrow f - 1.2m \Rightarrow 1.2m + m = 891 \Rightarrow m = 405, f = \boxed{486.}$$

□

Problem 7.9.4. (*1 point*) Terry drove along a scenic road using 9 gallons of gasoline. Then Terry went onto the freeway and used 17 gallons of gasoline. Assuming that Terry gets 6.5 miles per gallon better gas mileage on the freeway than on the scenic road, and Terry's average gas mileage for the entire trip was 30 miles per gallon, find the number of miles Terry drove.

Solution. Terry got an average of 30 miles per gallon of gas and used $9 + 17 = 26$ gallons of gas. This means he drove $26 \cdot 30 = \boxed{780}$ miles. □

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Problem 7.9.5. (*1 point*) We draw a radius of a circle. We draw a second radius 23 degrees clockwise from the first radius. We draw a third radius 23 degrees clockwise from the second. This continues until we have drawn 40 radii each 23 degrees clockwise from the one before it. What is the measure in degrees of the smallest angle between any two of these 40 radii?

Solution. 15 times 23 is 345, so the 16th radius drawn is 345 degrees from the first. Thus the 17th radius drawn is $345 + 23 - 360 = 8$ degrees from the first radius drawn. Similarly the 33rd radius drawn will be 8 degrees from the 17th radius drawn, 16 degrees from the first radius drawn. This places it 7 degree from the second radius drawn. The remaining seven radii are similarly spaced $\boxed{7}$ degrees from the nearest drawn radii. □

Problem 7.9.6. (*1 point*) We glue together 990 one inch cubes into a 9 by 10 by 11 inch rectangular solid. Then we paint the outside of the solid. How many of the original 990 cubes have just one of their sides painted?

Solution. To have just one side painted, a cube needs to be on the face of the large rectangular solid but not on an edge of the solid. The large rectangular solid has two 9×10 faces, two 9×11 faces, and two 10×11 faces. The number of non-edge cubes forming these faces are

$$2(9-2)(10-2) + 2(9-2)(11-2) + 2(10-2)(11-2) = \boxed{382.}$$

□

Problem 7.9.7. (*1 point*) Find the sum of all positive integers x such that there is a positive integer y satisfying $9x^2 - 4y^2 = 2021$.

Solution.

$$9x^2 - 4y^2 = 2021 \Leftrightarrow (3x-2y)(3x+2y) = 2021 = 43 \cdot 47 = 1 \cdot 2021$$
$$\Rightarrow x = 15, y = 1 \text{ or } x = 337, y = 505$$

The requested sum is $15 + 337 = \boxed{352.}$ □

Problem 7.9.8. (*1 point*) The value of

$$\left(1 - \frac{1}{2^2-1}\right)\left(1 - \frac{1}{2^3-1}\right)\cdots\left(1 - \frac{1}{2^{29}-1}\right)$$

can be written as $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $2m - n$.

Solution. Note that

$$1 - \frac{1}{2^k-1} = \frac{2^k-2}{2^k-1} = 2 \cdot \frac{2^{k-1}-1}{2^k-1}.$$

Thus the given expression is a telescopic product and its value is:

$$\left(2 \cdot \frac{2^1-1}{2^2-1}\right)\left(2 \cdot \frac{2^2-1}{2^3-1}\right)\cdots\left(2 \cdot \frac{2^{28}-1}{2^{29}-1}\right)$$
$$= \frac{2^{28}}{2^{29}-1} \Rightarrow 2m - n = 2 \cdot 2^{28} - (2^{29}-1) = \boxed{1.}$$

□

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Problem 7.9.9. (*1 point*) Find the positive integer n such that

$$1 + 2 + 3 + \cdots + n = (n + 1) + (n + 2) + \cdots + (n + 35).$$

Solution.

$$\begin{aligned}
&1 + 2 + 3 + \cdots + n = \frac{n(n+1)}{2} \\
&(n + 1) + (n + 2) + \cdots + (n + 35) = 35n + \frac{35 \cdot 36}{2} \\
&\Rightarrow n^2 - 69n - 1260 = 0 \Rightarrow n = \boxed{84.}
\end{aligned}$$

□

Problem 7.9.10. (*1 point*) For positive integer n, let $s(n)$ be the sum of the digits of n when n is expressed in base ten. For example, $s(2022) = 2 + 0 + 2 + 2 = 6$. Find the sum of the two solutions to the equation:

$$n - 3s(n) = 2022.$$

Solution. If n has k digits, then $s(n) \leq 9k$, so $n > n - 3s(n) \geq 10^{k-1} - 27k$. Thus, if $n - 3s(n) = 2022$, $k < 5$, and because $n > 2022$, it is clear that any solution to the given equation has 4 digits.

Moreover, the thousands digit of n must be 2. Then, because $s(n) \leq 2 + 9 + 9 + 9 = 29$, any solution n must be less than or equal to $2022 + 3 \cdot 29 = 2109$.

But then, $s(n) \leq 2 + 1 + 9 + 9 = 21$, implying that $n \leq 2022 + 3 \cdot 21 = 2085$.

Assume that $n = 20ab$ for digits a and b. Then $2000 + 10a + b - 3(2 + a + b) = 2022$, implying $7a - 2b = 28$.

Because a and b are digits, it follows that $(a, b) = (4, 0)$ or $(6, 7)$, and $n = 2040$ or 2067.

The requested sum is $2040 + 2067 = \boxed{4107.}$ □

Problem 7.9.11. (*1 point*) For some integers a and b the function $f(x) = ax + b$ has the properties that $f(f(0)) = 0$ and $f(f(f(4))) = 9$. Find $f(f(f(f(10))))$.

Solution.

$$\begin{aligned}
&f(0) = b \Rightarrow f(f(0)) = f(b) = ab + b = b(a + 1),\ f(f(0)) = 0 \Rightarrow a = -1 \text{ or } b = 0 \\
&f(4) = 4a + b, f(f(4)) = a(4a + b) + b = 4a^2 + ab + b, \\
&f(f(f(4))) = a(4a^2 + ab + b) + b = 4a^3 + ab(a + 1) + b = 4a^3 + b
\end{aligned}$$

Case 1: $b = 0$, thus $a = \sqrt[3]{\frac{9}{4}}$ is not an integer.

Case 2: $a = -1$, then $b = 13$, or $f(x) = -x + 13$,

Thus $f(f(f(f(10)))) = f(f(f(3))) = f(f(10)) = f(3) = \boxed{10.}$ □

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Problem 7.9.12. (*1 point*) A farmer wants to create a rectangular plot along the side of a barn where the barn forms one side of the rectangle and a fence forms the other three sides. The farmer will build the fence by fitting together 75 straight sections of fence which are each 4 feet long. The farmer will build the fence to maximize the area of the rectangular plot. Find the length in feet along the side of the barn of this rectangular plot.

Note that the farmer can only use a whole numbers of sections of fence for any side.

Solution. Suppose the farmer builds a rectangle with 2 sides each made of n sections of fence and the other side parallel to the barn made of $75 - 2n$ sections of fence. Then the total area enclosed is

$$42n(75 - 2n) = 32n(37.5 - n)$$

This is a quadratic expression in n which reaches a maximum at $n = \frac{1}{2}(37.5) = 18.75$. But to form a rectangle, the farmer can only use a whole numbers of sections of fence for 2 side of the rectangle, and because $19 \cdot (75 - 2 \cdot 19) > 18 \cdot (75 - 2 \cdot 18)$, the integer value of n that maximizes the area is $n = 19$.

Therefore, the length of the fence along the barn is $4(75 - 2 \cdot 19) = \boxed{148}$ feet. □

Problem 7.9.13. (*1 point*) Each different letter in the following addition represents a different decimal digit. The sum is a six-digit integer whose digits are all equal.

$$\begin{array}{cccccccc} & & P & U & R & P & L & E \\ + & & & C & O & M & E & T \\ \hline \end{array}$$

Find the greatest possible value that the five-digit number COMET could represent.

Solution. Let X represent the digit that is repeated six times in the sum, and note that X might be a value shared by one of the other letters in the problem.

In order to maximize COMET, try $C = 9$ and $O = 8$. Because P cannot also be 8 or 9, P cannot exceed 7, and X cannot exceed 8.

If $R = 0$, then the $R + O$ sum would have to be 8. But this cannot be the result when U is added to $C = 9$ because then U would have to be 8 or 9, which are already used. Thus, R cannot be 0.

This implies that there must be a carry when R is added to O.

Because there is a carry of 1 when U is added to 9, it follows that $X = U$, and $U = P + 1 \geq 2$.

Also, L is different from T, so $E + T$ must carry over and $L = T - 1$. Since 9 and 8 are already used, $E + T$ could be 12 (5 and 7 in some order) or 13 ($E = 7$ and $T = 6$ because $L = T - 1$ cannot be 6, as E would be). So the only possibility is as below, because $E = 7$ and $T = 5$ would lead to $R = L = 4$, a contradiction, and $E = 7$ and $T = 6$ would yield $R = L = 3$.

$$\begin{array}{cccccccc} & & 1 & 2 & 4 & 1 & 6 & 5 \\ + & & & 9 & 8 & 0 & 5 & 7 \\ \hline & & 2 & 2 & 2 & 2 & 2 & 2 \end{array}$$

Hence, the greatest possible value of COMET is $\boxed{98\ 057.}$ □

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Problem 7.9.14. (*1 point*) A square, a regular pentagon, and a regular hexagon are all inscribed in the same circle. The 15 vertices of these polygons divide the circle into at most 15 arcs. Let M be the degree measure of the longest of these arcs. Find the minimum possible value for M.

Solution. Because there are 6 vertices of the hexagon and 5 vertices of the pentagon, there must be an arc of the circle where 2 vertices of the hexagon lie between 2 adjacent vertices of the pentagon.

Because there are $72°$ between adjacent vertices of the pentagon and $60°$ between adjacent vertices of the hexagon, one of these 2 vertices of the hexagon is within 6 degrees of the nearest vertex of the pentagon.

Thus, without loss of generality, there is an x with $0 \leq x \leq 6$ such that the location in degrees around the circle of the vertices of the pentagon are $0, 72, 144, 216$, and 288, and the vertices of the hexagon are at $x, x+60, x+120, x+180, x+240$, and $x+300$.

These 11 vertices divide the circle into the following arcs:

Arc	1	2	3	4	5	6	7	8	9	10	11
Start	0	x	$x+60$	72	$x+120$	144	$x+180$	216	$x+240$	288	$x+300$
Measure	x	60	$12-x$	$48+x$	$24-x$	$36+x$	$36-x$	$24+x$	$48-x$	$12+x$	$60-x$

Notice that arcs numbered 2, 4, and 11 each measure at least $48\circ$, and that the arc of the circle made up of arcs 11, 1, 2, 3, and 4 measures $180°$. This means that no matter how the square is placed in the circle, at most two vertices of the square lie within arcs 2, 4, and 11, so no matter how the square is placed in the circle, the resulting arcs between the vertices of the polygons will have at least one arc which measures at least $48°$. On the other hand, letting $x = 0$ and placing the square so that its vertices are at degree locations 48, 138, 228, and 318, results in the following arcs:

Arc	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Start	0	48	60	72	120	138	144	180	216	228	240	288	300	318
Measure	48	12	12	48	18	6	36	36	12	12	48	12	18	42

This shows that the three polygons can be placed in the circle so that the measure of the longest arc created is $48°$, and, therefore, $\boxed{48°}$ is the requested minimum. □

Problem 7.9.15. (*1 point*) Find the remainder when 7^{7^7} is divided by 1000.

Solution.

$$7^2 = 49 = 50 - 1 \Rightarrow 7^4 = (50-1)^2 = 2500 - 2 \cdot 50 + 1 = 2401$$
$$\Rightarrow 7^{20} = (2400+1)^5 = (2400)^5 + 5 \cdot 2400^3 + 10 \cdot 2400^2 + 5 \cdot 2400 + 1 \equiv 1 \pmod{1000}$$
$$7^4 \equiv 1 \pmod{20} \Rightarrow 7^7 \equiv 7^3 = 343 \equiv 3 \pmod{20}$$
$$\Rightarrow 7^{7^7} \equiv 7^3 = \boxed{343} \pmod{1000}$$

□

Problem 7.9.16. (*1 point*) On $\triangle ABC$ let D be a point on side AB, F be a point on side AC, and E be a point inside the triangle so that $DE \parallel AC$ and $EF \parallel AB$. Given that $AF = 6, AC = 33, AD = 7, AB = 26$, and the area of quadrilateral $ADEFis14$, find the area of $\triangle ABC$.

Solution. Let X be the point such that $BX \parallel AC$, $CX \parallel AB$. Then parallelograms $ABXC$ and $ADEF$ have the same angles. It follows that the area os ABC

$$[ABC] = \frac{1}{2} \cdot \frac{AD}{AB} \cdot \frac{AF}{AC} \cdot [ADEF] = \frac{1}{2} \cdot \frac{26}{7} \cdot \frac{33}{6} \cdot 14 = \boxed{143.}$$

□

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Problem 7.9.17. (*1 point*) Find the greatest integer n such that 5^n divides $2019! - 2018! + 2017!$.

Solution.

$$2019! - 2018! + 2017! = 2017!(2019 \cdot 2018 - 2018 + 1) = 2017!(2018^2 + 1).$$

The number of factors of 5 in 2017! is:

$$\left\lfloor \frac{2017}{5} \right\rfloor + \left\lfloor \frac{2017}{25} \right\rfloor + \left\lfloor \frac{2017}{15} \right\rfloor + \left\lfloor \frac{2017}{625} \right\rfloor = 403 + 80 + 16 + 3 = 502.$$

Note that $2018^2 + 1 \equiv 18^2 + 1 \equiv 325 \pmod{1000}$, thus $25 \mid 2018^2 + 1$, but $125 \nmid 2018^2 + 1$.

Thus, the number of factors of 5 is the given expression is $502 + 2 = \boxed{504.}$ □

Problem 7.9.18. (*1 point*) Three red books, three white books, and three blue books are randomly stacked to form three piles of three books each. The probability that no book is the same color as the book immediately on top of it is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $10m + n$.

Solution. There are 9 positions into which 3 reds, 3 whites, and 3 blues are placed. This can be done in $\binom{9}{3\ 3\ 3} = \frac{9!}{3!3!3!}$ equally likely ways. There are three ways for the colors to be placed so that no two adjacent places have the same color.

Case 1: All 3 stacks can contain all 3 colors. This can be done in $(3!)^3 = 216$ ways.

Case 2: All 3 stacks can contain exactly 2 colors. There are 3! ways to assign a repeated color to each stack. The repeated color in a stack must be in the top and bottom position of the stack. There are 2 ways to determine the third color in each stack, so this case accounts for $3! \cdot 2 = 12$ ways.

Case 3: Two stacks contain 2 colors, and 1 stack contains all 3 colors. There are 3 ways to select the stack with 3 colors, and 3! ways to arrange the colors in that stack. Then there are $3 \cdot 2 = 6$ ways to determine which are the repeated colors represented in the other 2 stacks. So, this case accounts for $3 \cdot 3! \cdot 6 = 108$ ways.

Thus, the probability is

$$\frac{(216 + 12 + 108) \cdot 3! \cdot 3! \cdot 3!}{9!} = \frac{1}{5} \Rightarrow 10m + n = \boxed{15.}$$

□

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Problem 7.9.19. (*1 point*) Given that $a_1, a_2, a_3, \ldots, a_{99}$ is a permutation of $1, 2, 3, \ldots, 99$, find the maximum possible value of

$$|a_1 - 1| + |a_2 - 2| + |a_3 - 3| + \cdots + |a_{99} - 99|.$$

Solution. Note that $|a_k - k|$ is either $a_k - k$ or $k - a_k$. Thus for each permutation, there is a subset $S \subseteq \{1, 2, \ldots, 99\}$, such that:

$$|a_1 - 1| + |a_2 - 2| + |a_3 - 3| + \cdots + |a_{99} - 99| = \left(\sum_{k \in S} a_k - \sum_{k \notin S} a_k\right) + \left(\sum_{k \notin S} k - \sum_{k \in S} k\right)$$

If $|S| = m$ (S contains m elements), the maximum possible value for $\left(\sum_{k \in S} a_k - \sum_{k \notin S} a_k\right)$ is

$$\sum_{k=100-m}^{99} k - \sum_{k=1}^{99-m} k = \sum_{k=1}^{99} k - 2\left(\sum_{k=1}^{99-m} k\right) = 99 \cdot 50 - (99 - m)(100 - m).$$

When S has m elements, the complement of $S : \{1, 2, \ldots, 99\} \setminus S$ has $99 - m$ elements, so for a given value of m, the maximum for the given sum is

$$[99 \cdot 50 - (99 - m)(100 - m)] + [99 \cdot 50 - (m)(m + 1)] = 2m(99 - m).$$

This reaches its maximum when m is as close as possible to $\frac{99}{2}$ which is 49 or 50. The maximum is, therefore, $2 \cdot 49 \cdot 50 = \boxed{4900}$.

For example, this is achieved when the permutation $a_1, a_2, a_3, \ldots, a_{99}$ is $50, 51, 52, \ldots, 1, 2, 3, \ldots, 49$. □

Problem 7.9.20. (*1 point*) Nine light bulbs are equally spaced around a circle. When the power is turned on, each of the nine light bulbs turns blue or red, where the color of each bulb is determined randomly and independently of the colors of the other bulbs. Each time the power is turned on, the probability that the color of each bulb will be the same as at least one of the two adjacent bulbs on the circle is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $n - m$.

Solution. Because each bulb has 2 possible colors, there are $2^9 = 512$ equally likely ways for the colors to be chosen.

Suppose the colors are chosen so that each bulb is next to a bulb of the same color. There are 2 ways for the lights to be all the same color: either all blue or all red.

If there are bulbs of both colors and all the blue bulbs appear next to each other, then there can be either 2, 3, 4, 5, 6, or 7 red bulbs, and they will also appear next to each other. Thus, there are 6 ways to choose the number of red bulbs and 9 ways to choose the positions of the red bulbs, so this accounts for $6 \cdot 9 = 54$ arrangements.

Otherwise, there must be 4 blocks of bulbs with the same color with 2 bulbs in each block except for one block that contains 3 bulbs. There are 2 ways to choose the color of the lights in the block of 3 bulbs and 9 ways to choose the position of that block of 3 bulbs, so this accounts for $2 \cdot 9 = 18$ arrangements.

The required probability is

$$\frac{2 + 54 + 18}{512} = \frac{37}{256} \Rightarrow n - m = 256 - 37 = \boxed{219.}$$

□

7.10 High School - Test 5

You have **90 minutes** to complete the test. You have to **submit only the answers**. No solution is required.

Note that you have to **follow the instructions by the COs** *for submitting the answers.*

- **Intermediate (I) level: Problems 1-10**
- **Advanced (A) level: Problems 11-20**
- **Olympiad (O) level: Problems 21-30**

If you submit solution based on coding, please make sure that your submission is compliant. Read the introduction chapter for more information.

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Problem 7.10.1. (*1 point*) In eight years Henry will be three times the age that Sally was last year. Twenty five years ago their ages added to 83. How old is Henry now?

Solution. Let h and s represent be the ages of Henry and Sally now, then we have:

$$\left.\begin{aligned} h+8 = 3(s-1) \Rightarrow h = 3s-11 \\ (h-25)+(s-25) = 83 \Rightarrow h = 133-s \end{aligned}\right\} \Rightarrow 3s-11 = 133-s \Rightarrow s = \frac{144}{4} = 36 \Rightarrow h = \boxed{97.}$$

□

Problem 7.10.2. (*1 point*) *The day of the month of Monday, March 11, 2024 is 11. The day of the month of Saturday, March 16, 2024 is 16.*

What is the smallest number that could be the day of month of the first Saturday after the second Monday following the second Thursday of a month?

Solution. If the month in question is a 28-day February starting on a Saturday, then the first Thursday is the 6th. The second Thursday is the 13th. The first Monday after that is the 17th. The second Monday after the second Thursday is the 24th. The following Saturday is then March 1.

Since the day of the month must be a positive integer, the smallest possible value is $\boxed{1.}$ □

Problem 7.10.3. (*1 point*) What is the largest integer whose prime factors add to 17?

Solution. Note that $2 \times 2 \times 2 = 8 < 3 \times 3 = 9$. So you get a larger product by multiplying two threes than multiplying three twos, though $2+2+2 = 3+$. Following the same reasoning with $5 \times 5 = 25 < 2 \times 2 \times 2 \times 2 \times 2$, whereas $5+5 = 2+2+2+2+2$.

So, to get larger product, you would take partition 14 into a sum of as many threes as possible: $17 = 3+3+3+3+3+2$. Then their product is $3 \times 3 \times 3 \times 3 \times 3 \times 2 = \boxed{486.}$ □

Problem 7.10.4. (*1 point*) The lengths of the diagonals of a rhombus are, in inches, two consecutive even integers. The area of the rhombus is 24 square inches. Find its perimeter, in inches.

Solution. Let x and $x+1$ be the length of the diagonals. Then its area is

$$\frac{x(x+2)}{2} = 24 \Rightarrow (x-6)(x+8) = 0 \Rightarrow x = 6.$$

So the rhombus consists of four right triangles with legs 3 and 4. Therefore it hypotenuse is 5, hence its perimeter is $4 \cdot 5 = \boxed{20}$. □

Problem 7.10.5. (*1 point*) Let a, b, and c be nonzero real numbers such that

$$a + \frac{1}{b} = 6,\ b + \frac{1}{c} = 13,\ c + \frac{1}{a} = 15.$$

Find $abc + \frac{1}{abc}$.

Solution.

$$\begin{aligned} &\left(a+\frac{1}{b}\right)\left(b+\frac{1}{c}\right)\left(c+\frac{1}{a}\right) = 6 \cdot 13 \cdot 15 - 1170 \\ &\Leftrightarrow abc + \left(a+\frac{1}{b}\right) + \left(b+\frac{1}{c}\right) + \left(c+\frac{1}{a}\right) = 1170 \\ &\Rightarrow abc + \frac{1}{abc} = 1170 - 6 - 13 - 15 = \boxed{1136.} \end{aligned}$$

□

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Problem 7.10.6. (*1 point*) Evaluate

$$\frac{1}{\log_2\left(\frac{1}{6}\right)} - \frac{1}{\log_3\left(\frac{1}{6}\right)} - \frac{1}{\log_{24}\left(\frac{1}{6}\right)}.$$

Solution.

$$\frac{1}{\log_2\left(\frac{1}{6}\right)} - \frac{1}{\log_3\left(\frac{1}{6}\right)} - \frac{1}{\log_{24}\left(\frac{1}{6}\right)} = \log_{\frac{1}{6}} 2 - \log_{\frac{1}{6}} 3 - \log_{\frac{1}{6}} 24 = \log_{\frac{1}{6}} \frac{2}{3 \cdot 24} = \log_{\frac{1}{6}} \frac{1}{36} = \boxed{2.}$$

□

Problem 7.10.7. (*1 point*) Find the smallest n such that every subset of $\{1, 2, 3, \ldots, 2024\}$ with n elements contains at least two elements that are relatively prime.

Solution. Note that the set contains at least 1012 even numbers so there exists a subset containing 1012 even numbers. Thus $n > 1012$. Now, consider the following collection of 1012 sets:

$$\{1, 2\},\ \{3, 4\},\ \ldots,\ \{2023, 2024\}.$$

If 1013 number are chosen from the sets, then by the Pigeonhole Principle, at least two of the element must be from the same set $\{k, k+1\}$, these two are relatively prime. Hence the least number is $\boxed{1013.}$ □

Problem 7.10.8. (*1 point*) Three lines are drawn parallel to each of the three sides of triangle ABC so that the three lines intersect in the interior of ABC. The resulting three smaller triangles have areas 2.4, 5.4, and 15. Find the area of triangle ABC.

Solution. Let D, E, F, G, H, I, and J be points as denoted in the diagram. Let $s = [ABC]$.

$$\triangle IDE \sim \triangle JEF \sim \triangle EGH \sim \triangle ABC \Rightarrow EF = BC\sqrt{\frac{2.4}{s}}, DE = BC\sqrt{\frac{5.4}{s}}, GH = BC\sqrt{\frac{15}{s}}$$

$$\Rightarrow EF + DE = BC\sqrt{\frac{1}{s}}(\sqrt{2.4} + \sqrt{5.4}) = BC(2\sqrt{0.6} + 3\sqrt{0.6}) = BC(5\sqrt{0.6}) = BC\sqrt{15}$$

$$\Rightarrow GH = \frac{1}{2}BC \Rightarrow [ABC] = 4 \cdot [EGH] = \boxed{60.}$$

□

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Problem 7.10.9. (*1 point*) Let f be a real-valued function of real and positive argument such that

$$f(x) + 3xf\left(\frac{1}{x}\right) = 2(x+1) \text{ for all real numbers } x > 0.$$

Find $2f(2024)$.

Solution. Note that

$$\begin{cases} f(x) + 3xf\left(\frac{1}{x}\right) = 2(x+1) \\ f\left(\frac{1}{x}\right) + 3\left(\frac{1}{x}\right)f(x) = 2\left(\frac{1}{x}+1\right) \end{cases}$$

Multiplying the second equation by $3x$ and subtracting the first one:

$$3x\left[f\left(\frac{1}{x}\right) + 3\left(\frac{1}{x}\right)f(x)\right] - \left[f(x) + 3xf\left(\frac{1}{x}\right)\right] = 6x\left(\frac{1}{x}+1\right) - 2(x+1)$$
$$\Rightarrow 8f(x) = 4x + 4 \Rightarrow f(x) = \frac{1}{2}(x+1) \Rightarrow 2f(2024) = \boxed{2025.}$$

□

Problem 7.10.10. (*1 point*) How far is it from the point $(9, 17)$ to its reflection across the line $3x + 4y = 10$?

Solution. The answer is $\boxed{34}$, twice the distance from the point $(9, 17)$ to the line $3x + 4y = 10$, which is:

$$\frac{3 \cdot 9 + 4 \cdot 17 - 10}{\sqrt{3^2 + 4^2}} = \frac{27 + 68 - 10}{5} = 17.$$

□

Problem 7.10.11. (*1 point*) Find the number of nonnegative integers n for which $(n^2 - 3n + 1)^2 + 1$ is a prime number.

Solution. Since both n^2 and $3n$ are odd or even, thus $(n^2 - 3n + 1)^2 + 1$ is an even number, thus

$$(n^2 - 3n + 1)^2 + 1 = 2 \Rightarrow n^2 - 3n + 1 = \pm 1 \Rightarrow \begin{cases} n^2 - 3n = 0 \\ n^2 - 3n + 2 = 0 \end{cases} \Rightarrow n = 0, 1, 2, 3$$

Hence, there are $\boxed{4}$ such numbers. □

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Problem 7.10.12. (*1 point*) How many triangles appear in the diagram below?

Solution. To count the triangles notice that all triangles are right triangles.

There are 10 triangles with a right angle at the intersection of two diagonal lines and a hypotenuse along the left vertical side of the rectangle. By symmetry, there are just as many triangles with a hypotenuse along the top, right, or bottom side of the rectangle. So there are 40 of such triangles.

There are 4 triangles with right angle at the lower right corner of the rectangle. By symmetry, there are four times of this many triangles, or 16.

In total, there are $\boxed{56}$ triangles. □

Problem 7.10.13. (*1 point*) Let $P(x)$ be a polynomial such that, when divided by $x-2$, the remainder is 3 and, when divided by $x-3$, the remainder is 2. If, when divided by $(x-2)(x-3)$, the remainder is $ax+b$, find a^3+b^3.

Solution. By the remainder theorem: $P(2)=3, P(3)=2$. By the division algorithm, there exists $Q(x)$ polynomial:

$$P(x)=(x-2)(x-3)Q(x)+ax+b \Rightarrow \begin{cases} 3=P(2)=2a+b \\ 2=P(3)=3a+b \end{cases} \Rightarrow a=-1, b=5$$

Thus $a^3+b^3=-1+125=\boxed{124.}$ □

Problem 7.10.14. (*1 point*) Jerry purchased some stock for \$115200 at the same time that Susan purchased a bond for \$$x$. Jerry's investment went up 20 percent the first year, fell 10 percent the second year, and rose another 20 percent the third year. Susan's investment grew at a constant rate of compound interest of 44% for three years. If both investments are worth the same after three years, what is x?

Solution. Jerry investment and Susan investment ended up being equal, thus if r be the constant rate of compound interest of Susan's investment, then:

$$115200(1.20)(0.9)(1.20)=x(1+0.44)^3 \Rightarrow x=\frac{115200(1.20)(0.9)(1.20)}{(1+0.44)^3}=\boxed{50\ 000.}$$

□

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Problem 7.10.15. (*1 point*) We want to paint some identically-sized cubes so that each face of each cube is painted a solid colour and each cube is painted with six different colours. If we have eight different colours to choose from, how many distinguishable cubes can we produce?

Solution. We can choose a unique way to colour a cube by first choosing the one colour whoch will not appear on a face of the cube. There are $\binom{8}{2} = 28$ ways to do that.

Assuming the colours are in some natural order (perhaps alphabetical) paint one side of the cube with the colour of the first of the six colours. Then choose the colour which goes on the opposite side face of the first colour. There are 5 ways to do that.

Finally, chose an ordering for the four remaining colours to fit on the four remaining sides. There are $3! = 6$ ways to order four items in a circle.

Thus, the total number of ways is $28 \cdot 5 \cdot 6 = \boxed{840}$. □

Problem 7.10.16. (*1 point*) Five boys and two girls sit at a circular table. How many distinct arrangements are there of these six people if the two girls sit opposite each other?

Solution. There is only one way to seat the two girls across from each other. Each way the five boys now can take the remaining five seats results in a distinct arrangement, so there are $5! = \boxed{120}$ ways. □

Problem 7.10.17. (*1 point*) Let $a_k = (k^2+1)k!$ and $b_k = a_1 + a_2 + \cdots + a_k$. Let

$$\frac{a_{49}}{b_{49}} = \frac{m}{n}.$$

where m and n are relatively prime natural numbers. Find $n - m$.

Solution.

$$\begin{aligned}
&a_k = (k^2+1)k! = ((k^2+k)-(k-1))k! = k(k+1)! - (k-1)k! \\
&\Rightarrow b_k = k(k+1)1 - 0 \cdot 1! = k(k+1)! \Rightarrow \frac{a_k}{b_k} = \frac{k^2+1}{k^2+k} \\
&\Rightarrow \frac{a_{49}}{b_{49}} = \frac{49^2+1}{49^2+49} = \frac{1201}{1225} \Rightarrow n - m = \boxed{24.}
\end{aligned}$$

□

Problem 7.10.18. (*1 point*) Given that $3\sin x + 4\cos x = 5$, where x is in $\left(0, \frac{\pi}{2}\right)$. Find $2\sin x + \cos x + 8\tan x$.

Solution. Let $\tan\left(\frac{x}{2}\right) = t$, then

$$\sin x = \frac{2t}{1+t^2}, \ \cos x = \frac{1-t^2}{1+t^2}.$$

Therefore

$$\begin{aligned}
&\frac{6t}{1+t^2} + \frac{4(1-t^2)}{1+t^2} = 5 \Rightarrow 9t^2 - 6t + 1 = 0 \Rightarrow t = \frac{1}{3}, \text{ since } \left(\tan\left(\frac{x}{2}\right) > 0\right) \\
&\Rightarrow \sin x = \frac{3}{5}, \ \cos x = \frac{4}{5}, \ \tan x = \frac{3}{4}. \Rightarrow 2\sin x + \cos x + 4\tan x = \frac{2 \cdot 3}{5} + \frac{4}{5} + \frac{8 \cdot 3}{4} = \boxed{8.}
\end{aligned}$$

□

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Problem 7.10.19. (*1 point*) In triangle ABC, $\max \angle A, \angle B = \angle C + 30°$, and $\dfrac{R}{r} = 1 + \sqrt{3}$, where R is the radius of the circumcircle and r is the radius of the incircle. Find the smallest angle in $\triangle ABC$.

Solution. Let's assume that $A \geq B$. Note that $\cos 15° = \dfrac{\sqrt{6}+\sqrt{4}}{4}$,

$$r = 4R \sin\frac{\angle A}{2} \sin\frac{\angle B}{2} \sin\frac{\angle C}{2} \Rightarrow \left(2\sin\frac{\angle A}{2}\sin\frac{\angle C}{2}\right)\sin\frac{\angle B}{2} = \frac{2}{1+\sqrt{3}}$$
$$\Leftrightarrow \left(\cos\frac{\angle A - \angle C}{2} - \cos\frac{\angle A + \angle C}{2}\right)\sin\frac{\angle B}{2} = \frac{\sqrt{3}-1}{4}$$
$$\Leftrightarrow \left(\frac{\sqrt{6}+\sqrt{4}}{4} - \sin\frac{\angle B}{2}\right)\sin\frac{\angle B}{2} = \frac{\sqrt{3}-1}{4}$$

With $x = \sin\frac{\angle B}{2}$,

$$x^2 - x\left(\frac{\sqrt{6}+\sqrt{4}}{4}\right) + \frac{\sqrt{3}-1}{4} = 0 \Rightarrow x = \frac{\sqrt{6}-\sqrt{4}}{4},\ x = \sqrt{2}2.$$

Thus $\frac{\angle B}{2} = 15°$, or $\frac{\angle B}{2} = 45°$. Note that $\angle A \geq \angle B$, therefore $\angle B = \boxed{30°}$, and $\angle C = 60°, \angle A = 90°$. □

Problem 7.10.20. (*1 point*) In triangle ABC, $\angle A = 30°$, and $AB = AC = 16$. Let D lie on segment BC such that $DB = 2$. Let E and F be the orthogonal projections of D onto AB and AC, respectively. If $\dfrac{m}{n} = DF - DE$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. Let BG be the altitude in $\triangle ABC$.

Since ABG is a $30 - 60 - 90$ triangle, thus, $BG = \frac{1}{2}AB = 8$. Furtheremore

$$\frac{DF}{BG} = \frac{DC}{BC} = \frac{3}{5} \Rightarrow DF = \frac{24}{5},\ \text{similarly } DE = \frac{24}{5}$$
$$\Rightarrow DF - DE = \frac{24}{5} - \frac{16}{5} = \frac{8}{5} \Rightarrow m + n = 8 + 5 = \boxed{13.}$$

□

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Problem 7.10.21. (*1 point*) In triangle ABC, $AB = 52$, $BC = 56$, $CA = 60$. Let D be the foot of the altitude from A and E be the intersection of the internal angle bisector of $\angle BAC$ with BC. Find DE.

Solution. Let $AD = h, BD = x, EC = y$.

$$\left.\begin{aligned} h^2 + x^2 &= AB^2 \\ h^2 + (BC - x^2) &= AC^2 \end{aligned}\right\} \Rightarrow AB^2 - x^2 = AC^2 - (BC - x)^2 \Rightarrow 52^2 - x^2 = 60^2 - (56 - x)^2$$

$$\Rightarrow x = 20, h = 48, \frac{EC}{AC} = \frac{EB}{AB} \Rightarrow \frac{y}{60} = \frac{56 - y}{52} \Rightarrow y = 30. \Rightarrow DE = 56 - x - y = \boxed{6.}$$

□

Problem 7.10.22. (*1 point*) The side lengths of a trapezoid are $\sqrt[4]{3}$, $\sqrt[4]{3}$, $\sqrt[4]{3}$, and $2\sqrt[4]{3}$. Its area is the ratio of two relatively prime positive integers m and n. Find mn.

Solution. Let E be the foot of the altitude from D to AB. It is easy to see that $EB = \frac{1}{2}DC = \frac{\sqrt[4]{3}}{2}$.

$$DE = \sqrt{BD^2 - BE^2} = \frac{\sqrt[4]{3}}{2} \cdot \sqrt{3} \Rightarrow [ABCD] = \left(\frac{\sqrt[4]{3}}{2} \cdot \sqrt{3}\right) \frac{1}{2}(2\sqrt[4]{3} + \sqrt[4]{3}) = \frac{9}{4}.$$

Hence $mn = 9 \cdot 4 = \boxed{36.}$ □

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Problem 7.10.23. (*1 point*) Let a and b be two different real numbers satisfying

$$\begin{cases} a^4 + 8b = 4(a^3 - 1) - 16\sqrt{3} \\ b^4 + 8a = 4(b^3 - 1) + 16\sqrt{3} \end{cases}$$

Find $a^2 + b^2$

Solution. By adding the two given equations together

$$a^4 - 4a^3 + 8a + 4 + b^4 - 4b^3 + 8b + 4 = 0 \Rightarrow (a^2 - 2a - 2)^2 + (b^2 - 2b - 2)^2 = 0$$

Thus a, b are the roots of $x^2 - 2x - 2 = 0$ or $a, b \in \{1 \pm \sqrt{3}\}$.
Hence $a^2 + b^2 = (1 + \sqrt{3})^2 + (1 - \sqrt{3})^2 = \boxed{8.}$ □

Problem 7.10.24. (*1 point*) For each positive integer m and n define function $f(m, n)$ by

$$f(1, 1) = 1,\ f(m + 1, n) = f(m, n) + m,\ f(m, n + 1) = f(m, n) - n.$$

Find the sum of all the values of p such that $f(p, q) = 2024$ for some q.

Solution. We have

$$\begin{aligned} &f(1,1) = 1,\ f(2,1) = f(1+1,1) = f(1,1) + 1,\ f(3,1) = f(2,1) + 1 = f(1,1) + 1 + 2, \ldots \\ &\Rightarrow f(m,1) = 1 + 1 + 2 + \cdots + (m-1) \\ &\Rightarrow f(m,2) = f(m,1) - 1, f(m,3) = f(m,1) - 1 - 2, \ldots \\ &\Rightarrow f(m,n) = f(m,1) - 1 - 2 - 3 - \cdots - (n-1) = 1 + 1 + 2 + \cdots + (m-1) - 1 - 2 - 3 - \cdots - (n-1) \end{aligned}$$

When $m \le n$, $f(m, n) \le 1 \Rightarrow f(m, n) \ne 2024$.
If $m > n$, then

$$f(m, n) = 1 + \sum_{i=n}^{m-1} i = 1 + \frac{(m - n)(m + n - 1)}{2}$$

Now, if $f(m, n) = 2024$, then

$$1 + \frac{(m - n)(m + n - 1)}{2} = 2024 \Rightarrow (m - n)(m + n - 1) = 2 \cdot 2023 = 2 \cdot 7 \cdot 17^2.$$

Thus $m - n \le 34$, and $m - n \in \{1, 2, 7, 14, 17, 34\}$, we have

$$(m, n) = (2024, 2023),\ (1013, 1011),\ (293, 286),\ (152, 138),\ (128, 111),\ (77, 43)$$

The requested sum is $2024 + 1013 + 293 + 152 + 128 + 77 = \boxed{3687.}$ □

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Problem 7.10.25. (*1 point*) $P(x)$ is the remainder polynomial when $x^{203} - 1$ is divided by $x^4 - 1$.

Find $P(7)$.

Solution.

$$x^{203} - 1 = (x^4 - 1)g(x) + r(x),$$

where $\deg r(x) < 4$, so we can write $r(x) = ax^3 + bx^2 + cx + d$.

We put in the roots of $x^4 - 1$ for x, making $(x^4 - 1)g(x) = 0$. These roots are 1, -1, i, and $-i$ (since $x^4 - 1 = (x^2 - 1)(x^2 + 1)$); trying each of these in turn, we have

$$\begin{aligned} 0 &= a + b + c + d \\ -2 &= -a + b - c + d \\ -i - 1 &= -ai - b + ci + d \\ i - 1 &= ai - b - ci + d \end{aligned}$$

If we add the first two equations, we get $b + d = -1$. Equating real parts of the last equation, we have $d - b = -1$. Adding these two gives $d = -1$, so $b = 0$. Similarly, subtracting the second equation from the first gives $a + c = 1$ and equating imaginary parts of the last equation gives $a - c = 1$. From these we find $a = 1$ and $c = 0$. Hence the remainder is $P(x) = x^3 - 1$.

Thus $P(7) = 7^3 - 1 = \boxed{342.}$ □

Problem 7.10.26. (*1 point*) Let d_k be the greatest odd divisor of k, for $k = 1, 2, 3, \ldots$ Find

$$d_1 + d_2 + d_3 + \cdots + d_{256}$$

Solution. We prove the following claim by induction

Claim — $s_n = d_1 + d_2 + d_3 + \cdots + d_{2^n} = \frac{2^{2n}+2}{3}$, $\forall n \geq 0$.

Proof. It is easy to verify that $s_0 = d_1 = 1$. Note that for any odd k, $d_k = k$, and for any k: $d_{2k} = d_k$. Thus,

$$\begin{aligned} s_{n+1} &= \sum_{k=1}^{2^{n+1}} d_k = \sum_{k=1}^{2^n} d_{2k-1} + \sum_{k=1}^{2^n} d_{2k} = \sum_{k=1}^{2^n} (2k-1) + \sum_{k=1}^{2^n} d_k = (2^n)^2 + s_n \\ s_n &= \frac{2^{2n}+2}{3} \Rightarrow s_{n+1} = (2^n)^2 + \frac{2^{2n}+2}{3} = \frac{2^{2(n+1)}+2}{3}. \end{aligned}$$

■

Hence $s_{2^8} = \frac{2^{16}+2}{3} = \boxed{21846.}$ □

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Problem 7.10.27. (*1 point*) Anthony has a fair coin. He writes the number +1 on a blackboard.

Then he flips the coin. If it comes up heads (**H**), he writes $+\frac{1}{2}$, and otherwise, if he flips tails (**T**), he writes $-\frac{1}{2}$.

Then he flips the coin again. If it comes up heads, he writes $+\frac{1}{4}$, and otherwise he writes $-\frac{1}{4}$.

Anthony continues to flip the coin, and on the nth flip, if he flips heads, he writes $+\frac{1}{2^n}$, and otherwise he writes $-\frac{1}{2^n}$,.

For example, if Binhao flips **HHTHTHT**, he writes

$$1+\frac{1}{2}+\frac{1}{4}-\frac{1}{8}+\frac{1}{16}-\frac{1}{32}+\frac{1}{64}-\frac{1}{128}.$$

The probability that Anthony will generate series whose sum is greater than $\frac{1}{7}$ is $\frac{p}{q}$, where p and q are relatively prime positive integers. Find pq.

Note that

$$1-\frac{1}{2}-\frac{1}{4}-\frac{1}{8}+\frac{1}{16}-\frac{1}{32}-\frac{1}{64}+\frac{1}{128}-\frac{1}{256}-\frac{1}{512}+\frac{1}{1024}+\cdots=\frac{1}{7}.$$

Solution. Note that, for all $n \geq 0$

$$\frac{1}{2^n}=\frac{1}{2^{n+1}}+\frac{1}{2^{n+2}}+\frac{1}{2^{n+3}}+\cdots \quad (*)$$

Furtheremore

$$1-\frac{1}{2}-\frac{1}{4}-\frac{1}{8}+\frac{1}{16}-\frac{1}{32}-\frac{1}{64}+\frac{1}{128}-\frac{1}{256}-\frac{1}{512}+\cdots=\frac{1}{7}.$$

Now, it is clear that if a negative number in the sequence above turns positive (head instead of tail), then the probability is larger than $\frac{1}{7}$. Further more if a positive number in the sequence above turns negative, then the probability is less than $\frac{1}{7}$.

(*) shows that if a position changes sign then it does not matter if the rest of the positions after that change signs. Thus, the probability is larger than $\frac{1}{7}$ if and only if Anthony flips a T to H in the sequence

$$T\ TTH\ TTH\ TTH\ TTH\ \ldots$$

Thus, the probability is

$$\begin{aligned}&\frac{1}{2}+\frac{1}{4}+\frac{1}{8}+\frac{1}{32}+\frac{1}{64}+\frac{1}{256}+\frac{1}{512}+\cdots\\&=\left(\frac{1}{2}+\frac{1}{4}+\frac{1}{8}+\frac{1}{16}+\cdots\right)-\left(\frac{1}{16}+\frac{1}{128}+\frac{1}{1024}+\cdots\right)\quad=1-\frac{1}{14}=\frac{13}{14}\Rightarrow pq=13\cdot 14=\boxed{182.}\end{aligned}$$

□

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Problem 7.10.28. (*1 point*) Rose writes all the 7-digit numbers in which all the digits are different and each digit is greater than the one to its right (so the tens digit is greater than the units, the hundreds greater than the tens, and so on).

Rose circles the middle digit of each number, then adds up all the circled digits. What sum does she get?

Solution. First, we count the number in the list. Take any 7 numbers from the list of digits $0, 1, \ldots, 9$. If we arrange the 7 numbers in a decreasing order to form a 7-digit number, then we get a number in Rose's list. In fact, we can obtain any number in Rose's list. Thus the number of 7-digit numbers in Rose's list corresponds to the number of ways we can pick 7 digits from the 10 digits 0 through 9. The answer is $\binom{10}{7} = 120$.

Now, given any number in Rose's list, we can pair it with another number in her list by subtracting each digit from 9, then reversing the digits. (For example, the number 9764210 pairs with the number 9875320.) This operation is reversible: doing the same operation to the new number gives the original number back again. So the numbers in Rose's list come in pairs. Also note that the middle digits in each pair always sum to 9. Therefore, the sum of all of the middle digits is 9 times the number of pairs. From part (a), we know there are 120 numbers in the list, so there are 60 pairs, and the sum is $9 \times 60 = \boxed{540}$. □

Problem 7.10.29. (*1 point*) Two base-120 units digits (not necessarily different) are chosen randomly and their product is written in base 120. $\frac{m}{n}$ is the probability that the units digit of the base-120 product is 1. Find $m + n$.

Solution. The product of two modulo 120 units digits has a units digit of 1 if the units digits are modulo 120 inverses of each other. Only integers relatively prime to 120 have modulo 120 inverses. We count these integers using the principle of inclusion-exclusion:

$$120 - \frac{120}{2} - \frac{120}{3} - \frac{120}{5} + \frac{120}{6} + \frac{120}{10} + \frac{120}{15} - \frac{120}{30} = 32.$$

So, the first units digit has a $\frac{32}{120}$ chance of having a modulo 120 inverse at all. When it does have an inverse, there is a $\frac{1}{120}$ chance that the other units digit will be that inverse. These probabilities are independent, so the overall probability that the units digit of the product is 1 is

$$\frac{32}{120} \cdot \frac{1}{120} = \frac{32}{14400} = \frac{1}{450} \Rightarrow m + n = 1 + 450 = \boxed{451.}$$

□

Problem 7.10.30. (*1 point*) Evaluate

$$\sum_{n=0}^{\infty} \frac{\cos(n\theta)}{2^n},$$

where $\cos\theta = \frac{1}{5}$.

Solution. Note that $\cos n\theta = \operatorname{Re}(e^{in\theta})$. Thus, we can write our sum, which we'll call S, as

$$S = \operatorname{Re}\left(\sum_{n=0}^{\infty} \frac{e^{in\theta}}{2^n}\right) = \operatorname{Re}\left(\sum_{n=0}^{\infty} \left(\frac{e^{i\theta}}{2}\right)^n\right).$$

The last sum is a geometric series with first term 1 and ratio $\frac{1}{2}e^{i\theta}$. Hence, S becomes

$$S = \operatorname{Re}\left(\frac{1}{1 - e^{i\theta}/2}\right) = \operatorname{Re}\left(\frac{1}{1 - \frac{1}{2}\cos\theta - \frac{i}{2}\sin\theta}\right).$$

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To determine the real part of S, we must rationalize the denominator by multiplying top and bottom by $1 - \frac{1}{2}\cos\theta + \frac{i}{2}\sin\theta$, yielding

$$S = \operatorname{Re}\left(\frac{1 - \frac{1}{2}\cos\theta + \frac{i}{2}\sin\theta}{(1 - \frac{1}{2}\cos\theta)^2 + \frac{1}{4}\sin^2\theta}\right) = \frac{1 - \frac{1}{2}\cos\theta}{(1 - \frac{1}{2}\cos\theta)^2 + \frac{1}{4}\sin^2\theta}.$$

Since $\cos\theta = \frac{1}{5}$, we have $\sin^2\theta = 1 - \frac{1}{25} = \frac{24}{25}$ and

$$S = \frac{1 - \frac{1}{10}}{(\frac{9}{10})^2 + (\frac{1}{4})(\frac{24}{25})} = \boxed{\frac{6}{7}}.$$

$\square$

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Chapter 8

Session 6

8.1 IC Test for Level 1

- All test lasts for **60 minutes**.
- The test consists of 4 **show-you-work** problems. For each of 4 show-you-work problems, you have to provide a complete solution in details. If your solution uses any diagram, please submit them too.
- Paper-based book, calculators are allowed. Computers are allowed for solving problem with coding. No searching on Internet for ideas, hints, or solutions are allowed. No help from anyone is allowed. Be honest.
- Grading:
  1. For a *show-you-work problem* the total number of points can be earned is 10**.** For a complete solution for each question of a show-you-work problem, you earn all available points for that question. If your solution for that question is not correct, you may earn some but not all available points for that question. The actual number of points to be awarded is based on the discretion of the grading COs.
- Students, if not able to join the contest at the official designated time, are eligible to write at an earlier time. They must contact the COs in time for arrangement. They must not discuss any of the received contest problems with anyone until the official contest time passed.
- Qualification: The minimum number of points **to pass the level test is** $\boxed{25.}$

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Problem 8.1.1. Find all values of x such that $\dfrac{1}{x-1} + \dfrac{2x}{x-1} = 6$.

Solution. We can combine the two terms on the left side to get $\dfrac{1+2x}{x-1} = 6$. We then multiply both sides of this equation by $x-1$ to get rid of the fractions. This gives us $1+2x = 6(x-1)$. Expanding the right side gives $1+2x = 6x-6$. Subtracting $5x$ from both sides gives $1-4x = -6$, and subtracting 1 from both sides of this equation yields $-4x = -7$. Dividing both sides of this equation by -4 gives $x = \boxed{-\dfrac{7}{4}}$. □

Problem 8.1.2. Given the segments shown, construct segments with the following length $AB + CD - EF$.

Solution. We draw a line, pick a starting point X, then copy segment $\overline{AB}$ onto the line to find point Y such that $XY = AB$. Then we find point Z beyond Y on $\overrightarrow{XY}$ such that $YZ = CD$. Finally, we find point W such that $WZ = EF$, but notice that we locate W between X and Z, so that $XW = AB + CD - EF$.

□

Problem 8.1.3. Lucius, Sarah, Brandon, and Scott take Algebra together. On their first exam, Lucius got a 94, Sarah got a 91, Brandon got a 93, and Scott's score was between 79 and 85 inclusive. If the average of all four of their scores is an integer, what was Scott's score on the first exam?

Solution. Let Scott's score be $79 + n$, where n is an integer between 0 and 6 inclusive. The average of all four scores is

$$\frac{94 + 91 + 93 + (79 + n)}{4} = \frac{357 + n}{4} = 89 + \frac{1+n}{4}.$$

The average will be an integer when $4 \mid (n+1)$. The value of $n+1$ is between 1 and 7 inclusive, so it must be 4 (the only multiple of 4 in that range). Since $n+1 = 4$, $n = 3$ and Scott's score is $79 + 3 = \boxed{82}$. □

Problem 8.1.4. Determine the number of arrangements of the letters of the word LONDON.

Solution. Since there are 6 letters in the word LONDON, thus the total number of permutations of the letters in this word is 6!. It means that we count the arrangements as if two O's are unique, or the two N's are unique.

Then since the O's are not unique, we divide by 2! for the arrangements of the O's. Furthermore since the N's are not unique, we divide by 2! for the arrangements of the N's.

The answer is $\dfrac{6!}{2! \times 2!} = \boxed{180}$. □

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8.2 IC Test for Level 3

- All test lasts for **60 minutes**.
- The test consists of 4 **show-you-work** problems. For each of 4 show-you-work problems, you have to provide a complete solution in details. If your solution uses any diagram, please submit them too.
- Paper-based book, calculators are allowed. Computers are allowed for solving problem with coding. No searching on Internet for ideas, hints, or solutions are allowed. No help from anyone is allowed. Be honest.
- Grading:
  1. For a *show-you-work problem* the total number of points can be earned is 10**.** For a complete solution for each question of a show-you-work problem, you earn all available points for that question. If your solution for that question is not correct, you may earn some but not all available points for that question. The actual number of points to be awarded is based on the discretion of the grading COs.
- Students, if not able to join the contest at the official designated time, are eligible to write at an earlier time. They must contact the COs in time for arrangement. They must not discuss any of the received contest problems with anyone until the official contest time passed.
- Qualification: The minimum number of points **to pass the level test is** $\boxed{25.}$

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Problem 8.2.1. Suppose a is directly proportional to b, but inversely proportional to c. If $a = 3$ when $b = 7$ and $c = 11$, then what is c when $b = 3$?

Solution. Because a is directly proportional to b and $a = 3$ when $b = 75$, we have $a/b = 3/7$.

Because a is inversely proportional to c and $a = 3$ when $c = 11$, we have $ac = (3)(11) = 33$. Therefore, when $b = 3$, we have $a/3 = 3/7$, which gives us $a = (3/7)(3) = 9/7$.

Since $ac = 33$, we have

$$\left(\frac{9}{7}\right)(c) = 33 \Rightarrow c = \frac{33}{9/7} = 33 \cdot \frac{7}{9} = \boxed{\frac{77}{3}}.$$

□

Problem 8.2.2. In the diagram below the lengths of the segments AB, AD, and AE are correct. The length of BC is incorrect. Why? What is the correct value of it?

Solution. Since $\overline{DB} \parallel \overline{EC}$, we have $\triangle DAB \sim \triangle EAC$. Therefore, we must have $AD/AE = AB/AC$. However, using the lengths given in the diagram, we have $AD/AE = 2/(6.5) = 4/13$ and $AB/AC = 3.5/9.5 = 7/19$. These two ratios are not equal!

To correct the diagram

$$\frac{BC}{AB} = \frac{DE}{AD} \Rightarrow BC = (AB)\frac{DE}{AD} = (3.5)\frac{4.5}{2} = \boxed{7.875.}$$

□

Problem 8.2.3. The largest power of 3 that divides 18 is 3^2. The largest power of 3 that divides 27 is 3^3.

Find the largest power of 3 that divides 81!.

Solution. Every multiple of 3 less than or equal to 81 contributes at least one factor of 3 to 81!.

Every multiple of $3^2 = 9$ that is less than or equal to 81 contributes one more additional factor of 3 to 81!.

Every multiple of 27 contributes yet one more additional extra factor of 3 to 81!.

Every multiple of 81 contributes yet one more additional extra factor of 3 to 81!.

Since 81! is a product of $\frac{81}{3} = 27$ multiples of 3, of which $\frac{81}{3^2} = 9$ are multiples of 3^2, of which $\frac{81}{3^3} = 3$ are multiples of 3^3, and of which $\frac{81}{3^4} = 1$ are multiples of 3^4, there are a total of $27 + 9 + 3 + 1 = 40$ factors of 3 in 81!.

This means $\boxed{3^{40}}$ is the largest power of 3 that divides 81!. □

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Problem 8.2.4. How many ways are there to put 5 balls in 3 boxes if the balls are not distinguishable but the boxes are distinguishable?

Solution. Since the balls are indistinguishable, we only have to consider the number of balls in the boxes. The arrangements for balls in boxes are (5,0,0), (4,1,0), (3,2,0), (3,1,1), and (2,2,1). However, since the boxes are distinguishable, we must also consider the arrangement of balls in the boxes in order.

For (5,0,0), there are 3 different ways (box #1 can have 5, box #2 can have 5, or box #3 can have 5).

For (4,1,0), there are $3! = 6$ ways: we have 3 choices for the box containing 4 balls, then 2 choices for the box containing 1 ball.

For (3,2,0) there are $3! = 6$ ways: we have 3 choices for the box containing 3 balls, then 2 choices for the box containing 2 ball.

For (3,1,1) there are 3 ways: we must choose the box which gets 3 balls.

For (2,2,1) there are 3 ways: we must choose the box which gets 1 ball.

This gives a total of $3 + 6 + 6 + 3 + 3 = \boxed{21}$ arrangements. □

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8.3 IC Test for Level 4

- All test lasts for **60 minutes**.
- The test consists of 4 **show-you-work** problems. For each of 4 show-you-work problems, you have to provide a complete solution in details. If your solution uses any diagram, please submit them too.
- Paper-based book, calculators are allowed. Computers are allowed for solving problem with coding. No searching on Internet for ideas, hints, or solutions are allowed. No help from anyone is allowed. Be honest.
- Grading:
  1. For a *show-you-work problem* the total number of points can be earned is 10**.** For a complete solution for each question of a show-you-work problem, you earn all available points for that question. If your solution for that question is not correct, you may earn some but not all available points for that question. The actual number of points to be awarded is based on the discretion of the grading COs.
- Students, if not able to join the contest at the official designated time, are eligible to write at an earlier time. They must contact the COs in time for arrangement. They must not discuss any of the received contest problems with anyone until the official contest time passed.
- Qualification: The minimum number of points **to pass the level test is** $\boxed{25.}$

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Problem 8.3.1. If $a > b > c > d$, then which is larger, $(a-c)(b-d)$ or $(a-d)(b-c)$

Solution. Let compare $(a-c)(b-d)$ with $(a-d)(b-c)$.

$$(a-c)(b-d) = ab - ad - bc + cd,\ (a-d)(b-c) = ab - ac - bd + cd$$
$$Rightarrow (a-c)(b-d) - (a-d)(b-c) = ac - ad + bd - bc = a(c-d) - b(c-d) = (a-b)(c-d) > 0$$

So $\boxed{(a-c)(b-d) > (a-d)(b-c).}$ □

Problem 8.3.2. $\triangle TUV$ is isosceles with $TU = UV = 15$ and $TV = 18$. UY bisects $\angle TUV$ and TM is a median of $\triangle TUV$. UY and TM meet at X. Find XY.

Solution. We have $UT = UV$ and $\angle TUY = \angle VUY$. Hence, by SAS, triangles UYT and UYV are congruent. Then corresponding sides are equal, and in particular, $TY = YV$.

The corresponding angles of triangle UYT and UYV are also equal, so $\angle UYT = \angle UYV$. The sum of these two angles makes a straight angle, or $180°$, so both angles are $90°$. Therefore, $UY \perp TV$.

$TY = TV/2 = 18/2 = 9$. Triangle UYT has a right angle at Y, so

$$UY = \sqrt{UT^2 - TY^2} = \sqrt{15^2 - 9^2} = 12.$$

We have shown that UY is a median. We are also given that TM is a median, so their intersection X is the centroid. The centroid X divides median UY in the ratio $XU : XY = 2 : 1$, so $XY = UY/3 = \boxed{4}$. □

Problem 8.3.3. How many four-digit integers are multiples of 12, 21, and 35?

Solution. An integer that is a multiple of 12, 21, and 35 must be a multiple of their LCM, which is 420. We can express such integers in the form $420n$ for integer values of n. Our goal is to count the integers in this form such that

$$1000 \le 420n < 10000.$$

Dividing each part of the inequality by 420 isolates n:

$$\frac{1000}{420} \le n < \frac{10000}{420} \Rightarrow 3 \le n \le 23$$

There are $23 - 3 + 1 = 21$ integer values of n in this range, each of which corresponds to a four-digit multiple of each of 12, 21, and 35, so $\boxed{21}$ is the answer. □

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Problem 8.3.4. Anna has a weighted coin that lands on heads with probability $\frac{1}{3}$, and thus lands on tails with probability $\frac{2}{3}$. If she flips the coin 9 times (where n is a positive integer) then what is the probability that exactly 6 of the flips come up heads.

Solution. There are $\binom{9}{6}$ ways for 6 of the times the coin to land on head and $9-6=3$ of the times for the coin to land on tail. Each of these sequences has a probability

$$\left(\frac{1}{3}\right)^6\left(\frac{2}{3}\right)^3.$$

since heads are flipped 6 times and tails are flipped 3. Thus, the probability that exactly 6 of the flips come up heads is

$$\binom{9}{6}\left(\frac{1}{3}\right)^6\left(\frac{2}{3}\right)^3=\frac{7\cdot 8\cdot 9}{3!}\frac{2^3}{3^9}=\frac{7\cdot 32}{3^8}=\boxed{\frac{224}{6561}.}$$

□

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8.4 IC Test for Level 5

- All test lasts for **60 minutes**.
- The test consists of 4 **show-you-work** problems. For each of 4 show-you-work problems, you have to provide a complete solution in details. If your solution uses any diagram, please submit them too.
- Paper-based book, calculators are allowed. Computers are allowed for solving problem with coding. No searching on Internet for ideas, hints, or solutions are allowed. No help from anyone is allowed. Be honest.
- Grading:
  1. For a *show-you-work problem* the total number of points can be earned is 10**.** For a complete solution for each question of a show-you-work problem, you earn all available points for that question. If your solution for that question is not correct, you may earn some but not all available points for that question. The actual number of points to be awarded is based on the discretion of the grading COs.
- Students, if not able to join the contest at the official designated time, are eligible to write at an earlier time. They must contact the COs in time for arrangement. They must not discuss any of the received contest problems with anyone until the official contest time passed.
- Qualification: The minimum number of points **to pass the level test is** $\boxed{25.}$

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Problem 8.4.1. Simplify

$$(i^{1011} - i^{-1011})^{-1}, \text{ where } i = \sqrt{-1}.$$

Solution.

$$i^{1011} - i^{-1011} = i^{1011} - \frac{1}{i^{1011}} = \frac{i^{2022} - 1}{i^{1011}}$$
$$i^{2022} = (i^2)1011 = (-1)^{1011} = -1, \; i^{1011} = (i^2)505(i) = (-1)^{505}(i) = -i$$
$$\Rightarrow \frac{i^{2022} - 1}{i^{1011}} = \frac{-2}{-i} \Rightarrow (i^{1011} - i^{-1011})^{-1} = \boxed{\frac{i}{2}.}$$

□

Problem 8.4.2. In the convex quadrilateral $ABCD$, $AB = BC = 13$ and $CD = DA$. The diagonals of $ABCD$ meet at E as shown. Find the length AD if $AC = 24, BD = 21$.

Solution. Triangles ABD and CBD are congruent by SSS. Corresponding angles of these triangles are equal, so $\angle ABD = \angle CBD$.

Since triangles ABD and CBD congruent, we have $\angle EDA = \angle EDC$. Therefore, triangles EDA and EDC are congruent by SAS. Corresponding angles of these triangles are equal, so $\angle DEA = \angle DEC$. These two angles add up to a straight angle, so both must be right angles. In other words, $AC \perp BD$.

Since $\triangle ABC$ is isosceles, $AC \perp BD$, so BE is also median of $\triangle ABC$, thus $AE = EC = 12$.

Now, by Pythagorean Theorem:

$$EB = \sqrt{AB^2 - AE^2} = \sqrt{13^2 - 12^2} = 5 \Rightarrow ED = BD - EB = 21 - 5 = 16.$$
$$\Rightarrow AD = \sqrt{AE^2 + ED^2} = \sqrt{12^2 + 16^2} = \boxed{20.}$$

□

Problem 8.4.3. Prove that for positive integer b the number 1331_b (in base b) has at least 4 distinct divisors.

Solution. Note that,

$$1331_b = b^3 + 3b^2 + 3b + 1 = (b+1)^3.$$

Thus, $1331_b = (b+1)^3$ has at least $\boxed{4}$ divisors: $1, b+1, (b+1)^2, (b+1)^3$. □

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Problem 8.4.4. A real number x is chosen at random such that $0 < x < 100$. What is the probability that

$$x - \lfloor x \rfloor \geq \frac{2}{5}.$$

Note: for any real number y, $\lfloor y \rfloor$ is defined to be the greatest integer less than or equal to y.

Solution. Note that $x - \lfloor x \rfloor$ is the fractional part of x. Thus $0 \leq x - \lfloor x \rfloor < 1$. We have $x - \lfloor x \rfloor \geq \frac{2}{5}$ if and only if the fractional part of x, denoted by $\{x\}$, is at least $\frac{2}{5}$. The probability is

$$\frac{\text{Length of segment with } \frac{2}{5} \leq \{x\} < 1}{\text{Length of segment with } 0 \leq \{x\} < 1} = \frac{1 - \frac{2}{5}}{1 - 0} = \boxed{\frac{3}{5}}.$$

□

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8.5 IC Test for Level 6

- All test lasts for **60 minutes**.
- The test consists of 4 **show-you-work** problems. For each of 4 show-you-work problems, you have to provide a complete solution in details. If your solution uses any diagram, please submit them too.
- Paper-based book, calculators are allowed. Computers are allowed for solving problem with coding. No searching on Internet for ideas, hints, or solutions are allowed. No help from anyone is allowed. Be honest.
- Grading:
  1. For a *show-you-work problem* the total number of points can be earned is 10**.** For a complete solution for each question of a show-you-work problem, you earn all available points for that question. If your solution for that question is not correct, you may earn some but not all available points for that question. The actual number of points to be awarded is based on the discretion of the grading COs.
- Students, if not able to join the contest at the official designated time, are eligible to write at an earlier time. They must contact the COs in time for arrangement. They must not discuss any of the received contest problems with anyone until the official contest time passed.
- Qualification: The minimum number of points **to pass the level test is** $\boxed{25.}$

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Problem 8.5.1. P is a parabola with axis of symmetry parallel to the x-axis passes through the points $(5, 0)$, $(12, -1)$, and $(3, 2)$.

Does P passes through point $(2, 1)$?

Solution. Because the axis of symmetry is parallel to the x-axis, it opens either leftward or rightward. Therefore, its general form is $x = ay^2 + by + c$. Substituting the three given points in this equation gives us the system

$$\begin{cases} 4 &= c, \\ 12 &= a - b + c, \\ 3 &= 4a + 2b + c. \end{cases} \Rightarrow c = 5, a = 2, b = -5$$

Therefore, our equation is $x = 2y^2 - 5y + 5$. Since $2 = 2(1)^2 - 5(1) + 5$ so P passed through point $(2, 1)$. □

Problem 8.5.2. $EFGHIJ$ is a regular hexagon. Find EH/EG.

Solution. By symmetry, long diagonal $\overline{EH}$ bisects $\angle FEJ$, so $\angle FEH = (1/2)(\angle FEJ) = 60°$. Since $EF = FG$ and $\angle EFG = 120°$, we have

$$\angle FGE = \angle FEG = (180° - 120°)/2 = 30° \Rightarrow \angle GEH = \angle FEH - \angle FEG = 30° \Rightarrow \angle HGE = \angle HGF - \angle FGE = 90°.$$

Hence, $\triangle EGH$ is a 30-60-90 triangle with hypotenuse EH and short leg GH. Therefore, $EH/EG = 2/\sqrt{3} = \boxed{2\sqrt{3}/3}$. □

Problem 8.5.3. Find the possible units digits of a perfect square in base 8.

Solution. Squaring each possible base-8 units digit

$$\begin{aligned} (0_8)^2 &= 0_8 \\ (1_8)^2 &= 1_8 \\ (2_8)^2 &= 4_8 \\ (3_8)^2 &= 11_8 \\ (4_8)^2 &= 20_8 \\ (5_8)^2 &= 31_8 \\ (6_8)^2 &= 44_8 \\ (7_8)^2 &= 61_8 \end{aligned}$$

we see that $\boxed{0}$, $\boxed{1}$, and $\boxed{4}$ are the only possible units digits of perfect squares expressed in base 8. Note that this means a perfect square must leave a remainder of 0, 1, or 4 when divided by 8. □

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Problem 8.5.4. Box A has one white ball and four black balls. Box B has three balls labeled "\$2" and one ball labeled "\$14". Box W has five balls labeled "\$4" and one ball labeled "\$460".

A game is played as follows: a ball is randomly selected from box A. If it is black, then a ball is randomly selected from box B; otherwise, if the original ball is white, then a ball is randomly selected from box W.

You win the amount printed on the second ball selected. What is your expected win?

Solution. Since box A has one white ball and four black balls, the money ball has a $\frac{1}{5}$ chance of coming from box W and a $\frac{4}{5}$ chance of coming from box B.

The total expected value therefore is $E = \frac{1}{5}E_W + \frac{4}{5}E_B$, where E_W and E_B are the expected values of a ball drawn from boxes W and B, respectively.

Since box W has five \$8 balls and 1 \$500 ball, its expected value is

$$E_W = \frac{5}{6} \times \$4 + \frac{1}{6} \times \$460 = \$80.$$

Since box B has three \$1 balls and one \$7 ball, its expected value is

$$E_B = \frac{3}{4} \times \$2 + \frac{1}{4} \times \$14 = \$5.$$

Therefore

$$E = \frac{1}{5}E_W + \frac{4}{5}E_B = \frac{1}{5}(\$80) + \frac{4}{5}(\$5) = \boxed{\$20}.$$

□

8.6 Middle School - Test 6

You have **60 minutes** to complete the test. You have to **submit only the answers**. No solution is required.

Note that you have to **follow the instructions by the COs** *for submitting the answers.*

- **Intermediate (I) level: Problems 1-10**
- **Advanced (A) level: Problems 11-20**

If you submit solution based on coding, please make sure that your submission is compliant. Read the introduction chapter for more information.

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Problem 8.6.1. (*1 point*) Elves and ogres live in the land of Pixie. The average height of the elves is 80 cm, the average height of the ogres is 200 cm, and the average height of the elves and the ogres together is 140 cm. If 36 elves live in Pixie, how many ogres live there?

Solution. Let x be the number of ogres in Pixie. Then the total height of all the ogres is $200x$, and the total height of all the elves is $36 \cdot 80 = 2880$. Therefore the total height of all the creatures in Pixie is $2880 + 200x$.

On the other hand, the average height of the $36 + x$ creatures in Pixie is 140, so their total height is $140(36 + x) = 5040 + 140x$. Thus $2880 + 200x = 5040 + 140x$, so $x = \boxed{36.}$ □

Problem 8.6.2. (*1 point*) You are given a two-digit positive integer. If you reverse the digits of your number, the result is a number which is 20% larger than your original number. What is your original number?

Solution. Let x be the given two-digit number. Increasing x by 20%, that is, by $\frac{1}{5}x$, yields an integer, so x must be divisible by 5. Thus x ends in 0 or in 5. If the ones digit of x is 0, reversing the digits would decrease the number, so x must end in 5. If the tens digit is larger than 5, reversing the digits would again decrease the number. Thus only the numbers 15, 25, 35, 45, and 55 remain to be checked. Only $\boxed{45}$ works out. □

Problem 8.6.3. (*1 point*) A 9×12 rectangular piece of paper is folded once so that a pair of diagonally opposite corners coincide. The length of the crease is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. By the Pythagorean Theorem,

$$9^2 + x^2 = (12 - x)^2 \Rightarrow 24x = 63 \Rightarrow x = \frac{21}{8},\ c^2 = 9^2 + (12 - 2x)^2 \Rightarrow c^2 = \frac{2025}{16} \Rightarrow c = \frac{45}{4}$$

Hence, $m + n = 45 + 4 = \boxed{49.}$ □

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Problem 8.6.4. (*1 point*) In calm weather, an aircraft can fly from one city to another 200 kilometres north of the first and back in exactly two hours. In a steady north wind, the round trip takes five minutes longer. Find the speed (in kilometres per hour) of the wind.

Solution. The airspeed of the plane is $\frac{1}{2}400 = 200$ kilometres per hour. Let w denote the speed of the wind. Then, if you fly with the wind, the ground speed is $200 + w$; and if you fly against the wind, the ground speed is $200 - w$. Therefore, the plane takes $\frac{200}{200+w}$ hours to fly with the wind and $\frac{200}{200-w}$ hours to fly against the wind. If you add these two expressions, you get the total time for the round trip,

$$\frac{200}{200+w} + \frac{200}{200-w} = 2 + \frac{5}{60} \Rightarrow \frac{200 \cdot 400}{(200+w)(200-w)} = \frac{25}{12} \Rightarrow 200^2 - w^2 = (8)(400)(12) \Rightarrow w = \boxed{40.}$$

□

Problem 8.6.5. (*1 point*) A rectangular floor, 24 feet × 40 feet, is covered by squares of sides 1 foot. A chalk line is drawn from one corner to the diagonally opposite corner. How many tiles have a chalk line segment on them?

Solution. Since $\frac{24}{8} = 3$ and $\frac{40}{8} = 5$, consider instead the 3×5 rectangle on the left in the figure below. You can easily count that the diagonal crosses seven squares.

Now tile the 24×40 rectangle with 3×5 rectangles as in the righthand side of the figure. The diagonal of the 24×40 rectangle is also the diagonal of each of eight of the 3×5 rectangles. Therefore the diagonal crosses $7 \cdot 8 = \boxed{56}$ of the 1×1 squares. □

Problem 8.6.6. (*1 point*) How many eight-digit positive integers $abcdefgh$ are there that satisfy the relations

$$a^3 - b^2 = 2,\ c^3 - d^2 = 4,\ 2^e - f^2 = 7, g^3 - h^2 = -1.$$

Solution.

$$\begin{cases} 2 = 0^2 + 2 \le a^3 \le 9^2 + 2 = 83 \Rightarrow 2 \le a \le 4 \\ a^3 - 2 = b^2 \text{ is a perfect square } \Rightarrow a = 3, b = 5 \end{cases}$$

$$\begin{cases} 4 = 0^2 + 4 \le c^3 \le 9^2 + 4 = 85 \Rightarrow 2 \le c \le 4 \\ c^3 - 4 = d^2 \text{ is a perfect square } \Rightarrow c = 2, d = 3 \end{cases}$$

$$\begin{cases} 7 = 0^2 + 7 \le 2^e \le 9^2 + 7 = 88 \Rightarrow 3 \le e \le 6 \\ 2^e - 7 = f^2 \text{ is a perfect square } \Rightarrow (e, f) \in \{(3,1), (4,3), (5,5)\} \end{cases}$$

$$\begin{cases} -1 = 0^2 - 1 \le g^3 \le 9^2 - 1 = 80 \Rightarrow 0 \le g \le 4 \\ g^3 + 1 = h^2 \text{ is a perfect square } \Rightarrow (g, h) \in \{(0,1), (2,3)\} \end{cases}$$

Thus, there are $1 \cdot 1 \cdot 3 \cdot 2 = \boxed{6}$ such numbers

35 223 101, 35 224 301, 35 225 501, 35 223 123, 35 224 323, 35 225 523.

□

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Problem 8.6.7. (*1 point*) Determine the smallest possible value of $x+y$, if x and y are positive integers with

$$\frac{2022}{2023} < \frac{x}{y} < \frac{2023}{2024}.$$

Solution. Let $y = x + d$, then

$$1 - \frac{1}{2023} < \frac{y-d}{y} < 1 - \frac{1}{2024} \Rightarrow \frac{1}{2023} > \frac{d}{y} > \frac{1}{2024} \Rightarrow d > 1.$$

For $d = 2$, then

$$\frac{1}{2023} > \frac{2}{y} > \frac{1}{2024} \Rightarrow 2 \cdot 2024 > y > 2 \cdot 2 \cdot 2023 \Rightarrow y = 4047 \ (= 2 \cdot 2023 + 1) \Rightarrow x = 4045.$$

If $d > 2$, then $y > 3 \cdot 2023 \Rightarrow x > 3 \cdot 2022$, so $x + y > 12000$.

The requested value is $4047 + 4045 = \boxed{8092.}$ □

Problem 8.6.8. (*1 point*) ABC is an acute triangle, such that $AB = 5, BC = 6, CA = 7$. D, E, and F are the feet of the altitudes from A, B, and C, respectively. Let H be the orthocenter. The sum

$$\frac{AH}{AD} + \frac{BH}{BE} + \frac{CH}{CF}$$

is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $4m + 5n$.

Solution. Note that

$$\frac{AH}{AD} = 1 - \frac{HD}{AD} = 1 - \frac{[BHC]}{[ABC]}, \frac{BH}{BE} = 1 - \frac{[CHA]}{[ABC]}, \frac{CH}{CF} = 1 - \frac{[AHB]}{[ABC]} \quad \Rightarrow \frac{AH}{AD} + \frac{BH}{BE} + \frac{CH}{CF} = 2$$

Thus $4m + 5n = 4 \cdot 2 + 5 \cdot 1 = \boxed{13.}$ □

Problem 8.6.9. (*1 point*) An autobiographical number is a natural number with ten digits or less in which the first digit of the number (reading from left to right) tells you how many zeros are in the number, the second digit tells you how many 1's, the third digit tells you how many 2's, and so on. For example, 6 210 001 000 is an autobiographical number.

Find the smallest autobiographical number.

Solution. When you add the digits of an autobiographical number, you count the total number of digits. (For example the digits of the above 10 digit autobiographical number must sum to 10.) Using this fact and the process of elimination we can find the smallest autobiographical number.

The only possible one-digit number whose digits sum to 1 is 1 and it is not autobiographical so there are no one digit autobiographical numbers.

The only possible two digit numbers whose digits sum to two are (in increasing order) 11 and 20, and they are not autobiographical so there are no two digit autobiographical numbers.

The only possible three digit numbers whose digits sum to three are (in increasing order) 102, 111, 120, 201, 210, and 300, and they are not autobiographical so there are no three digit autobiographical numbers.

The possible four digit numbers whose digits sum to four are (in in- creasing order) 1003, 1012, 1021, 1030, 1102, 1111, 1120, 1201, ... It is easy to verify that the smallest autobiographical number is $\boxed{1210.}$ □

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Problem 8.6.10. (*1 point*) What is the sum of all integers less than 100 which have exactly 12 divisors?

Solution. Let's consider as different cases the possible numbers of prime factors which an integer could have.

Case 1: If it has one prime factor p, then to have 12 divisors it must be of the form p^{11}. But even for $p = 2$, p^{11} is much larger than 100, so there is no contribution from this case.

Case 2: If the number has two prime factors p and q, then we need to consider the ways of factoring 12 into two numbers: $2 \cdot 6$ and $3 \cdot 4$. Thus the number can be pq^5 or p^2q^3, decreasing the exponents by 1 as discussed in the text. Now p and q must be different. Trying $q = 2$, $p = 3$, pq^5 yields 96, a valid answer, and p^2q^3 yields $9 \cdot 8 = 72$, which is also fine. However, all other choices of p and q yield answers greater than 100, even letting $p = 2$, $q = 3$ (since q is taken to higher powers than p).

Case 3: If the number has three prime factors p, q, and r, then we need to consider only the one way of factoring 12 into three numbers which aren't 1: $2 \cdot 2 \cdot 3$. Thus the number will be of the form pqr^2. Here we have more possibilities, which we explore by trial and error.

Letting $r = 2$, $q = 3$, $p = 5$ gives $5 \cdot 3 \cdot 4 = 60$. Letting $r = 2$, $q = 3$, $p = 7$ gives 84. These two are the only possibilities with $r = 2$, since the next higher, $q = 5$ and $p = 7$, gives a result bigger than 100.

We then move on to $r = 3$; here the only solution which is small enough is $5 \cdot 2 \cdot 3^2 = 90$.

We have thus explored all the possible cases, and the sum of all the answers thus obtained is $96 + 72 + 60 + 84 + 90 = \boxed{402.}$ □

Problem 8.6.11. (*1 point*) The probability that a five-card poker hand has exactly two cards of the same value, but no other cards duplicated, is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. First we pick the number which will be duplicated; we can do this in $\binom{13}{1}$ ways.

Then we can pick two of the four cards of that number in $\binom{4}{2}$ ways.

To fill out the hand, we then need three cards, all of different number, so we can choose 3 of the remaining 12 numbers in $\binom{12}{3}$ ways, and for each can choose one of the four suits in $\binom{4}{1}$ ways. Then the total number of ways is given by

$$\binom{13}{1}\binom{4}{2}\binom{12}{3}\binom{4}{1}\binom{4}{1}\binom{4}{1}.$$

To find the probability, we need to divide this by the total number of ways to choose a poker hand. Since this is just picking 5 cards from a set of 52, the number is $\binom{52}{5}$.

The probability of getting a hand of the type we desire is the monstrous

$$\frac{\binom{13}{1}\binom{4}{2}\binom{12}{3}\binom{4}{1}\binom{4}{1}\binom{4}{1}}{\binom{52}{5}} = \frac{352}{833}$$

Hence, $m + n = 352 + 833 = \boxed{1185.}$. □

Problem 8.6.12. (*1 point*) Consider the sets of consecutive integers $S_1 = \{1\}$, $S_2 = \{2, 3\}$, $S_3 = \{4, 5, 6\}$, $S_4 = \{7, 8, 9, 10\}$, ..., where each set contains one more element than the preceding one, and where the first element of each set is one more than the last element of the preceding set. Let S_n be the sum of the elements in the nth set. Find S_{21}.

Solution. The number of elements of in $S_1, S_2, \ldots, S_{20}$ are $1, 2, \ldots, 20$, thus the last element in S_{20} is $1 + 2 + \ldots + 20 = \frac{20 \cdot 21}{2} = 210$. Therefore the first element of the 21st set is 211, and its last element is $210 + 21 = 231$. Thus the sum of its elements is

$$211 + 212 + 213 + \cdots + 231 = 21(210) + (1 + 2 + \cdots + 21) = 4410 + \frac{21 \cdot 22}{2} = 4410 + 231 = \boxed{4641.}$$

□

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Problem 8.6.13. (*1 point*) In the diagram, the curved paths are arcs of circles centered at vertices A and B of a square of side 6.

The area of the shaded section is $\frac{m}{n}\pi - p\sqrt{q}$, where m and n are relatively prime positive integers, p, q are positive integers and q is not divisible by any perfect square larger than 1. Find $m + n + p + q$.

Solution. We can find the desired area by subtracting sector DAB from the region bounded by $\widehat{AE}, \widehat{EB}$, and side AB.

To find the latter region, we draw EA and EB. The desired region is then the sum of the areas of circular segments AE and EB and the area of $\triangle ABE$. Since the sides of ABE are radii of length 6, the triangle is equilateral, and the two circular segments span $\frac{60^\circ}{360^\circ} = \frac{1}{6}$ of the circle.

Since the circular segment AE has area equal to sector EBA minus the area of $\triangle EAB$, its area is

$$\frac{6^2\pi}{6} - \frac{6^2\sqrt{3}}{4} = 6\pi - 9\sqrt{3}.$$

Thus the region enclosed by the two arcs and AB has area

$$2(6\pi - 9\sqrt{3}) + \frac{6^2\sqrt{3}}{4} = 12\pi - 9\sqrt{3}.$$

Since AD is part of the diagonal of the square, we find $\angle DAB = 45^\circ$ and sector DAB is $\frac{1}{8}$ of the circle. Thus the area of the sector is $\frac{6^2\pi}{8} = \frac{9\pi}{2}$.

Finally, the desired shaded area is

$$12\pi - 9\sqrt{3} - \frac{9\pi}{2} = \boxed{\frac{15}{2}\pi - 9\sqrt{3}}.$$

Hence, $m + n + p + q = 15 + 2 + 9 + 3 = \boxed{29.}$ □

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Problem 8.6.14. (*1 point*) Find $5a + 7b + 9c$ if nonzero a, b, and c satisfy the equations

$$\begin{cases} ab &= 2(a+b) \\ bc &= 3(b+c) \\ ca &= 4(c+a) \end{cases}$$

Solution. Generally, equations are easiest to attack if all the variables are on one side. Hence, we divide by the $(a+b)$ or the ab terms. Trying the former isn't promising (try and see), but the latter yields

$$\begin{cases} 1 = 2(\frac{1}{b} + \frac{1}{a}) \Rightarrow \frac{1}{a} + \frac{1}{b} = \frac{1}{2} \\ 1 = 3(\frac{1}{c} + \frac{1}{b}) \Rightarrow \frac{1}{b} + \frac{1}{c} = \frac{1}{3} \\ 1 = 4(\frac{1}{a} + \frac{1}{c}) \Rightarrow \frac{1}{c} + \frac{1}{a} = \frac{1}{4} \end{cases} \Rightarrow \frac{1}{a} + \frac{1}{b} + \frac{1}{c} = \frac{13}{24}$$

$$\Rightarrow \frac{1}{a} = \frac{13}{24} - \frac{1}{3} = \frac{5}{24} \Rightarrow a = \frac{24}{5}, b = \frac{24}{7}, c = 24.$$

Thus $5a + 7b + 9c = 5 \cdot \frac{24}{5} + 7 \cdot \frac{24}{7} + 9 \cdot 24 = \boxed{264.}$ □

Problem 8.6.15. (*1 point*) Consider the sets of consecutive integers $S_1 = \{1\}$, $S_2 = \{2, 3\}$, $S_3 = \{4, 5, 6\}$, $S_4 = \{7, 8, 9, 10\}$, ..., where each set contains one more element than the preceding one, and where the first element of each set is one more than the last element of the preceding set. Let S_n be the sum of the elements in the nth set. Find S_{51}.

Solution. The first element of the 51st set is one more than the last element of the 50th, which is $1 + 2 + 3 + \cdots + 50 = 1275$. Thus the first element of the 51st set is 1276, and its last element is $210 + 21 = 1326$. Thus the sum of its elements is

$$1276 + 1277 + \cdots + 1326 = 51(1275) + (1 + 2 + \cdots + 51) = \boxed{66\ 351.}$$

□

Problem 8.6.16. (*1 point*) In the figure PA is tangent to semicircle SAR. PB is tangent to semicircle RBT.SRT is a straight line. The arc measures (not lengths!) are indicated in the figure:

$$a = 122^\circ, b = 131^\circ, c = 58^\circ, d = 49^\circ.$$

Find $\angle APB$ in degrees.

Solution. Connect the points of tangency to the centers of the circles, points C and D, as shown.

Since $\angle PAC = \angle PBD = 90^\circ$, $\angle BDR = b$, and $\angle ACR = a$, we have $\angle APB = 540^\circ - 180^\circ - a - b$ from pentagon $APBDC$. Thus, $\angle APB = 360^\circ - a - b$. Since a and c together make a semi-circle, as do b and d, we have $a + b + c + d = 360^\circ$. Hence $a + b = 360^\circ - c - d$ and $\angle APB = c + d = 58 + 49 = \boxed{107^\circ}$. $\square$

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Problem 8.6.17. (*1 point*) The club has 85 students, each of whom plays on at least one of the sports teams: football, baseball, and volleyball. 74 students are on the football; 26 are on the baseball; and 17 are on both the football and volleyball teams; 18 are on both the baseball and football teams; and 13 are on both the baseball and volleyball teams. Compute the number of students playing all three sports, given that twice this number are members of the volleyball team.

Solution. Let F, B, and L be the sets of students who are on the football team, baseball team, and volleyball team, respectively. Let x be the number of students on all three teams. Then the number of students on the volleyball team is $2x$.

By Principle of Inclusion and Exclusion,

$$\#(F \cup B \cup L) = \#(F) + \#(B) + \#(L) - \#(F \cap B) - \#(F \cap L) - \#(B \cap L) + \#(F \cap B \cap L)$$

Substituting, we get $85 = 74 + 26 + 2x - 18 - 17 - 13 + x \Rightarrow 3x = 33 \Rightarrow x = \boxed{11.}$ □

Problem 8.6.18. (*1 point*) A ball of radius R is tangent to the floor and one wall of the room. The radius of the largest sphere that can be rolled through the space between the ball, the wall, and the floor, is $R(m - \sqrt{n})$, where m, n are positive integers. Find $m + n$.

Solution. To solve this, we consider the cross-section perpendicular to the wall and the floor and passing through the centers of both spheres when the smaller sphere is directly "under" the larger ball. Clearly, the largest such ball will be tangent to the larger ball, so in the diagram the two circles are tangent at H. We find the radius, r, of the smaller circle by finding AC in two different ways, first as a diagonal of square $ABCD$ and second as the sum $AG + GH + HC$:

$$AC = AG + GH + HC \Rightarrow R\sqrt{2} = r\sqrt{2} + r + R \Rightarrow r = \frac{R(\sqrt{2} - 1)}{\sqrt{2} + 1} = R(3 - 2\sqrt{2}) = R(3 - \sqrt{8}).$$

Hence, $m + n = 3 + 8 = \boxed{11.}$ □

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Problem 8.6.19. (*1 point*) Find the last three digits of 9^{2024}.

Solution. [Solution 1] Finding the last three digits of 9^{2024} is equivalent to evaluating $9^{2024} \pmod{1000}$. By the Binomial Theorem, we have

$$9^{2024} = (10-1)^{2024} == \binom{2024}{2024}10^{2024} - \binom{2024}{2023}10^{2023} + \cdots + \binom{2024}{2}10^2 - \binom{2024}{1}10^1 + \binom{2024}{0}.$$

Since $10^k \equiv 0 \pmod{1000}$ for $k \geq 3$, we need only look at the last three terms of the expression above.

$$\binom{2024}{2}10^2 = \frac{1}{2}(2024)(2023)(10^2) \equiv 600 \pmod{1000}$$
$$-\binom{2024}{1}10^1 = -20240 \equiv -240 \pmod{1000}, \ \binom{2024}{0} \equiv 1 \pmod{1000}$$

Thus $9^{2024} \equiv 600 - 240 + 1 = \boxed{361} \pmod{1000}$. □

Solution. [Solution 2] Note that $\phi(1000) = 400$, and $\gcd(9, 1000) = 1$ thus

$$9^{400} \equiv 1 \pmod{1000} \Rightarrow 9^{2024} \equiv 9^{24} \pmod{1000}$$
$$9^{24} \equiv (9^4)^6 \equiv 561^6 \equiv 481^2 \equiv \boxed{361} \pmod{1000}$$

□

Problem 8.6.20. (*1 point*) A coin is flipped 24 times in a row. Given that exactly 20 heads appeared, the probability that no two consecutive coin flips were both tails is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. Since all of the outcomes are equally likely, we can just count outcomes.

The number of ways that 20 heads appear is just $\binom{24}{20}$.

Now we count the number of ways that 20 heads can appear, such that no two tails occur on consecutive flips. Let H and T denote a head and a tail, respectively, and consider 20 Hs in a row. Then we can insert 4 Ts, where each T is inserted either between two Hs or at the ends of the row. The number of such ways of inserting 4 Ts is $\binom{20+1}{4} = \binom{21}{4}$.

Therefore, the probability is

$$\frac{\binom{21}{4}}{\binom{24}{20}} = \frac{285}{506}$$

Hence $m + n = 285 + 506 = \boxed{791.}$ □

8.7 High School - Test 6

You have **90 minutes** to complete the test. You have to **submit only the answers**. No solution is required.

Note that you have to **follow the instructions by the COs** *for submitting the answers.*

- **Intermediate (I) level: Problems 1-10**
- **Advanced (A) level: Problems 11-20**
- **Olympiad (O) level: Problems 21-30**

If you submit solution based on coding, please make sure that your submission is compliant. Read the introduction chapter for more information.

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Problem 8.7.1. (*1 point*) Joan has a collection of nickels, dimes, and quarters worth \$2.00. If the nickels were dimes and the dimes were nickels, the value of the coins would be \$1.70. Determine the largest possible number of the dimes.

Solution. Let n, d, and q be the numbers of nickels, dimes, and quarters. Then

$$\begin{cases} 5n + 10d + 25q &= 200 \\ 10n + 5d + 25q &= 170 \end{cases} \Rightarrow 5d - 5n = 30 \Rightarrow d = n + 6$$

$$\Rightarrow 5n + 10(n+6) + 25q = 200 \Rightarrow 15n + 25q = 140 \Rightarrow n = \frac{28 - 5q}{3}.$$

Since $n \geq 0$, thus $0 \leq q \leq 5$, by testing, $(n, q) \in \{(6, 2), (1, 5)\}$. Therefore $(n, d, q) \in \{(6, 12, 2), (1, 7, 5)\}$. The largest possible value of d is $\boxed{17.}$ □

Problem 8.7.2. (*1 point*) In rectangle $ABCD$, P is on side BC and Q is on side DC so that $BP = 1$, $AP = PQ = 2$, and $\angle APQ = 90°$. The length of QD is $\sqrt{m} - n$, where m and n are positive integers. Find $2m + 3n$.

Solution. In the diagram below,

$$\angle APQ = \angle ABP = \angle PCQ = 90°, \ AB = DC, \ AD = BC.$$

$AP = 2 = 2BP$, $\angle APB = 90°$, thus $\triangle APB$ is a 30-60-90 triangle. Thus $AB = \frac{AP\sqrt{3}}{2} = \sqrt{3}$, and $\angle APB = 60°$. Furthermore,

$$\angle QPC = 180° - \angle APQ - \angle APB = 180° - 90° - 60° = 30° \Rightarrow \triangle QPC \text{ is a } 30 - 60 - 90 \text{ triangle.}$$

Hence, $\angle PQC = 60°$, $QC = \frac{1}{2}PQ = 1$. Hence $QD = DC - QC = \sqrt{3} - 1$, $2m + 3n = 2 \cdot 3 + 3 \cdot 1 = \boxed{9.}$ □

Problem 8.7.3. (*1 point*) Determine the sum of all real numbers x such that:

$$\sqrt{2 + 4x - 2x^2} + \sqrt{6 + 6x - 3x^2} = x^2 - 2x + 6$$

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Solution. We have

$$\sqrt{2+4x-2x^2}+\sqrt{6+6x-3x^2}=\sqrt{4-2(x^2-2x+1)}+\sqrt{9-3(x^2-2x+1)}$$
$$\sqrt{4-2(x-1)^2}+\sqrt{9-3(x-1)^2}\le 2+3=5\le (x-1)^2+5=x^2-2x+6$$

Therefore $(x-1)^2=0$, or $x=1$. The desired sum is $\boxed{1.}$ □

Problem 8.7.4. (*1 point*) Temperature can be measured in degrees Fahrenheit (F) or in degrees Celsius (C). The two scales are related by the formula $F=1.8C+32$. When a two-digit integer degree temperature in Celsius is converted to Fahrenheit and rounded to the nearest integer degree, it turns out the ones and tens digits of the original Celsius temperature sometimes switch places to give the rounded Fahrenheit equivalent. Find the sum of all two-digit integer values of C for which this occurs.

Solution. Let $C=10a+b$, where $1\le a\le 9$, $0\le b\le 9$ are integers.

$$F=\frac{9}{5}C+32=18a+\frac{9}{5}b+32\Rightarrow 10b+a-\frac{1}{2}\le 18a+\frac{9}{5}b+32\le 10b+a+\frac{1}{2}$$
$$\Rightarrow 100b+10a-5\le 180a+18b+320<100b+10a+5\Rightarrow 315<82b-170a\le 325$$
$$b\le 9\Rightarrow 82b<738\Rightarrow 170a<82b-315<738-315=423\Rightarrow a\le 2$$

Case 1: $a=1$, then

$$315<82b-170\le 325\Rightarrow 5\frac{75}{82}<b\le 6\frac{3}{82}\Rightarrow b=6\Rightarrow C=16.$$

Case 2: $a=2$, then

$$315<82b-340\le 325\Rightarrow 7\frac{81}{82}<b\le 8\frac{9}{82}\Rightarrow b=8\Rightarrow C=28.$$

Hence, the desired sum is $16+28=\boxed{44.}$ □

Problem 8.7.5. (*1 point*) The positive odd integers are arranged in a triangular diagram as shown below. Find the sum of the numbers in the seventeenth row.

$$\begin{array}{cccc} & & & 1 \\ & & 3 & 5 \\ & 7 & 9 & 11 \\ 13 & 15 & \dots & \dots \end{array}$$

Solution. It is easy to see that there are n numbers on the nth, thus there are

$$1+2+\ldots+(n-1)=\frac{(n-1)n}{2}\text{ numbers in rows }1,2,\ldots,n-1.$$

Thus, the numbers in row n are n odd integers, starting with

$$2\left(\frac{(n-1)n}{2}\right)+1=(n-1)(n)+1.$$

Therefore the sum of the numbers in row n is

$$(n)\left[(n-1)(n)+1\right]+(0+2+\ldots+2(n-1))=n^2(n-1)+n+2\frac{(n-1)n}{2}=n^3.$$

Therefore the sum of the number in the seventeenth row is $17^3=\boxed{4913.}$ □

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Problem 8.7.6. (*1 point*) In the cyclic quadrilateral $ABCD$, $AB = 13, BC = 5, CA = 12$, diagonal AC bisects the angle DAB. The side AD is extended beyond D to a point E such that $CE = 12$. The length of AE is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution. First

$$\begin{cases} CE = CA \Rightarrow \angle CED = \angle CAD = \angle CAB \\ \angle CDE = 180^\circ - \angle CDA = 180^\circ - (180^\circ - \angle CBA) = \angle CBA \end{cases} \Rightarrow \triangle DCE \cong \triangle BCA \Rightarrow DE = AB = 13.$$

Let $\alpha = \angle BAC$, then since $AB^2 = BC^2 + CA^2$, so

$$\sin\alpha = \sin\angle BAC = \frac{BC}{BA} = \frac{5}{13} \Rightarrow \cos 2\alpha = 1 - 2(\sin\alpha)^2 = 1 - 2 \cdot \frac{25}{169} = \frac{119}{169}$$

It is easy to see that AB is the diameter, thus $\angle BDA = 90^\circ$, therefore

$$\cos 2\alpha = \cos\angle DAB = \frac{DA}{AB} \Rightarrow DA = \cos 2\alpha AB = \frac{119}{13}.$$

Hence

$$AE = 13 + \frac{119}{13} = \frac{288}{13} \Rightarrow m + n = 288 + 13 = \boxed{301.}$$

□

Problem 8.7.7. (*1 point*) Find the sum of all y numbers whereas x, y are positive integers satisfying

$$\frac{1}{x} - \frac{1}{y} = \frac{1}{12}.$$

Solution. Since both x, y are positive integers, so $\frac{1}{x} > \frac{1}{12}$, therefore $x < 12$

$$\frac{1}{x} - \frac{1}{y} = \frac{1}{12} \Rightarrow y = \frac{12x}{12 - x}.$$

By testing, it is easy to see that $(x, y) \in \{(3, 4), (4, 6), (6, 12), (8, 24), (9, 36), (10, 60), (11, 132)\}$.

The sum of all such y is $4 + 6 + 12 + 24 + 36 + 60 + 132 = \boxed{274.}$ □

Problem 8.7.8. (*1 point*) Find the maximum value of $(x^3 + 1)(y^3 + 1)$ if x and y are real numbers such that $x + y = 1$.

Solution. Let $p = xy$, then

$$(x^3 + 1)(y^3 + 1) = (xy)^3 + (x + y)^3 - 3xy(x + y) + 1 = p^3 - 3p + 2 = 4 + (p + 1)^2(p - 2).$$

Since $xy \le \frac{1}{4}(x + y)^2 = \frac{1}{4}$, thus $p - 2 < 0$. Therefore $4 + (p + 1)^2(p - 2) \le \boxed{4.}$

The expression reaches the maximum value of 4 when $xy = -1$, or $x, y = \frac{1 \pm \sqrt{5}}{2}$. □

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Problem 8.7.9. (*1 point*) Three squares are placed side-by-side inside a right-angled triangle as shown in the diagram. The side length of the smallest of the three squares is 16. The side length of the largest of the three squares is 36. What is the side length of the middle square?

Solution. Impose a coordinate system as in the figure. If the middle square has side length n, then the coordinates are as indicated. Since the slanted line passes through (0, 16), the equation of the line is $y = mx + 16$ for some slope, m.

Using the two other points yields

$$\begin{cases} n &= 16m + 16 \\ 36 &= m(16+n) + 16 \end{cases} \Rightarrow 36 = m(16 + 16m + 16) + 16 = 16m^2 + 32m + 16$$

$$\Rightarrow 16m^2 + 32m - 20 = 0 \Rightarrow 4(2m+5)(2m-1) = 0 \Rightarrow m = -\frac{5}{2}, \text{ or } m = \frac{1}{2}.$$

From the diagram, the slope is positive, thus $m = \frac{1}{2}$, thus $n = 16m + 16 = \boxed{24.}$ □

Problem 8.7.10. (*1 point*) Friends Maya and Naya ordered finger food in a restaurant, Maya ordering chicken wings and Naya ordering bite-size ribs. Each wing cost the same amount, and each rib cost the same amount, but one wing was more expensive than one rib. Maya received 20% more pieces than Naya did, and Maya paid 50% more in total than Naya did. The price of one wing was what percentage higher than the price of one rib?

Solution. Say Naya gets n pieces at $\$r$ each. Then Maya gets $1.2n$ pieces at, say, $\$w$ each. Then Naya pays $\$nr$ and Maya pays $\$1.2nw$. Since Maya pays 50% more than Naya,

$$1.2nw = 1.5nr \Rightarrow w = 1.5r = 1.25r.$$

one wing is $\boxed{25}$% expensive than one rib. □

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Problem 8.7.11. (*1 point*) The value of the sum

$$\sum_{k=1}^{2024} \sqrt{1 + \frac{1}{k^2} + \frac{1}{(k+1)^2}}$$

is $\frac{m}{n}$, where m and n are relatively prime positive integers. Find $m + n$.

Solution.

$$\left(1 + \frac{1}{k} - \frac{1}{k+1}\right)^2 = \left(1 + \frac{1}{k(k+1)}\right)^2 = 1 + \frac{2}{k(k+1)} + \frac{1}{k^2(k+1)^2}$$
$$\Rightarrow \left(1 + \frac{1}{k} - \frac{1}{k+1}\right)^2 - 1 - \frac{1}{k^2} - \frac{1}{(k+1)^2} = \frac{2k(k+1) + 1 - (k+1)^2 - k^2}{k^2(k+1)^2} = 0$$
$$\Rightarrow \sum_{k=1}^{2024} \sqrt{1 + \frac{1}{k^2} + \frac{1}{(k+1)^2}} = \sum_{k=1}^{2024} \left(1 + \frac{1}{k} - \frac{1}{k+1}\right) = 2024 + 1 - \frac{1}{2024+1} = \frac{2025^2 - 1}{2025}.$$

The requested sum is $2025^2 - 1 + 2025 = \boxed{4\ 102\ 649.}$ □

Problem 8.7.12. (*1 point*) Three cubes are stacked as shown. The cubes have edge lengths 1, 2, and 3. $m\sqrt{n}$ is the length of the portion of segment AB that is contained in the center cube, where m and n are positive integers and n is not divisible by any perfect square larger than 1. Find $5m + 2n$.

Solution. We find the length of AB as the hypotenuse of $\triangle ACB$. Since $AC = 1 + 2 + 3 = 6$ and $BC = 3\sqrt{2}$, we have $AB = \sqrt{36 + 18} = 3\sqrt{6}$. Just as $\frac{2}{1+2+3} = \frac{1}{3}$ of segment AC is in the cube of edge length 2, 1/3 of AB is in the middle cube. (Make sure you see why.) Thus the desired length is $\frac{1}{3}(3\sqrt{6}) = \sqrt{6}$.

Hence, $5m + 2n = 5 \cdot 1 + 2 \cdot 6 = \boxed{17.}$ □

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Problem 8.7.13. (*1 point*) E is an ellipse with the lengths of minor and major axis are 21 and 128. ABC is a triangle inscribed in E. The largest possible area of ABC is $m\sqrt{n}$ where m and n are positive integers and n is not divisible by any perfect square larger than 1. Find $m+n$

Solution. Dealing with inscribed figures in an ellipse can be pretty tricky, so we perform an orthogonal projection to map the ellipse to a circle with diameter 1. Let DEF be the triangle of maximum area inscribed in the circle and $\triangle ABC$ be the triangle inscribed in the ellipse whose projection is $\triangle DEF$. Since the ratio of areas is preserved, $\triangle ABC$ must be the largest possible triangle inscribed in the ellipse.

Now our problem is finding the maximum area of a triangle inscribed in a circle of diameter 1. This is just an equilateral triangle, which has area $[DEF] = \frac{3\sqrt{3}}{16}$. From the preservation of ratios, we have

$$\frac{[DEF]}{\text{Area of circle}} = \frac{[ABC]}{\text{Area of ellipse}}, \text{ where } \text{ Area of circle} = \pi\left(\frac{1}{2}\right)^2, \quad \text{Area of ellipse} = \pi(\frac{21}{2}\cdot\frac{128}{2})$$

$$\Rightarrow [ABC] = \frac{\pi(\frac{21}{2}\cdot\frac{128}{2})\cdot\frac{3\sqrt{3}}{16}}{\pi\left(\frac{1}{2}\right)^2} = 504\sqrt{3} \Rightarrow m+n = 504+3 = \boxed{507.}$$

□

Problem 8.7.14. (*1 point*) Consider triangle ABC with medians AD, BE, and CF. If the area of $\triangle ABC$ is 12, what is the area of the triangle $D'E'F'$, where D', E', and F' are the reflections of D, E, and F through A, B, and C respectively?

Solution. Let G be the centroid of ABC. Let $AD = 3x$. Then, $GD = x$, $AG = 2x$, $AD' = 3x$, and $GD' = 5x$.

Hence, D', E' and F' are dilations of D, E, and F with ratio -5, meaning that $GD' = 5(GD)$ and D' is on the other side of G from D.

Thus, $D'E'F'$ is homothetic to ABC (since $\triangle D'E'F' \sim \triangle DEF \sim \triangle ABC$ and lines through corresponding parts are concurrent) with center G and ratio $\frac{D'G}{AG} = \frac{5}{2}$.

Hence,

$$\frac{[D'E'F']}{[ABC]} = \left(\frac{5}{2}\right)^2 \Rightarrow [D'E'F'] = \boxed{75.}$$

□

Problem 8.7.15. (*1 point*) For every n the sum of the first n terms of an arithmetic progression is $2n+3n^2$. What is the 2024th term of the sequence?

Solution. Let a be the first term and d be the common difference. The sum of the first n terms is always

$$a + (a+d) + \cdots + (a+(n-1)d) = na + \frac{(n-1)n}{2}d = (n)\left(a - \frac{d}{2}\right) + (n^2)\frac{d}{2}$$

$$(n)\left(a - \frac{d}{2}\right) + (n^2)\frac{d}{2} = 2n + 3d^2, \ \forall n \Rightarrow \begin{cases} a - \frac{d}{2} & = 2 \\ \frac{d}{2} & = 3 \end{cases}$$

$$\Rightarrow a = 5, d = 6 \Rightarrow a + (2024-1)d = 5 + (2023)6 = \boxed{12\ 143.}$$

□

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Problem 8.7.16. (*1 point*) How many 7-digit numbers, written in decimal notation, have at least one 1, one 2, and one 3 among their digits?

Solution. Let S_1, S_2, and S_3 be the sets of 7-digit numbers that do not contain the digits 1, 2, and 3, respectively. Then by Principle of Inclusion - Exclusion, the number of 7-digit numbers that are missing at least one of the digits 1, 2, or 3 is

$$\#(S_1 \cup S_2 \cup S_3) = \#(S_1) + \#(S_2) + \#(S_3) - \#(S_1 \cap S_2) - \#(S_1 \cap S_3) - \#(S_2 \cap S_3) + \#(S_1 \cap S_2 \cap S_3).$$

First we count $\#(S_1)$, the number of 7-digit numbers that do not contain the digit 1. The first digit has 8 possible values (2 through 9), and each of the remaining 6 digits has 9 possible values, so $\#(S_1) = 8 \cdot 9^6$. Similarly, $\#(S_2) = \#(S_3) = 8 \cdot 9^6$.

Next we count $\#(S_1 \cap S_2)$, the number of 7-digit numbers that do not contain the digit 1 or 2. The first digit has 7 possible values (3 through 9), and each of the remaining 6 digits has 8 possible values, so $\#(S_1 \cap S_2) = 7 \cdot 8^6$. Similarly,

$$\#(S_1 \cap S_3) = \#(S_2 \cap S_3) = 7 \cdot 8^6.$$

Finally, we count $\#(S_1 \cap S_2 \cap S_3)$, the number of 7-digit numbers that do not contain the digits 1, 2, or 3. The first digit has 6 possible values (4 through 9), and each of the remaining 6 digits has 7 possible values, so $\#(S_1 \cap S_2 \cap S_3) = 6 \cdot 7^6$.

Therefore,

$$\#(S_1 \cup S_2 \cup S_3) = 3 \cdot 8 \cdot 9^6 - 3 \cdot 7 \cdot 8^6 + 6 \cdot 7^6 = 7\ 955\ 454.$$

There are a total of $9 \cdot 10^6 = 9\ 000\ 000$ 6-digit numbers, so there are $9\ 000\ 000 - 7\ 955\ 454 = \boxed{1\ 044\ 546}$ 7-digit numbers that have at least one 1, one 2, and one 3. □

Problem 8.7.17. (*1 point*) The equation $x^4 - 16x^3 + 94x^2 + px + q = 0$ has two double roots. Find $(p+q)^2$.

Solution. Let the doubled roots be r and s. From the coefficient of x^3, we have $2r + 2s = 16$, or $r + s = 8$. From the coefficient of x^2 we find $r^2 + s^2 + 4rs = 94$. Since

$$p = -(2r^2s + 2rs^2) = -2rs(r+s)$$

and $q = r^2s^2$, if we find rs and $r+s$, we find p and q. We already have $r+s$, and we can find rs by squaring $r + s = 8$ to get $r^2 + 2rs + s^2 = 64$.

Subtracting this from $r^2 + s^2 + 4rs = 94$, we find $2rs = 30$, so $rs = 15$. Hence, $p = -30(8) = -240$ and $q = 15^2 = 225$, so $(p+q)^2 = (-15)^2 = \boxed{225.}$ □

Problem 8.7.18. (*1 point*) Find the volume of the region in space defined by $|x+y+z| + |x+y-z| \le 12$, where x, y, $z \ge 0$.

Solution. Let $a = x + y$. Thus, we have $|a+z| + |a-z| \le 12$. Since $|b| + |c| \ge b + c$ for all b and c, we have $12 \ge |a+z| + |a-z| \ge 2a$. Thus, we have $a = x + y \le 6$. Similarly, we have

$$12 \ge |a+z| + |a-z| \ge (a+z) - (a-z) = 2z \Rightarrow z \le 6 \Rightarrow 0 \le x+y \le 6, 0 \le z \le 6.$$

Thus, we have a right prism whose base is a right triangle (bounded by the line $x + y = 6$ and the x, y axes) and whose height is 6. The vertices of our triangle are $(0,0)$, $(6,0)$, and $(0,6)$. Hence the area of the triangle is $6\frac{6}{2} = 18$ and our volume is (base area)(height)$= (18)(3) = \boxed{54.}$ □

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Problem 8.7.19. (*1 point*) Triangle ABC has side lengths $AB = 6, AC = 5$, and $BC = 4$. A point P in the interior of $\triangle ABC$ is a distance x from BC, a distance y from AC, and a distance z from AB.

If $x^2 + y^2 + z^2 = \dfrac{225}{44}$, then $x = \frac{m\sqrt{p}}{n}$, where m and n are relatively prime positive integers, and p is a positive integer not divisible by any perfect square larger than 1. Find $m + n + p$.

Solution. From Heron's formula and in terms of the sides we have:

$$\frac{1}{2}(ax + by + cz) = [ABC] = \frac{15\sqrt{7}}{4}$$

Seeing this sum of products and the given sum of squares, we write out Cauchy's Inequality:

$$(a^2 + b^2 + c^2)(x^2 + y^2 + z^2) \geq (ax + by + cz)^2.$$

Using all of the given information on the sides, the area, and the sum $x^2 + y^2 + z^2$, we find that the left and the right sides of the above expression are equal. Thus, the equality condition for Cauchy'ss Inequality must hold, or $\frac{a}{x} = \frac{b}{y} = \frac{c}{z}$. Writing y and z in terms of x and using $x^2 + y^2 + z^2 = \dfrac{225}{44}$, we find $x = \frac{30\sqrt{7}}{77}$.

Hence $m + n + p = 30 + 7 + 77 = \boxed{114.}$ □

Problem 8.7.20. (*1 point*) In how many ways can a 3×12 rectangle be tiled with tiles of size 1×2?

Solution. Let a_n denote the number of ways to tile a $3 \times n$ rectangle.

First note that if n is odd, then it is impossible to tile: the total number of squares in the rectangle is odd, but each tile covers 2 squares. So $a_n = 0$ if n is odd.

If n is even, then look at the left column of our $3 \times n$ rectangle. If we tile it with 3 horizontal tiles, then what's left is a $3 \times (n-2)$ rectangle that can be tiled in a_{n-2} ways. Otherwise, we must use one vertical tile and one horizontal tile. This leaves two untiled spaces in the 2nd column.

If we tile them with a single vertical tile, then what's left is a $3 \times (n-2)$ rectangle. If not, then we tile them with 2 horizontal tiles. After placing another horizontal tile (in the remaining row), we're again left with 2 untiled squares in the left column.

If we tile them with a single vertical tile, then what's left is a $3 \times (n-4)$ rectangle; if not, we repeat and we again get back to 2 untiled squares in the left column.

This gives the recurrence relation

$$a_n = a_{n-2} + 2(a_{n-2} + a_{n-4} + \cdots + a_2 + a_0),$$

where the factor of 2 comes from the fact that a vertical tile can be placed in the initial column in 2 different ways. Noting that $a_0 = 1$, we compute:

$$\begin{aligned}
a_2 &= a_0 + 2a_0 = 3a_0 = 3,\\
a_4 &= a_2 + 2(a_2 + a_0) = 3 + 2(3 + 1) = 11,\\
a_6 &= a_4 + 2(a_4 + a_2 + a_0) = 11 + 2(11 + 3 + 1) = 41,\\
a_8 &= a_6 + 2(a_6 + a_4 + a_2 + a_0) = 41 + 2(41 + 11 + 3 + 1) = 153\\
a_{10} &= a_8 + 2(a_8 + a_6 + a_4 + a_2 + a_0) = 153 + 2(153 + 41 + 11 + 3 + 1) = 571\\
a_{12} &= a_{10} + 2(a_{10} + a_8 + a_6 + a_4 + a_2 + a_0) = 571 + 2(571 + 153 + 41 + 11 + 3 + 1) = \boxed{2131.}
\end{aligned}$$

□

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Problem 8.7.21. (*1 point*) If $f\left(\frac{x}{x-1}\right) = \frac{1}{x}$ for all $x \neq 0, 1$ and $0 < \theta < \frac{\pi}{2}$, then evaluate

$$\frac{f(\sec^2(\theta))}{\sin^2(\theta)}.$$

Solution. We write $\sec^2(\theta) = \frac{x}{x-1}$, yielding

$$x = \frac{\sec^2(\theta)}{\sec^2(\theta) - 1} = \frac{\sec^2(\theta)}{\tan^2(\theta)} = \frac{1}{\sin^2(\theta)}.$$

Thus

$$f(\sec^2(\theta)) = f(\frac{x}{x-1}) = \frac{1}{x} = \frac{1}{\frac{1}{\sin^2(\theta)}} = \sin^2(\theta) \Rightarrow \frac{f(\sec^2(\theta))}{\sin^2(\theta)} = \boxed{1.}$$

□

Problem 8.7.22. (*1 point*) Find the sum of all pq where p, q are primes such that $p^2 + 5pq + 4q^2$ is a square of an integer.

Solution.

$$p^2 + 5pq + 4q^2 = a^2 \Rightarrow q \mid (a+p)(a-p) \Rightarrow a = qk - p \text{ or } a = qk + p$$

Case 1: $a = qk - p$

$$p^2 + 5pq + 4q^2 = q^2k^2 - 2qpk + p^2 \Rightarrow q(k-2)(k+2) = p(2k+5) \Rightarrow p = q \text{ or } p \mid k-2 \text{ or } p \mid k+2$$

Case 1a: $p = q$, so $a^2 = 10p^2$, impossible.

Case 1b: $p \mid k-2$, so $k+2 \mid 2k+5 \Rightarrow k+2 \mid 1$, so $k = -1$ or $k = -3$. It is easy to verify that there is no solution.

Case 1c: $p \mid k+2$, so $k-2 \mid 2k+5 \Rightarrow k-2 \mid 9$, so $k \in \{-7, -1, 1, 3, 5, 11\}$. It is easy to verify that $(p, q) = (5, 11), (7, 5), (13, 3)$ are solutions.

Case b: $a = qk + p$

$$p^2 + 5pq + 4q^2 = q^2k^2 + 2qpk + p^2 \Rightarrow q(k-2)(k+2) = p(5-2k) \Rightarrow p = q \text{ or } p \mid k-2 \text{ or } p \mid k+2$$

In similar ways as above, we obtain the same three solutions.

Thus the answer is $5 \cdot 11 + 7 \cdot 5 + 13 \cdot 3 = \boxed{129.}$ □

Problem 8.7.23. (*1 point*) Consider a sequence $\{G_n\}$ with $G_{k+1} = G_k + 2G_{k-1}$ for $k \geq 1$, with $G_0 = 0$ and $G_1 = 1$. Find $\lfloor \log_{256}(3G_{2024} + 1) \rfloor$.

Solution. We write $G_n = ar^n + bs^n$. In order that this sequence satisfy the relation $G_{n+1} = G_n + 2G_{n-1}$, we must have

$$ar^{n+1} + bs^{n+1} = ar^n + bs^n + 2ar^{n-1} + 2bs^{n-1} \Rightarrow ar^{n-1}(r^2 - r - 2) = -bs^{n-1}(s^2 - s - 2)$$

Assuming $r \neq s$, this can only be satisfied if both r and s satisfy $x^2 - x - 2 = 0$, which by the quadratic formula has solutions $r = 2$ and $s = -1$. We then use $G_0 = 0$ and $G_1 = 1$ to write $a + b = 0$ and $ar + bs = 2a - b = 1$; solving the system gives $a = \frac{1}{3}$ and $b = -\frac{1}{3}$.

Thus,

$$G_n = \frac{1}{3}2^n - \frac{1}{3}(-1)^n \Rightarrow 3G_{2024} = 2^{2024} - 1 \Rightarrow 3G_{2024} + 1 = (2^8)^{253} = 256^{253} \Rightarrow \log_{256}(3G_{2024} + 1) = \boxed{253.}$$

□

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Problem 8.7.24. (*1 point*) Let $ABCD$ be a convex quadrilateral such that $AB+BC=2021$ and $AD=CD$. We are also given that $\angle ABC=\angle CDA=90^o$.

The length of the diagonal BD is $\frac{m\sqrt{p}}{n}$, where m and n are relatively prime positive integers, and p is a positive integer not divisible by any perfect square larger than 1. Find $m+n+p$.

Solution. Since two opposite of angles of quadrilateral $ABCD$ sum up to $180°$, we know that it is cyclic. By Ptolemy's Theorem, we have $BD\cdot AC=AB\cdot CD+AD\cdot BC$. We know that $\triangle ADC$ is an isosceles right triangle as $AD=CD$ and $\angle ADC=90°$, so $AC=\sqrt{2}AD$. Substituting AD for CD and AC we get $BD\cdot(\sqrt{2}AD)=AD\cdot(AB+BC)$ and cancelling out AD we are left with $\sqrt{2}BD=AB+BC=2021$. Thus BD $=\frac{2021}{\sqrt{2}}=\frac{2021\sqrt{2}}{2}$.

Hence, $m+n+p=2021+2+2=\boxed{2025.}$ □

Problem 8.7.25. (*1 point*) a, b, c, d are the solutions of the equation $x^4-38x-3=0$. Let $P(x)$ be the polynomial with leading coefficient 3 whose roots are

$$\frac{a+b+c}{d^2},\ \frac{a+b+d}{c^2},\ \frac{a+c+d}{b^2},\ \text{and}\ \frac{b+c+d}{a^2}.$$

Find $P(13)$

Solution. From the coefficient of x^3, $a+b+c+d=0$, so $a+b+c=-d$, and $\frac{a+b+c}{d^2}=-\frac{1}{d}$.

Proceeding similarly, the roots of the desired polynomial are $-\frac{1}{a}$, $-\frac{1}{b}$, $-\frac{1}{c}$, and $-\frac{1}{d}$.

The polynomial with roots $\frac{1}{a}$, $\frac{1}{b}$, $\frac{1}{c}$, and $\frac{1}{d}$ is found by reversing the coefficients of the original polynomial, to get $-3x^4-38x^3+1=0$.

The equation which has roots which are c times those of $f(x)=-3x^4-38x^3+1$ is $f(\frac{x}{c})$. Hence, one polynomial with the given roots is $f(-x)=-3x^4+38x^3+1$; we want the leading term to be 3, so we multiply by -1, giving

$$P(x)=3x^4-38x^3-1\Rightarrow P(13)=3(13)^4-38(13)^3-1=\boxed{2196.}$$

□

Problem 8.7.26. (*1 point*) Let $A=\{1,2,3,\ldots,16\}$. Find the number of subsets B of A, such that if the sum of two elements of A is a power of 2 then exactly one of them belong to B.

Solution. We solve a generic problem with $A=\{1,2,3,\ldots,2^n\}$, where $n\geq 2$. Let $\mathcal{B}_n$ be the collection of all admissible subsets B then

$$\mathcal{B}_2=\{\{1\},\{1,2\},\{1,2,4\},\{1,4\},\{2,3\},\{2,3,4\},\{3\},\{3,4\}\}\Rightarrow|\mathcal{B}_2|=8.$$

Consider a bipartite graph with two sets of nodes $\mathcal{B}_n$ and $\mathcal{B}_{n+1}$, where a node $B\in\mathcal{B}_n$ is adjacent to a node $B'\in\mathcal{B}_{n+1}$ if and only if $B\subset B'$.

For $2^n+1\leq k\leq 2^{n+1}-1$ we have $k\in B'$ if and only if $k-2^n\in B$. Thus, the elements of B' except 2^{n+1} are uniquely determined from B, whereas 2^{n+1} may or may not be a member of B'. Therefore, each node in $\mathcal{B}_n$ has degree 2, while each node in $\mathcal{B}_{n+1}$ has degree 1, hence $|\mathcal{B}_{n+1}|=2|\mathcal{B}_n|$.

From $|\mathcal{B}_2|=8$, and by the recurrance $|\mathcal{B}_{n+1}|=2|\mathcal{B}_n|$, it follows that $\mathcal{B}_n=2^{n+1}$.

Thus $\mathcal{B}_4=2^5=\boxed{32.}$ □

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Problem 8.7.27. (*1 point*) A mouse stands at the corner A of a regular ABCD tetrahedron. In a move, the mouse can choose an edge going out from the corner where he stands and move to a different corner. He repeats until he goes back to A. In how many ways can he can end up at A after 8 moves?

Solution. Let s_k be the number of ways he can get back to A after k moves starting from A and t_k be the number of ways to get to A in k moves starting from another vertex. Since from A vertex, our next move takes us to any of 3 other vertices, we have

$$s_k = 3t_{k-1}$$

or 3 times the number of ways he can get back to A in $k-1$ moves. From B, C, D, vertices, the mouse can go straight to A or to 2 other vertices, so we find

$$t_k = s_{k-1} + 2t_{k-1}.$$

Clearly $s_1 = 0$ and $t_1 = 1$, so we can repeatedly use our recursions to solve compute them as below:

iteration	s	t
1	0	1
2	3	2
3	6	7
4	21	20
5	60	61
6	183	182
7	546	547
8	1641	1640

Hence, the answer is $\boxed{1641.}$ □

Problem 8.7.28. (*1 point*) Two circles are internally tangent. Their radii are 1 and 3. A triangle is formed with one vertex on each circle (not at the tangent point) and the third at the tangent point. The maximum area of such a triangle is $\frac{m\sqrt{p}}{n}$, where m and n are relatively prime positive integers, and p is a positive integer not divisible by any perfect square larger than 1. Find $m+n+p$..

Solution. Extend side AD of a triangle which fits the description of the problem to point B on the larger circle.

Since $\triangle ABC$ and $\triangle ADC$ share an altitude, $\frac{[ADC]}{[ABC]} = \frac{AD}{AB}$. Since the two circles are homothetic with center A, $\frac{AD}{AB} = \frac{1}{3}$.

Finally, we see that by maximizing $[ABC]$, we maximize $[ADC]$. The maximum area of a circle inscribed in a circle of radius 3 is equilateral and has side length $3\sqrt{3}$, so its area is $\frac{27\sqrt{3}}{4}$. Thus, the maximum value of $[ADC]$ is $\frac{9\sqrt{3}}{4}$.

Hence, $m+n+n = 9+3+4 = \boxed{16.}$ □

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Problem 8.7.29. (*1 point*) In how many ways can we choose 4 vertices of a convex 17-gon to form a convex quadrilateral, such that at least 1 side of the quadrilateral is a side of the 17-gon?

Solution. We first count how many quadrilaterals have a particular side of the 17-gon as one of its sides. Once we have a side of the 17-gon, we need to choose 2 of the remaining $17 - 2 = 15$ vertices to complete the quadrilateral (we can't choose the two vertices that are the endpoints of our already existing side). So there are $\binom{15}{2}$ such quadrilaterals. Since there are 17 sides of the 17-gon that we could have started with, this gives us an initial count of $17\binom{15}{2}$.

This initial count, however, overcounts those quadrilaterals that have 2 or more of its sides as sides of the original 17-gon, so we have to correct for this. There are essentially two cases to consider for quadrilaterals with 2 sides on the original 17-gon: its 2 sides (on the original 17-gon) are either consecutive or nonconsecutive.

We can pick two consecutive sides in 17 ways. This gives 3 vertices of our quadrilateral. Then, we have to choose a fourth vertex, which we can do in $17 - 3 = 14$ ways. Thus there are a total of $17(14)$ quadrilaterals of this type.

Alternatively, we can pick two nonconsecutive sides: we have 17 choices for the first side, then 14 choices for the second non-adjacent side. We then divide by 2 since this counts every pair of non-adjacent sides twice, once in each order. Therefore we have $\frac{1}{2}(17)(14)$ pairs of non-adjacent sides. This gives us all 4 vertices of the quadrilateral, so there are no more choices to be made.

Thus, adding these two cases, we see that there are

$$17(14) + \frac{1}{2}(17)(14) = \frac{3}{2}(17)(14)$$

such quadrilaterals. These quadrilaterals are counted twice in our original count, so we need to subtract them once.

Finally, any quadrilateral with 3 sides on the original 17-gon must have all 3 of those sides adjacent (otherwise we use up too many vertices). There are n of these quadrilaterals, since there are 17 choices for the middle of the three adjacent sides on the 17-gon. These quadrilaterals are counted 3 times in our original count (once for each side on the original 17-gon), but are subtracted 3 times in our count of quadrilaterals with 2 sides on the 17-gon (once for each pair of sides on the original 17-gon). So we need to add these back once.

hus the number of quadrilaterals is

$$17\binom{15}{2} - \frac{3}{2}(17)(14) + 17 = \boxed{1445.}$$

□

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Problem 8.7.30. (*1 point*) A bottle in the shape of a cone lies on its base. Water is poured into the bottle until its level reaches a distance of 8 centimeters from the vertex of the cone (measured vertically). We now turn the bottle upside down without changing the amount of water it contains. This leaves an empty space in the upper part of the cone that is 2 centimeters high.

The height of the bottle is $m + \sqrt{n}$, where m and n are positive integers, and n is not divisible by any perfect square larger than 1. Find $m + n$

Solution. Let h, r be the height and the radius in centimeters of the bottle, respectively. The volume of the bottle is $\frac{h \cdot \pi r^2}{3}$. When the bottle lies on its base, the volume occupied by the water is obtained by subtracting the volume of the cone we get cutting the bottle with a plane parallel to its base 24 centimeters under the vertex to the volume of the bottle itself.

That cone that we obtain is similar to the bottle and the ratio between their elements is $8 : h$. Therefore the volume of the water, in this case, is given by

$$\frac{h \cdot \pi r^2}{3} - \frac{24 \cdot \pi(\frac{2}{4}hr)^2}{3} \quad (*)$$

When the bottle is upside down, the volume of the water is just the volume of the cone we get cutting the bottle with a plane parallel to the base 2 centimeters above the vertex. Since that cone is similar to the bottle with a ratio $(h-2) : h$, the volume of the water, in this case, is given by

$$\frac{h \cdot \pi(\frac{h-2}{h}r)^2}{3} \quad (**)$$

Since the volume of the water doesn't change when it lies on its base or it's turned upside down, we consider the equations (*) and (**) to be the same. After some simplifications, we end up with $h^2 - 2h - 84 = 0$, hence $h = 1 + \sqrt{85}$.

Hence, $m + n = 1 + 85 = \boxed{86.}$ □

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Chapter 9

Club Championships

9.1 Club Championship Individual - Test 1

Rules:

You have **60 minutes** to complete the test. You can submit **the answers, partial-, or full solutions**. Each submission is graded accordingly.

- A correct answer is worth of maximum 1 point.
- A partial solution is worth at most 5 points.
- A full solution is worth 10 points.

Important: if a problem has several questions, students must solve the questions in the order of encounter. Students earn **no points** when solving a later question without an early one.

For example in the following problem, students must solve (i), (ii), and (iii). The student earn no point by solving (ii) or (iii) without (i).

Problem. a, b, c are integers, are consecutive integers. $a + b + c$ is an odd integer.

(*1 point*) (i) Prove that one of a, b, c is odd.

(*1 point*) (ii)Prove that only one of the products ab, bc, and ca is odd.

(*1 point*) (iii) Prove that abc is divisible by 24.

Note that you have to **follow the instructions by the COs** *for submitting the answers.*

- **Pre-Algebra (PA) level: Problems 1-4**
- **Introductory Curriculum (IC) level: Problems 5-8**
- **Intermediate (I) level: Problems 9-12**
- **Advanced (A) level: Problems 13-16**
- **Olympiad (O) level: Problems 17-20**

No coding solution is accepted.

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Important: Read the rules before proceed!

Problem 9.1.1. (*10 points*) How many odd numbers with middle digit 5 are there between 40000 and 69999 inclusive, with no digits repeated?

Problem 9.1.2. (*10 points*) Adult tickets to a football game were \$3.25 and student tickets were \$1.75. If 1350 fans paid a total of \$2700 to attend the game, how many adults attended?

Problem 9.1.3. (*1 point*) ABC is an isosceles triangle such that $AC = BC$. CBD is an isosceles triangle such that $CB = DB$. BD meets AC at a right angle. If $\angle A = 57°$, what is $\angle D$?

Problem 9.1.4. (*10 points*) On an island, the natives are either knights, who always tell the truth, or liars, who always lie.

Alice and Bob were chatting

Alice: We are both liars, and this is the island of Maya.

Bob: That is true.

Is this the island of Maya? Explain.

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Important: Read the rules before proceed!

Problem 9.1.5. (*10 points*) Alice, Bob, Carol, and Denis were detained for questioning. They were suspected of stealing cookies. Inspector Erica established the following facts:

- (1) If both Alice and Bob are guilty, then Carol was an accomplice
- (2) If Alice is guilty, then at least one of Bob, Carol was an accomplice.
- (3) If Carol is guilty, then Denis was an accomplice
- (4) If Alice is innocent, then Denis is guilty.

Which ones are **definitely** guilty and which ones are doubtful?

Problem 9.1.6. (*10 points*) Circle A, circle B, and circle C are externally tangent. $BC = a, AC = b$, and $AB = c$, Express the radius of circle A in terms of a, b, c.

Problem 9.1.7. (*10 points*) Find the 1275th term of the sequence 1, 3, 5,..., 15, 1, 3, 5,..., 15, 1, ...

Problem 9.1.8. (*10 points*) The tens digit of a two-digit number exceeds its units digit by 4. The number exceeds twice the number obtained by reversing the digits of the original number by 10. What is the original number?

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Important: Read the rules before proceed!

Problem 9.1.9. a, b are positive integers. None of $a, b, a-b$ is a multiple of 3.

(*2 points*) Prove that $a+b$ is a multiple of 3.

(*3 points*) Prove that a^3+b^3 is a multiple of 9.

Solution. Since a, b are not multiple of 3, thus their remainders when divided by 3 is ± 1. In addition $a-b$ is not a multiple of 3, thus WLOG assum that the remainders of a, b when divided by 3 is $+1, -1$, respectively. Then there exist m, n positive integers such that $a = 3m+1$, $b = 3n-1$.

For the first question, $a+b = 3(m+n)$ is a multiple of 3.

For the second question,

$$a^3+b^3 = (3m+1)^3+(3n-1)^3 = (3m+1+3n-1)((3m+1)^2-(3m+1)(3n-1)+(3n-1)^2)$$
$$= 9(m+n)(3m^2-3mn+3m+3n^2-3n+1) \text{ is a multiple of 9.}$$

□

Problem 9.1.10. x, y are real numbers such that $x^2+xy+y = 2$.

(*5 points*) Find the largest value of x^2-xy+y^2

(*5 points*) Find the smallest value of x^2-xy+y^2

> **Remark.** The problem text has a typo. The given condition must be $x^2+xy+y^2 = 2$.

Solution. For the first question,

$$x^2-xy+y^2 = 3(x^2+xy+y)-2(x+y)^2 = 6-2(x+y)^2 \leq 6.$$

x^2-xy+y^2 reaches the largest value of $\boxed{6}$ when:

$$\begin{cases} x^2+xy+y^2 = 2 \\ x+y = 0 \end{cases} \Rightarrow x^2+x(-x)+(-x)^2 = 2 \Rightarrow x = \pm\sqrt{2}, y = \mp\sqrt{2}$$

For the second question,

$$x^2-xy+y^2 = \frac{1}{3}(x^2+xy+y^2)+\frac{2}{3}(x-y)^2 = 2+\frac{2}{3}(x-y)^2 \leq 2.$$

x^2-xy+y^2 reaches the smallest value of $\boxed{2}$ when:

$$\begin{cases} x^2+xy+y^2 = 2 \\ x-y = 0 \end{cases} \Rightarrow x^2+x(x)+(x)^2 = 2 \Rightarrow x = \pm\sqrt{\frac{2}{3}}, y = \pm\sqrt{\frac{2}{3}}.$$

□

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Problem 9.1.11. Diagonal AC and BD of quadrilateral $ABCD$ meet at E. If $AE = 2, BE = 5, CE = 10, DE = 4$, and $BC = \frac{15}{2}$.

(*1 point*) Prove that $\triangle AED \sim \triangle BEC$ is cyclic.

(*3 points*) Prove that $ABCD$ is cyclic.

(*6 points*) Find AB.

Remark. The problem text has a typo. The first question has an extra phrase *"is cyclic"* at the end.

Solution. In the diagram below,

$$\frac{EB}{EA} = \frac{EC}{ED} = \frac{5}{2} \Rightarrow \triangle AED \sim \triangle BEC$$

$\triangle AED \sim \triangle BEC$, so $\angle BDA = \angle EDA = \angle ECB = \angle ACB$, thus $ABCD$ is cyclic.

Furthermore

$$\frac{AD}{BC} = \frac{EA}{EB} = \frac{2}{5} \Rightarrow AD = BC\frac{2}{5} = 3.$$

In similar way, $\triangle AEB \sim \triangle DEA$ and $\frac{DC}{AB} = \frac{ED}{EA} = 2$.

By Ptolemy Theorem

$$AC \cdot BD = AB \cdot CD + AD \cdot BC \Rightarrow 12 \cdot 9 = 2(AB)^2 + 3 \cdot \frac{15}{2} \Rightarrow AB = \boxed{\frac{3\sqrt{19}}{2}.}$$

□

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Problem 9.1.12. (*1 point*) If (x_1, x_2) is a permutation of $(1, 2)$, find the largest value of

$$|x_1 - 1| + |x_2 - 2|$$

(*1 point*) If (x_1, x_2, x_3) is a permutation of $(1, 2, 3)$, find the largest value of

$$|x_1 - 1| + |x_2 - 2| + |x_3 - 3|$$

(*8 points*) If $(x_1, x_2, \ldots, x_n)$ is a permutation of $(1, 2, \ldots, n)$, find the largest value of

$$|x_1 - 1| + |x_2 - 2| + \cdots + |x_n - n|$$

Solution. For the first question, it is easy to see that $(x_1, x_2) = (2, 1)$ achieves the largest value of 2.

For the second question, it is easy to see that $(x_1, x_2, x_3) = (3, 2, 1)$ achieves the largest value of 4.

Thus, for the third question, we notice that the smaller the number is subtracted from, the greater is the result. We consider two cases.

Case $n = 2k$:

$$S = |x_1 - 1| + |x_2 - 2| + \cdots + |x_n - n| = (2k - 1) + (2k - 3) + \cdots + 1 + 1 + \cdots + (2k - 1) + (2k - 3)$$
$$= 2(1 + 3 + \cdots + (2k - 1)) = k^2 = \boxed{\frac{1}{2}n^2}$$

Case $n = 2k + 1$:

$$S = |x_1 - 1| + |x_2 - 2| + \cdots + |x_n - n| = (2k) + (2k - 2) + \cdots + 2 + 0 + 2 + \cdots + (2k - 2) + (2k)$$
$$= 4(1 + 2 + \cdots + k) = 2k(k + 1) = \frac{1}{2}((2k + 1)^2 - 1) = \boxed{\frac{1}{2}(n^2 - 1)}$$

□

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Important: Read the rules before proceed!

Problem 9.1.13. Consider the following inequation:

$$\sqrt{x-\frac{1}{x}}-\sqrt{1-\frac{1}{x}}>\frac{x-1}{x}.$$

(*1 point*) Prove that $x=1$ is not a solution.

(*3 points*) Prove that if x is a solution then $x>1$ or $-1\leq x<0$.

(*6 points*) Find all solutions.

Solution. If $x=1$, then

$$\sqrt{x-\frac{1}{x}}=0,\ \sqrt{1-\frac{1}{x}}=0,\ \frac{x-1}{x}=0 \text{ thus the inequality does not stand.}$$

Now, for the existence of the inequality

$$\begin{aligned}
&x\neq 0,\ x-\frac{1}{x}\geq 0,\ 1-\frac{1}{x}\geq 0\\
&1-\frac{1}{x}\geq 0\Rightarrow 1\geq\frac{1}{x}\Rightarrow x<0 \text{ or } x>1\\
&x-\frac{1}{x}\geq 0\Rightarrow (x+1)\left(\frac{x-1}{x}\right)\geq 0\Rightarrow -1\leq x<0 \text{ or } x>1
\end{aligned}$$

For x such that $-1\leq x<0$, or $x>1$:

$$\begin{aligned}
&\sqrt{x-\frac{1}{x}}-\sqrt{1-\frac{1}{x}}=\sqrt{\frac{x-1}{x}}(\sqrt{x+1}-1)\\
&\Rightarrow \sqrt{x+1}>1+\sqrt{\frac{x-1}{x}}
\end{aligned}$$

For $-1\leq x<0$ $0\leq\sqrt{x+1}<1$ thus the inequality cannot stand.

For $x>1$, by squaring both sides:

$$x+1>1+\frac{x-1}{x}+2\sqrt{\frac{x-1}{x}}\Leftrightarrow (x-1)+\frac{1}{x}>2\sqrt{\frac{x-1}{x}}.$$

By AM-GM

$$(x-1)+\frac{1}{x}\geq 2\sqrt{(x-1)\cdot\frac{1}{x}}=2\sqrt{\frac{x-1}{x}}$$

thus the strict inequality always stands except when $x-1=\frac{1}{x}$, or $x=\frac{1+\sqrt{5}}{2}$.

Thus, the solution is $x\in\boxed{(1,+\infty)\setminus\{\frac{1+\sqrt{5}}{2}\}.}$ □

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Problem 9.1.14. Let $M = \{1, 2, \ldots, 2005\}$. Let A be a subset of M. It is known that for any $i, j \in A$, $(i \neq j)$, there is exactly one isosceles triangle with side lengths i, j.

(*1 point*) What are the side lengths of a isosceles triangle if two of its side lengths are i, j, if $i < j$?

(*1 point*) If $i, j, k \in A$, $(i < j < k)$ prove that $i < 4k$.

(*8 points*) What is the maximum number of elements of A?

> **Remark.** The problem text has a typo. The second question requires to prove that $4i < k$.

Solution. For the first question, if an isosceles triangle has two side lengths a and b then there are two possible triangles with side lengths (a, b, b) or (a, a, b). The first one always occur if $a < b$. The second one cannot occur if $2a < b$.

Thus if $i, j \in A, i < j$, then $2i < j$.

It is easy to see for the second question that if $i, j, k \in A$, $(i < j < k)$ prove that $4i < 2j < k$.

For the last question, if A contains n elements $a_1 < a_2 < \ldots\ a_n$, then

$$2005 \geq a_n > 2a_{n-1} > \cdots > 2^{n-2}a_2 > 2^{n-1}a_1 \geq 2^{n-1} \Rightarrow n \leq 11.$$

The subset $\{1, 2, \ldots, 1024\}$ having 11 elements satisfies the requirements.

Thus, the maximum number of elements of A is $\boxed{11.}$ □

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Problem 9.1.15. Let ℓ be a straight line. A, B, C, and P are distinct points on ℓ.

Let O_1, O_2, and O_3 be the circumcircles of triangles PAB, PBC, and PCA, respectively.

(*3 points*) Prove that $\angle AO_1P = \angle CO_2P$

(*7 points*) Prove that P, O_1, O_2 and O_3 are concyclic (they are on the same circle).

Remark. The problem text has a typo. P is a point not on ℓ.

Solution. The diagram below shows a configuration for the points and their circles.

Note that

$$\angle AO_1P = \ (minor)\ \widehat{AP} = 360^\circ - \ (major)\ \widehat{AP} = 360^\circ - 2\angle ABP = 2(180^\circ - \angle ABP) = 2\angle PBC = \angle PO_2C$$

Now $\angle O_3O_1P = \frac{1}{2}\angle AO_1P = \frac{1}{2}\angle PO_2C = 180^\circ - \angle O_3O_2P$, thus P, O_1, O_2 and O_3 are $\boxed{concyclic.}$ $\square$

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Problem 9.1.16. a, b, c, d are positive integers such that $ab = cd$.

(*3 points*) Simplify

$$\frac{(a+c)(a+d)}{a+b+c+d}$$

(*7 points*) Prove that $a+b+c+d$ is not a prime.

Solution. For the first question,

$$\begin{aligned}
&a+d = a+\frac{ab}{c} = \frac{a(b+c)}{c} \Rightarrow (a+c)(a+d) = \frac{(a+c)a(b+c)}{c} \\
&a+b+c+d = a+b+c+\frac{ab}{c} = \frac{a(b+c)}{c} + (b+c) = \frac{(b+c)(a+c)}{c} \\
&\Rightarrow \frac{(a+c)(a+d)}{a+b+c+d} = a
\end{aligned}$$

For the second question, let

$$\frac{a}{c} = \frac{d}{b} = \frac{m}{n}, \text{ where } \gcd(m,n) = 1.$$

This means that there exist u, v positive integers (not necessarily larger than 1), such that

$$\left.\begin{aligned} a = mu, c = nu \\ d = mv, b = nv \end{aligned}\right\} \Rightarrow a+b+c+d = (m+n)(u+v)$$

Since $m+n, u+v \geq 2$, so $\boxed{a+b+c+d \text{ cannot be a prime.}}$ □

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Important: Read the rules before proceed!

Problem 9.1.17. Let $ABCD$ be a convex quadrilateral with an incircle. Let ω_1, ω_2, ω_3, and ω_4 be the excirles of $ABCD$ tangent to segments AB, BC, CD, and DA, respectively.

(*5 points*) Let r_1, r_2, r_3, and r_4 be the radius of ω_1, ω_2, ω_3, and ω_4. Prove that

$$r_1 r_3 = r_2 r_4.$$

(*5 points*) Prove that the lengths of the internal common tangent segments to the pairs of circles (ω_1, ω_3) and (ω_2, ω_4) are equal.

Solution. Let I, r, and s be the incenter, inradius, and semi-perimeter of $ABCD$. Let I_i, r_i be the center and radius of ω_i $(i = 1..4)$ Label the points as shown in the diagram below.

First,

$$\triangle JI_1A \sim \triangle HAI \Rightarrow \frac{JI_1}{AJ} = \frac{HA}{IH} \Rightarrow r_1 = \frac{AH \cdot BE}{r} \Rightarrow r_3 = \frac{CF \cdot DG}{r}$$

It is easy to see that

$$AJ = AS = BE = BF,\ AH = AE = BS$$
$$DH = DG = CD,\ DK = DT = CG = CF.$$

Therefore

$$r_1 r_3 = \frac{AH \cdot BE \cdot CF \cdot DG}{r^2} = \frac{AE \cdot BF \cdot CG \cdot DH}{r^2} = r_2 r_4 \Rightarrow \boxed{r_1 r_3 = r_2 r_4}$$

For the second question, since $\triangle PXI_1 \sim \triangle I_2YP$, thus:

$$\frac{PX}{XI_1} = \frac{I_3Y}{YP} \Rightarrow PX \cdot PY = r_1 r_3$$
Similarly $QX \cdot QY = r_1 r_3$
$\Rightarrow PX(PQ - QY) = (PQ - PX)QY \Rightarrow PX = QY$
$\Rightarrow PX + PY = QX + QY = QJ + QK = JK = s$

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This means that both PX, QY are the smaller root of the quadratic polynomial:

$$x^2 - sx + r_1r_3 = x^2 - sx + r_2r_4.$$

Therefore $XY = XQ - QY = JK - 2QK = s - 2QY$, which should be $\boxed{thesame}$ as the length of the internal common tangent segment to the pair of circle (ω_2, ω_4). □

Problem 9.1.18. Let a, b, c be positive real numbers such that $a + b + c = 3$. Prove that

(*2 points*)

$$ab + bc + ca \le \sqrt{a} + \sqrt{b} + \sqrt{c}.$$

(*3 points*)

$$\frac{a}{a+5c} + \frac{b}{b+5a} + \frac{c}{c+5b} \ge \frac{1}{2}.$$

(*5 points*)

$$\frac{a}{b(a+5c)^2} + \frac{b}{c(b+5a)^2} + \frac{c}{a(c+5b)^2} \ge \frac{1}{4(\sqrt{a}+\sqrt{b}+\sqrt{c})}.$$

Solution. For the first question, by AM-GM inequality:

$$\begin{aligned}
&a^2 + \sqrt{a} + \sqrt{a} \ge 3\sqrt[3]{a^2 \cdot \sqrt{a} \cdot \sqrt{a}} = 3a,\ b^2 + \sqrt{b} + \sqrt{b} \ge 3b,\ c^2 + \sqrt{cb} + \sqrt{c} \ge 3c,\\
&\Rightarrow a^2 + b^2 + c^2 + 2(\sqrt{a} + \sqrt{b} + \sqrt{c}) \ge 3(a+b+c) = (a+b+c)^2\\
&\Rightarrow \sqrt{a} + \sqrt{b} + \sqrt{c} \ge ab + bc + ca.
\end{aligned}$$

For the second question, by Cauchy-Schwartz inequality

$$\begin{aligned}
&\left(\frac{a}{a+5c} + \frac{b}{b+5a} + \frac{c}{c+5b}\right)(a(a+5c) + b(b+5a) + c(c+5b))\\
&\ge \left(\sqrt{\frac{a}{a+5c}} \cdot \sqrt{a(a+5c)} + \sqrt{\frac{b}{b+5a}} \cdot \sqrt{b(b+5a)} + \sqrt{\frac{c}{c+5b}} \cdot \sqrt{c(c+5b)}\right)^2 = (a+b+c)^2
\end{aligned}$$

Since

$$\begin{aligned}
&a(a+5c) + b(b+5a) + c(c+5b) = (a+b+c)^2 + 3(ab+bc+ca) \le 2(a+b+c)^2\\
&\Rightarrow \frac{a}{a+5c} + \frac{b}{b+5a} + \frac{c}{c+5b} \ge \frac{(a+b+c)^2}{2(a+b+c)^2} = \frac{1}{2}.
\end{aligned}$$

Now, by Cauchy-Schwartz inequality, then results of the previous question:

$$\begin{aligned}
S &= \frac{a}{b(a+5c)^2} + \frac{b}{c(b+5a)^2} + \frac{c}{a(c+5b)^2} = \frac{a^2}{ab(a+5c)^2} + \frac{b^2}{bc(b+5a)^2} + \frac{c^2}{ca(c+5b)^2}\\
&\ge \frac{\left(\frac{a}{a+5c} + \frac{b}{b+5a} + \frac{c}{c+5b}\right)^2}{ab+bc+ca} \ge \frac{\left(\frac{1}{2}\right)^2}{ab+bc+ca} \ge \frac{1}{4(\sqrt{a}+\sqrt{b}+\sqrt{c})}.
\end{aligned}$$

□

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Problem 9.1.19. Let n be a positive integer. Let a, b be odd positive integers.

(*3 points*) Find all integer triples $(x.y, z)$ such that $x^3 = 2y^3 + 4z^3$.

(*7 points*) Find all integer pairs (m, n) such that

$$\text{each of } 6(m+1)(n-1),\ (m-1)(n+1)+6,\ (m+2)(n-2) \text{ is a perfect cube.}$$

Solution. The first question is a classic example of application of *Infinite descent* or *Extremal Principle*. First, it is easy to see that $\boxed{(0,0,0)}$ is a solution.

Let's assume that there is (x, y, z) integer triple that $x^3 = 2y^3 + 4z^3$, and $|x| + |y| + |z| > 0$. Among all the triples, let assume that (x, y, z) has the smallest value for $|x| + |y| + |z|$.

Then since $x^3 = 2y^3 + 4z^3$, thus x is even, so there exists x_1 such that $x = 2x_1$,

$$\begin{aligned}
&x^3 = (2x_1)^3 = 2y^3 + 4z^3 \Rightarrow 4x_1^3 = y^3 + 2z^3 \\
&\Rightarrow 2 \mid y \Rightarrow \exists y_1 \in \mathbb{Z}:\ y = 2y_1,\ 4x_1^3 = (2y_1)^3 + 2z^3 \Rightarrow 2x_1^3 = 4y_1^3 + z^3 \\
&\Rightarrow 2 \mid z \Rightarrow \exists z_1 \in \mathbb{Z}:\ z = 2z_1,\ x_1^3 = 2y_1^3 + 4z_1^3
\end{aligned}$$

Now (x, y, z) is a triple satisfying the given equation and $|x_1|+|y_1|+|z_1| = \frac{1}{2}(|x| + |y| + |z|) < |x|+|y|+|z|$. This contradicts that (x, y, z) has the smallest value for $|x| + |y| + |z|$.

Thus, there is no such triple (x, y, z).

For the second question, let

$$\left.\begin{aligned}
a^3 &= 6(m+1)(n-1) \\
b^3 &= (m-1)(n+1)+6 \\
c^3 &= (m+2)(n-2)
\end{aligned}\right\} \Rightarrow a^3 = 2b^3 + 4c^3$$

From the first question, there $(a, b, c) = (0, 0, 0)$, thus from $c = 0$, we have $m = -2$ or $n = 2$.

Case 1: $m = -2$ then

$$\left.\begin{aligned}
&a^3 = 0 = 6(m+1)(n-1) = 6(-1)(n-1) \Rightarrow n = 1 \\
&\text{Test: } b^3 = (m-1)(n+1)+6 = (-3)(2)+6 = 0
\end{aligned}\right\} \Rightarrow (m, b) = \boxed{(-2, 1).}$$

Case 2: $n = 2$ then

$$\left.\begin{aligned}
&a^3 = 0 = 6(m+1)(n-1) = 6(m+1)(1) \Rightarrow m = -1 \\
&\text{Test: } b^3 = (m-1)(n+1)+6 = (-2)(3)+6 = 0
\end{aligned}\right\} \Rightarrow (m, b) = \boxed{(-1, 2).}$$

□

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Problem 9.1.20. (*2 points*) Find all pairs of positive integers such that $|n^2 - m^3| = 1$.

(*8 points*) For any two number sets A and B, define their sum and difference as

$$A + B = \{a + b \mid a \in A \text{ and } b \in B\},\ A - B = \{a - b \mid a \in A \text{ and } b \in B\},$$

Let $P = \{2, 3, 5, \ldots\}$ be the set of primes and

$$S = \{0, 1, 8, 16, 27, 64, 81, 125, 216, 256, \ldots\} \text{ be the set of perfect cubes and fourth powers.}$$

Let n be positive integer such that $n \equiv 3 \pmod{7 \cdot 103}$,

Prove that $64n^{12} \notin (P + S) \cup (P - S) \cup (S - P)$.

Solution. For the first question, to earn maximum number of points, it is enough to submit the answers

Case 1a: $n^2 - m^3 = -1$, then $n^2 = m^3 - 1$. There are one positive integer solution for this case $(n, m) = \boxed{(3, 2).}$ Note that for *integer solutions*, we have $(m, n) = (1, 0)$.

Case 1b: $n^2 - m^3 = 1$, there is no positive integer solutions for this case. Note that the *integer solutions* for this case are $(m, n) \in \{(2, \pm 3), (0, \pm 1)\}$.

Read the remark below for an advanced solution.

For the second question, let assume the contrary that

$$\exists n \equiv 3 \pmod{7 \cdot 103} :\ 64n^{12} \in (P + S) \cup (P - S) \cup (S - P).$$

Then $\exists m \in \mathbb{Z}^+$, such that one of $a - m^3$, $a - m^4$, $a + m^3$, $a + m^4$, $m^3 - a$, and $m^4 - a$ is a prime.

Note the following identities:

$$\begin{cases} u^3 - v^3 = (u - v)(u^2 + uv + v^2) \\ u^4 - v^4 = (u^2 - v^2)(u^2 + v^2) \\ 4u^4 + v^4 = (2u^2 + 2uv + v^2)(2u^2 - 2uv + v^2) \end{cases}$$

Since of the following is a prime:

$$\begin{cases} |64n^{12} - m^3| = |4n^4 - m|(16n^8 + 4n^4m + m^2) \\ |64n^{12} - m^4| = |8n^6 - m^2|(8n^6 + m^2) \\ 64n^{12} + m^3 = (4n^4 + m)(16n^8 - 4n^4m + m^2) \\ 64n^{12} + m^4 = (8n^8 + 4n^3m + m^2)(8n^8 - 4n^3m + m^2) \end{cases}$$

This means that one of the factors on the right of the four equations should be 1. Now

$$\begin{aligned} &8n^6 + m^2 > 8n^6 > 1, 4n^4 + m > 4n^4 > 1 \\ &16n^8 + 4n^4m + m^2 > 16n^8 - 4n^4m + m^2 > 12n^8 > 1 \\ &8n^8 + 4n^3m + m^2 > 8n^8 - 4n^3m + m^2 > 4n^6 > 1 \end{aligned}$$

Therefore $4n^4 - m = \pm 1$ or $m^2 = 8n^6 \pm 1$.

Case 2a: $4n^4 - m = 1$, then

$$\begin{aligned} &16n^8 + 4n^4m + m^2 = 48n^8 \pm 12n^4 + 1 \text{ is a prime.} \\ &n \equiv 3 \pmod 7 \Rightarrow 48n^8 - 12n^4 + 1 \equiv 5 - 6 + 1 \equiv 0 \pmod 7 \\ &n \equiv 3 \pmod{103} \Rightarrow 48n^8 - 12n^4 + 1 \equiv 57 - 58 + 1 \equiv 0 \pmod{103} \end{aligned}$$

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Case 2b: $4n^4 - m = -1$, then similarly $16n^8 - 4n^4m + m^2 \equiv 0 \pmod{7 \cdot 13}$.

Case 2c: $m^2 = 8n^6 \pm 1$, By the first question, the only possible positive integer solution for $m^2 = (2n^2)^3 \pm 1$, is $(m, 2n^2) = (3, 2)$, or $n = 1$. but then $n \not\equiv 3 \pmod{7 \cdot 103}$, contradiction.

Hence, $64n^{12} \notin (P + S) \cup (P - S) \cup (S - P)$. □

Remark. Below, we show a solution based on Gauss-integers $\mathbb{Z}[i]$, using complex numbers. Note that for any $a + bi \in \mathbb{Z}[i]$, the norm of $a + bi$, $N(a + bi) = a^2 + b^2$.

Case a: $n^2 - m^3 = -1$: or $m^3 = n^2 + 1$. It is easy to see that m even leads to $n^2 + 1 \equiv 0 \pmod 8$, which is impossible. Thus m is odd and n is even. Now,

$$m^3 = n^2 + 1 \Leftrightarrow m^3 = (n + i)(n - i), \text{ where} i = \sqrt{-1}$$

Let d a common divisor in $\mathbb{Z}[i]$, then $d \mid (n + i) - (n - i) = 2i$, Thus $N(d)$, the norm of d in $\mathbb{Z}[i]$, divides $N(2i) = 4$. Also $N(d) \mid N(y + i) = n^2 + 1 = m^3$, which is odd, thus $N(d)$ is odd. Hence $N(d) = 1$, so d is a unit. Thus $n + i$ and $n - i$ are relatively prime. Thus, there exist $a, b \in \mathbb{Z}$:

$$n + i = (a + bi)^3 \Rightarrow n = a^3 - 3ab^2 = a(a^2 - 3b^2),\ 1 = 3a^2b - b^3 = b(3a^2 - b^2).$$

From the second equation, $b = \pm 1$. If $b = 1$, then $1 = 3a^2 - 1$, impossible. If $b = -1$, then $1 = -(3a^2 - 1)$, or $a = 0$, so $n = 0$, $m = 1$.

The only integer solution is $(m, n) = \boxed{(1, 0)}$.

Case b: $n^2 - m^3 = 1$, then $m^3 = n^2 - 1 = (n - 1)(n + 1)$. If n is even, then both $n - 1, n + 1$ are odd, thus relatively primes. Since their product is a perfect cube, thus their are both (negative or positive) cubes. So there exist integer a, b, such that:

$$n + 1 = a^3, n - 1 = b^3 \Rightarrow a^3 - b^3 = 2 \Rightarrow (a - b)(a^2 + ab + b^2) = 2 \Rightarrow a - b = 1 \text{ or } 2$$
$$a - b = 1 \Rightarrow a^2 + ab + b^2 = (b + 1)^2 + (b + 1)b + b^2 = 3b^2 + 3b + 1 \text{ is odd } \neq 2$$
$$a - b = 2 \Rightarrow a^2 + ab + b^2 = (b + 2)^2 + (b + 2)b + b^2 = 3b^2 + 6b + 4 = 1 \Rightarrow b = -1, a = 1 \Rightarrow (m, n) = \boxed{(-1, 0)}$$

If n is odd, then m is even. Then $n - 1, n + 1$ are consecutive even number. Thus $n \equiv 1$ or $3 \pmod 4$. Since (m, n) is a solution then $(m, -n)$ is also a solution. Thus, WLOG, $n \equiv 1 \pmod 4$.

$$\left(\frac{m}{2}\right)^3 = \frac{n - 1}{4} \cdot \frac{n + 1}{2}$$

Now, $\gcd\left(\frac{n-1}{2}, \frac{n+1}{2}\right) = 1$, their product is a cube, thus each of them is a cube.

$$\frac{n + 1}{2} = a^3, \frac{n - 1}{4} = b^3 \Rightarrow a^3 - 2b^3 = 1.$$

The result of a rather complex proof lead to $(a, b) \in \{(1, 0), (-1, -1)\}$ are the two solutions for $a^3 - 2b^3 = 1$. Then the integer solutions for (m, n) are $\boxed{(2, \pm 3), (0, \pm 1).}$

9.2 Club Championship Team - Test 1

Rules:

You have **60 minutes** to solve **10** problems. Both Middle School and High School Teams solve the same problems. Any team member can choose any problem to work on. Several students can work on the same problem. However for each problem the whole team can submit a single answer. No individual answer is allowed.

The students can use any book, calculator, computer. The students can chat, talk, or use any mean of communications. They can sit next to each other if that is convenient.

No searching on the Internet is allowed. Nobody outside of the team can provide help.

Read carefully what submission (a number, a list of answers, a formula, a diagram, etc) is required by a problem. Each team submit a **single** image, pdf/excel file, or online spreadsheet containing the answers. It is the team responsibility that the answers are readable without any ambiguity. The submission must be done in time (within 60 minutes) and as instructed by the COs.

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Important: Read the rules before proceed!

Problem 9.2.1. (*10 points*) ABC is a right triangle, $\angle ACB = 90°$. D and E are points on AB such that $AD = DE = EB$. Furthermore $CD = 7, CE = 6$. What is the length of AB?

Solution. Let F and G be the feet of the perpendiculars from E and D to BC and AC, respectively. Let $AG = x, BF = y$.

It is easy to see that $\triangle AGD \sim \triangle ACB$, $\triangle BFE \sim \triangle BCA$. Furthermore $AD = \frac{1}{2}DB, BE = \frac{1}{2}EA$, thus $CG = 2x, CF = 2y, DG = y, EF = x$. By Pythagorean Theorem for $\triangle CDG$ and $\triangle CFE$:

$$\left.\begin{aligned} 7^2 &= y^2 + (2x)^2 \\ 6^2 &= x^2 + (2y)^2 \end{aligned}\right\} \Rightarrow 85 = 5(x^2 + y^2) \Rightarrow x^2 + y^2 = 17 \Rightarrow AB = 3BE = 3\sqrt{x^2 + y^2} = \boxed{3\sqrt{17}.}$$

□

Problem 9.2.2. (*10 points*) In the Forest of Forgetfulness, the Lion lies on Mondays, Tuesdays, and Wednesdays and tells the truth on the other days of the week. On what days of the week is it possible for the Lion to make the following statement: *I lied yesterday and I will lie again tomorrow*?

Solution. Let consider two cases.

Case 1: Today Lion tells the truth. Then today is such a day when she tells the truth between two lying days. It is impossible.

Case 2: Today, the Lion lies, then what she said was lies. It is important to note that the statement "A and B" is true if both are true, but it is false if at least one is false. There are three possibilities.

Case 2a: The statement *I lied yesterday* is false and *I will lie again tomorrow* is false, too. Thus today is such a day when she lies between two truth-telling days. It is impossible since the Lion tells the truth on Thursday, Fridays, Saturdays, and Sundays,

Case 2b: The statement *I lied yesterday* is false and *I will lie again tomorrow* is true. Thus yesterday she told the truth, today she lies, and tomorrow she will lie again. Therefore yesterday is Sunday, today is $\boxed{\text{Monday,}}$ and tomorrow is Tuesday.

Case 2c: The statement *I lied yesterday* is true and *I will lie again tomorrow* is false. Thus yesterday she lied, today she lies, and tomorrow she will tell the truth. Therefore yesterday is Tuesday, today is $\boxed{\text{Wednesday,}}$ and tomorrow is Thursday. □

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Problem 9.2.3. (*10 points*) Find all distinct rectangular prisms with integer side lengths having the same volume of 36. For example $(33, 1, 1)$ is such a prism.

Note that $(33, 1, 1)$ *and* $(1, 33, 1)$ *are considered the same.*

Solution. Let $a \geq b \geq c$ be the side lengths of the prism. Then $abc = 36$. It is easy to see that

$$a^3 \geq abc = 36 \Rightarrow a \geq 4,\ a \mid 36 \Rightarrow a \in \{4, 6, 9, 12, 18, 36\}.$$

Working case by case for $bc = \frac{36}{a}$, we can obtain 8 different prisms:

$$\boxed{(4,3,3),\ (6,3,2),\ (6,6,1),\ (9,2,2),\ (9,4,1),\ (12,3,1),\ (18,2,1),\ (36,1,1).}$$

□

Problem 9.2.4. A red bug sits at a vertex of a tetrahedron. At each step, she chooses an *unvisited* edge that leads from where she is to an *unvisited* vertex, then crawls along the edge to that vertex. She *stops* when all vertices are visited. The vertices and edges that she visited in this way form *a path*. It is easy to see that there is a number of different paths that she can crawl in order to visit all the vertices.

A blue bug is doing the same with a cube.

(*3 points*) How many distinct paths the red bug can crawl?

(*7 points*) How many distinct paths the blue bug can crawl?

Solution. For the red bug, she has 4 choices of starting vertex A, from A she has 3 choices of the next one B, then 2 choices to the next one C, then one choice for D. All together $4! = \boxed{24.}$

For a cube, the blue bug can craw two edges from a starting vertex and still stays on the same face. Now, she can choose to stay on the same face or move to a new face.

If she choose to stay on the same face, she will have a single choice to move along an edge, then two choices to visit the rest of the vertices. If she choose move out of the face, she will have a single choice to visit the rest of the vertices.

So with each of our six options for the initial two moves there are three more options for how to finish the bug walk. This means that there are $6 \cdot 3 = 18$ path from a vertex. Since there are 6 vertices, so there are $6 \cdot 18 = \boxed{108}$ ways. □

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Problem 9.2.5. (*10 points*) a, b are integers such that $x^2 + x - 1$ is a factor of $x^3 + 4x^2 + ax + b$. What is the value of $a + 10b$.

Solution. If $x^2 + x - 1$ is a factor of $P(x) = x^3 + 4x^2 + ax + b$, then $P(x)$ should have a first degree factor $cx + d$. By the coefficient of x^3 in $P(x)$ that $c = 1$, similarly $d = -b$, thus

$$\begin{aligned}
&(x^2 + x - 1)(x - b) = x^3 + 4x^2 + ax + b \\
&\Rightarrow x^3 + (1 - b)x^2 + (-1 - b)x + b = x^3 + 4x^2 + ax + b \\
&\Rightarrow 1 - b = 4, -1 - b = a \Rightarrow b = -3, a = 2 \Rightarrow P(x) = x^3 + 4x^2 + 2x - 3.
\end{aligned}$$

Hence, $a + 10b = 2 + 10(-3) = \boxed{-28.}$ □

Problem 9.2.6. (*10 points*) In $\triangle ABC$ $AB = 2AC$. p is the perimeter of $\triangle ABC$. m, n are positive integers such that $m - n = 2$, and

$$\frac{p}{m} < AC < \frac{p}{n}.$$

What is the value of $m + n$?

Solution. Since $AB = 2AC$, so $AC = AB - AC < BC$, thus AC is the shortest side. Therefore,

$$\begin{aligned}
&AB + BC + CA > 2AC + AC + AC = 4AC \Rightarrow AC < \frac{p}{4}. \\
&AB + BC + CA < 2AC + (AB + AC) + AC < 6AC \Rightarrow \frac{p}{6} < AC. \\
&m = 6, n = 4 \Rightarrow m + n = \boxed{10}.
\end{aligned}$$

□

Problem 9.2.7. (*10 points*) S is a set of positive integers relatively prime to 105. What is the 9999990th smallest element of S?

Solution. The number of multiples of $3, 5$, or 7 smaller than $105 = 3 \cdot 5 \cdot 7$ is

$$\left\lfloor \frac{105}{3} \right\rfloor + \left\lfloor \frac{105}{5} \right\rfloor + \left\lfloor \frac{105}{7} \right\rfloor - \left(\left\lfloor \frac{105}{15} \right\rfloor + \left\lfloor \frac{105}{21} \right\rfloor + \left\lfloor \frac{105}{35} \right\rfloor \right) + \left\lfloor \frac{105}{105} \right\rfloor = 57.$$

Thus, the number of positive integers less than 105 and relatively prime to 105 is $105 - 57 = 48$. Therefore the first 48 elements of the sequence of positive integers relatively prime to 105, $\{a_i\}$ are:

$$a_1 = 1, a_2 = 2, a_3 = 4, a_4 = 8, a_5 = 11, a_6 = 13, \ldots, a_{48} = 104.$$

It implies that

$$\begin{aligned}
&a_{49} = 105 + 1, a_{50} = 105 + 2, a_{51} = 105 + 4, \ldots, a_{96} = 105 + 104 = 209 \\
&a_{48n+1} = 105n + 1, a_{48n+2} = 105n + 2, a_{48n+3} = 105n + 4, \ldots, a_{48n+48} = 105n + 104, \ \forall n \in \mathbb{Z}+
\end{aligned}$$

Since $9999990 = 208333 \cdot 48 + 6$, thus $a_{9999990} = 105 \cdot (208333) + a_6 = \boxed{21\ 874\ 978.}$ □

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Problem 9.2.8. (*10 points*) Some blue and green marbles are in a bag. The probability to select any of them is the same for every marble. If two marbles are selected at random without replacement, the probability that both are blue is $\frac{1}{6}$. If three marbles are selected randomly without replacement, the probability that three are blue is $\frac{1}{21}$. What is the fewest number of marbles that must have been in the bag initially?

Solution. Let b and g be the number of blue and green marbles.The probability to select two blue marbles is:

$$\frac{\binom{b}{2}}{\binom{b+q}{2}} = \frac{1}{6} \Rightarrow 6b(b-1) = (b+g)(b+g-1).$$

Similarly, by the probability to select three blue marbles are without replacement is:

$$\frac{\binom{b}{3}}{\binom{b+q}{3}} = \frac{1}{21} \Rightarrow 21b(b-1)(b-2) = (b+g)(b+g-1)(b+g-2)$$

Therefore by dividing the equations:

$$\frac{7}{2}(b-2) = b+g-2 \Rightarrow 7b-14 = 2b+2g-4 \Rightarrow 5b = 2g+10$$

Thus b is even, note that $b \geq 3$, so the smallest value for b is 4. Then $g = 5$, and the least value of $b+g$ is $4+5 = \boxed{9.}$ □

Problem 9.2.9. (*10 points*) Find all real numbers x, y, z, t such that:

$$\begin{aligned} x^2+y^2+z^2+t^2 &= 50 \\ x^2-y^2+z^2-t^2 &= -24 \\ xz &= yt \\ x-y+z+t &= 0 \end{aligned}$$

Solution. First, by combining the first two equations

$$x^2+z^2 = \frac{50-24}{2} = 13,\ y^2+t^2 = 50-13 = 37$$

Let combine them with the third equation in one way:

$$\begin{aligned} &\Rightarrow (x+z)^2 = (y-t)^2 \Rightarrow 13+2xz = 37-2xz \Rightarrow xz = 6 = yt \\ &\Rightarrow (x+z)^2 = 13+12 = 25, x+y = \pm 5, y-t = \pm 5 \quad (*) \end{aligned}$$

Then in another way

$$\begin{aligned} &\Rightarrow (x-z)^2 = (y+t)^2 = 13-12 = 1 \\ &\Rightarrow x-y = \pm 1, y+t = \pm 1 \quad (**) \end{aligned}$$

By combining (*) and (**) we have $\boxed{8}$ solutions for (x, y, z, t):

$$\boxed{\begin{aligned} &(3,6,2,1),(2,6,3,1),(3,-1,2,-6),(2,-1,3,-6), \\ &(-3,-6,-2,-1),(-2,-6,-3,-1),(-3,1,-2,6),(-2,1,-3,6). \end{aligned}}$$

□

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Problem 9.2.10. (*10 points*) Let $S = \{1, 2, 3, \ldots, 100\}$, and A be a subset of S. It is known that if $x, y \in A, x < y$, then $y \neq 3x$. Find the maximum number of elements in A.

Solution. It is easy to very find the following set satisfy the requirements:

$$A = \{3k + 1 \mid k = 0, 1, \ldots 33\} \cup \{3k + 2 \mid k = 0, 1, \ldots 32\} \cup \{9, 18, \ldots, 90, 99\}.$$

Note that $|A| = \boxed{76.}$

Now, consider the following 24 sets:

$$A_k = \{k, 3k\}, \forall k = 1, 2, \ldots, 33$$

These subsets contains 48 different numbers. There are $100 - 48 = 52$ numbers left in S. Consider each of these 52 numbers as a set with a single element.

Now, we have 76 sets in total. If there exists a set A having more than 76 numbers, then two numbers must come from one of the A_k sets, which then contradicts the requirements. $\square$

9.3 Club Championship Individual - Test 2

Rules:

You have **60 minutes** to complete the test. You can submit **the answers, partial-, or full solutions**. Each submission is graded accordingly.

For a problem with multiple questions, each of the questions can be answered independently of others. You don't have to use the result of any preceding question(s) to solve the following ones. However if you use the result of the preceding questions to solve the following ones then you have to provide a correct solution for the preceding questions.

Note that you have to **follow the instructions by the COs** *for submitting the answers.*

- **Intermediate (I) level: Problems 1-4**
- **Advanced (A) level: Problems 5-8**
- **Olympiad (O) level: Problems 9-12**

No coding solution is accepted.

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Problem 9.3.1. (*10 points*) Let $a > 1$ be a real number such that

$$22\left(a+\frac{1}{a}\right)=\sqrt{2017}$$

Evaluate $a-\dfrac{1}{a}$.

Solution. Note that

$$\left(a+\frac{1}{a}\right)^2-\left(a-\frac{1}{a}\right)^2=4.$$

Thus

$$\left(a-\frac{1}{a}\right)^2=\left(\frac{\sqrt{2017}}{22}\right)^2-4=\frac{81}{484}=\left(\frac{9}{22}\right)^2.$$

Thus $a-\dfrac{1}{a}=\boxed{\dfrac{9}{22}.}$ □

Problem 9.3.2. (*10 points*) Find the remainder when divided $(257^{33}+46)^{26}$ by 50.

Solution. Note that

$$257\equiv 7 \pmod{50} \Rightarrow 257^2\equiv 7^2\equiv -1 \pmod{50} \Rightarrow 257^{33}\equiv 257\equiv 7 \pmod{50}$$
$$257^{33}+46\equiv 3 \pmod{50},\ 3^5=243\equiv -7 \pmod{50} \Rightarrow 3^{26}\equiv 3(-7)^5\equiv -21\equiv \boxed{29} \pmod{50}$$

□

Problem 9.3.3. (*10 points*) In $\triangle ABC$, BD is the median, E is a point of AB such that CE bisects BD at F. If $BE=7$, find AB.

Solution. Draw a line through D parallel to AB and intersecting CE at G. It is easy to see that $DG=BE$ because $\triangle BFE\cong\triangle DFG$, so $DG=BE=7$. On the other hand, D is midpoint of AC, $DG\parallel AE$, thus $AE=2DG=14$. Hence, $AB=\boxed{21.}$ □

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Problem 9.3.4. (*10 points*) There are two bags of marbles. Bag A contains four black and three white marbles. Bag B contains three black and six white marbles.

Five marbles were selected randomly from bag A and placed into bag B. One marble is then selected randomly from bag B.

What is the probability that the marble selected from bag B is white?

Solution. There are three cases to select 5 marbles from bag A:

4 black and 1 white marbles: $\binom{4}{4}$ ways to select the black ones, $\binom{3}{1}$ ways to select the white one, in total $\binom{7}{5}$ ways to select 5 marbles from 7, thus the probability is

$$\frac{\binom{4}{4}\cdot\binom{3}{1}}{\binom{7}{5}} = \frac{3}{21} = \frac{1}{7}.$$

In this case, there are 7 black and 7 white marbles in B, thus the probability to select one while marble is

$$\frac{\binom{7}{1}}{\binom{14}{1}} = \frac{1}{2}.$$

Hence, for this case the probability is $\frac{1}{7}\frac{1}{2} = \frac{1}{14}$.

3 black and 2 white marbles: $\binom{4}{3}$ ways to select the black ones, $\binom{3}{2}$ ways to select the white one, in total $\binom{7}{5}$ to select 5 marbles from 7, thus the probability is

$$\frac{\binom{4}{3}\cdot\binom{3}{2}}{\binom{7}{5}} = \frac{12}{21} = \frac{4}{7}.$$

In this case, there are 6 black and 8 white marbles in B, thus the probability to select one while marble is

$$\frac{\binom{8}{1}}{\binom{14}{1}} = \frac{4}{7}.$$

Hence, for this case the probability is $\frac{4}{7}\frac{4}{7} = \frac{16}{49}$.

2 black and 3 white marbles: $\binom{4}{2}$ ways to select the black ones, $\binom{3}{3}$ ways to select the white one, in total $\binom{7}{5}$ to select 5 marbles from 7, thus the probability is

$$\frac{\binom{4}{2}\cdot\binom{3}{3}}{\binom{7}{5}} = \frac{6}{21} = \frac{2}{7}.$$

In this case, there are 5 black and 9 white marbles in B, thus the probability to select one white marble is

$$\frac{\binom{9}{1}}{\binom{14}{1}} = \frac{9}{14}.$$

Hence, for this case the probability is $\frac{2}{7}\frac{9}{14} = \frac{9}{49}$.

Therefore the total probability is

$$\frac{1}{14} + \frac{16}{49} + \frac{9}{49} = \boxed{\frac{57}{98}.}$$

□

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Problem 9.3.5. Let x be a root for the equation:

$$2x\lfloor x\rfloor + 2\{x\} = 2017,$$

where $\lfloor x\rfloor$ denotes the largest integer not exceeding x, for example $\lfloor 1.1\rfloor = 1, \lfloor -1.2\rfloor = -2$. Furthermore $\{x\} = x - \lfloor x\rfloor$.

(*2 points*) Prove that if $x \geq 0$, then:

$$2\left(\lfloor x\rfloor\right)^2 \leq 2x\lfloor x\rfloor + 2\{x\} \leq 2x^2 + 2.$$

(*2 points*) Prove that if $x < 0$, then:

$$2x^2 \leq 2x\lfloor x\rfloor + 2\{x\} \leq 2\left(\lfloor x\rfloor\right)^2 + 2.$$

(*6 points*) Find all values for x.

Solution. Let's assume that $x \geq 0$, then:

$$\begin{aligned}
&(2x\lfloor x\rfloor + 2\{x\}) - 2\left(\lfloor x\rfloor\right)^2 = 2\lfloor x\rfloor(x - \lfloor x\rfloor) + 2\{x\} = 2\{x\}(\lfloor x\rfloor + 1) \geq 0\\
&(2x^2 + 2) - (2x\lfloor x\rfloor + 2\{x\}) = 2x\{x\} + 2(1 - \{x\}) > 0.\\
&\text{Thus } 2\left(\lfloor x\rfloor\right)^2 \leq 2x\lfloor x\rfloor + 2\{x\} \leq 2x^2 + 2.
\end{aligned}$$

On the other hand, if $x < 0$, then

$$\begin{aligned}
&(2x\lfloor x\rfloor + 2\{x\}) - 2x^2 = 2x(\lfloor x\rfloor - x) + 2\{x\} = 2\{x\}(-x + 1) \geq 0\\
&(2\left(\lfloor x\rfloor\right)^2 + 2) - (2x\lfloor x\rfloor + 2\{x\}) = 2\lfloor x\rfloor(\lfloor x\rfloor - x) + 2(1 - \{x\}) = -2\{x\}\lfloor x\rfloor + 2(1 - \{x\}) > 0\\
&\text{Thus } 2x^2 \leq 2x\lfloor x\rfloor + 2\{x\} \leq 2\left(\lfloor x\rfloor\right)^2 + 2.
\end{aligned}$$

Now, if $x \geq 0$, then:

$$\begin{aligned}
&2\left(\lfloor x\rfloor\right)^2 \leq 2x\lfloor x\rfloor + 2\{x\} \leq 2x^2 + 2 \Rightarrow 2\left(\lfloor x\rfloor\right)^2 \leq 2017 \leq 2x^2 + 2\\
&\Rightarrow 31 < \sqrt{\frac{2015}{2}} < \lfloor x\rfloor \leq \sqrt{\frac{2017}{2}} < 32 \Rightarrow \text{ no solution.}
\end{aligned}$$

If $x < 0$, then:

$$\begin{aligned}
&2x^2 \leq 2x\lfloor x\rfloor + 2\{x\} \leq 2\left(\lfloor x\rfloor\right)^2 + 2 \Rightarrow 2x^2 \leq 2017 \leq 2\left(\lfloor x\rfloor\right)^2 + 2\\
&\Rightarrow x^2 \leq \frac{2017}{2} \Rightarrow x > -\sqrt{\frac{2017}{2}} > -32,\ \left(\lfloor x\rfloor\right)^2 \geq 2015 \Rightarrow \lfloor x\rfloor \leq -\sqrt{\frac{2015}{2}} < -31\\
&\Rightarrow \lfloor x\rfloor = -32 \Rightarrow \{x\} = \frac{1}{2} \Rightarrow x = \boxed{-\frac{63}{2}.}
\end{aligned}$$

For an alternative solution:

$$\begin{aligned}
&2x\lfloor x\rfloor + 2\{x\} = 2017 \Rightarrow 2x\lfloor x\rfloor + 2\{x\} - 2(\lfloor x\rfloor + \{x\}) = 2017 - 2x\\
&\Rightarrow \lfloor x\rfloor(2x - 2) = 2017 - 2x \Rightarrow \lfloor x\rfloor = \frac{2017 - 2x}{2x - 2}\\
&\text{Let integer } k = \lfloor x\rfloor \Rightarrow k = \frac{2017 - 2x}{2x - 2} \Rightarrow x = \frac{2017 + 2k}{2k + 2} = 1 + \frac{2015}{2k + 2}\\
&\Rightarrow 2k + 2 \mid 2015,\ k - 1 \leq \frac{2015}{2k + 2} < k \Rightarrow k = -32.
\end{aligned}$$

Hence, $x = \boxed{-\frac{63}{2}.}$ □

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Problem 9.3.6. Let $a < b < c$ be the real roots of the equation

$$x^3 - 3x + 1 = 0.$$

(*2 points*) Let $\alpha = \frac{1}{1+a}$. Prove that α is a root of the equation

$$3x^3 - 3x + 1 = 0.$$

(*3 points*) Find the value of

$$\frac{1-a}{1+a} + \frac{1-b}{1+b} + \frac{1-c}{1+c}$$

(*5 points*) Write an equation with the three roots $a^2 - 2$, $b^2 - 2$, $c^2 - 2$.

Solution. Note that a is a root of $x^3 - 3x + 1 = 0$, thus:

$$1 + \frac{1-a}{1+a} = \frac{2}{1+a}$$
$$\Rightarrow \frac{1-a}{1+a} + \frac{1-b}{1+b} + \frac{1-c}{1+c} = 2\left(\frac{1}{1+a} + \frac{1}{1+b} + \frac{1}{1+c}\right) - 3.$$

Now, let $\alpha = \frac{1}{1+a}$, then $a = \frac{1}{\alpha} - 1$, since $a^3 - 3a + 1 = 0$, so:

$$\left(\frac{1}{\alpha} - 1\right)^3 - 3\left(\frac{1}{\alpha} - 1\right) + 1 = 0 \Rightarrow 3\alpha^3 - 3\alpha + 1 = 0.$$

Thus α is a root of the equation $3x^3 - 3x + 1 = 0$. Similar conclusions can be derived for $\beta = \frac{1}{1+b}, \gamma = \frac{1}{1+c}$. Therefore α, β, γ are roots of $3x^3 - 3x + 1 = 0$, by Viete's Theorem:

$$\alpha + \beta + \gamma = 0 \Rightarrow \frac{1-a}{1+a} + \frac{1-b}{1+b} + \frac{1-c}{1+c} = \boxed{-3.}$$

Now, since a, b, c are the roots of $x^3 - 3x + 1 = 0$:

$$a + b + c = 0,\ ab + bc + ca = -3,\ abc = -1$$
$$(a^2 - 2) + (b^2 - 2) + (c^2 - 2) = (a + b + c)^2 - 2(ab + bc + ca) - 6 = 0 \quad (1)$$
$$(a^2 - 2)(b^2 - 2) + (b^2 - 2)(c^2 - 2) + (a^2 - 2)(c^2 - 2) = (a^2b^2 + b^2c^2 + c^2a^2) - 4(a^2 + b^2 + c^2) + 12 \quad (2)$$
$$= (ab + bc + ca)^2 - 2abc(a + b + c) - 4(6) + 12 = -3$$

Let $P(x) = x^3 - 3x + 1 = (x - a)(x - b)(x - c)$, then:

$$(a^2 - 2)(b^2 - 2)(c^2 - 2) = (\sqrt{2} - a)(\sqrt{2} - b)(\sqrt{2} - c)((-\sqrt{2} - a))(-\sqrt{2} - b)(-\sqrt{2} - c)$$
$$= P(\sqrt{2})P(-\sqrt{2}) = (\sqrt{2} + 1)(-\sqrt{2} + 1) = -1 \quad (3)$$

From (1), (2), and (3), by Viete's Theorem, $a^2 - 2$, $b^2 - 2$, $c^2 - 2$ are the three roots of:

$$\boxed{x^3 - 3x + 1 = 0.}$$

□

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Problem 9.3.7. (*2 points*) x, y, z are positive real numbers. Prove that:

$$8xyz \leq (x+y)(y+z)(z+x).$$

(*3 points*) a, b, c are side lengths of a triangle. Prove that:

$$(a+b-c)(b+c-a)(c+a-b) \leq abc.$$

(*5 points*) a, b, c are side lengths of a triangle. Prove that:

$$a^2(b+c-a) + b^2(c+a-b) + c^2(a+b-c) \leq 3abc$$

Hint: Use result of the first question for the second and the third.

Solution. By AM-GM inequalities, for $x, y, z > 0$:

$$x+y \geq 2\sqrt{xy}, y+z \geq 2\sqrt{yz}, z+x \geq 2\sqrt{zx} \Rightarrow (x+y)(y+z)(z+x) \geq 8xyz.$$

Let $a = x+y, b = y+z, c = z+x$, then by the result of the first inequality:

$$(a+b-c)(b+c-a)(c+a-b) = 8xyz \leq (x+y)(y+z)(z+x) = abc.$$

For the last one, by expanding $(a+b-c)(b+c-a)(c+a-b)$, and then grouping the terms:

$$(a+b-c)(b+c-a)(c+a-b) = a^2(b+c-a) + b^2(c+a-b) + c^2(a+b-c) - 2abc.$$

By the result of the second inequality,

$$a^2(b+c-a) + b^2(c+a-b) + c^2(a+b-c) = 2abc + (a+b-c)(b+c-a)(c+a-b) \leq 3abc.$$

There is an alternative solution for the last one as follows:

$$\begin{aligned} &b^2(c+a-b) + c^2(a+b-c) - 2abc = a(b^2+c^2-2bc) + b^2(c-b) + c^2(b-c) \\ &= a(b-c)^2 - (b^2-c^2)(b-c) = (b-c)^2(a-b-c) \leq 0 \end{aligned}$$

Similarly $a^2(b+c-a) + b^2(c+a-b) \leq 2abc, a^2(b+c-a) + c^2(a+b-c) \leq 2abc$. By summing them up, we arrive to the requested inequality. $\square$

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Problem 9.3.8. You are given a 7×7 board and severals 1×3 trominos as shown below.

(*2 points*) Prove that it is possible to tile the board with the trominos by removing a single square. Show a tiling.

(*8 points*) Which single square can be removed from the board so that the rest can be tiled with trominos?

Hint: To do that, try to fill each of the 1×1 *squares in the board with one of the numbers* $0, 1,$ *and* 2, *then use the sums of the numbers in each of the trominos to arrive at the conclusion which squares can be removed.*

Solution. For the first question, look at one of the ways to fill the squares with the numbers $0, 1,$ and 2 in the diagram below on the left. By removing the lower right corner, the remaining of the board can be tiled with trominos, each cover a set of 0, 1, and 2 numbers.

Now, for the second question, in two ways of filling the squares, we have the sum of the label inside each of a tromino is 0 modulo 3. It is easy to see that there are 17 0s, 16 1s, 16 2s, thus the square to be removed is one of those which contains a 0 *in both fillings* (shaded in both diagram).

0	1	2	0	1	2	0
1	2	0	1	2	0	1
2	0	1	2	0	1	2
0	1	2	0	1	2	0
1	2	0	1	2	0	1
2	0	1	2	0	1	2
0	1	2	0	1	2	0

0	1	2	0	1	2	0
2	0	1	2	0	1	2
1	2	0	1	2	0	1
0	1	2	0	1	2	0
2	0	1	2	0	1	2
1	2	0	1	2	0	1
0	1	2	0	1	2	0

The required squares containing 0 in both fillings are at rows 1, 4, 7:

$$\boxed{(1,1),(1,4),(1,7),(4,1),(4,4),(4,7),(7,1),(7,4),(7,7).}$$

□

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Problem 9.3.9. n is a positive integer such that

$$\sigma(n) = n + 55, \text{ where } \sigma(n) \text{ is the sum of all divisors of } n, \text{ including 1 and } n.$$

(*1 point*) Prove that the number of distinct prime divisors of n is more than 1.

(*2 points*) Prove that the number of distinct prime divisors of n is less than 4.

(*2 points*) Prove that the number of distinct prime divisors of n cannot be 3.

(*5 points*) Find all n satisfying the given equation.

Solution. Let $n = p_1^{\alpha_1} p_2^{\alpha_2} \cdots p_k^{\alpha_k}$, where $k \geq 1$.

For the first question,

$$2 \cdot 3^3 = 54 = \sigma(n) - n - 1 = p_1(1 + \cdots + p_1^{\alpha_1 - 2}) \Rightarrow p_1 = 2, 1 + \cdots + p_1^{\alpha_1 - 2} = 3^3, \text{ impossible.}$$

For the second question, let's assume that $k \geq 4$, then:

$$\begin{aligned} &\sigma(n) > n + p_1p_2p_3 + p_1p_2p_4 + p_1p_3p_4 + p_2p_3p_4 \\ &\geq n + 2 \cdot 3 \cdot 5 + 2 \cdot 3 \cdot 7 + 2 \cdot 5 \cdot 7 + 3 \cdot 3 \cdot 7 = n + 205, \text{ impossible.} \end{aligned}$$

For the third question, let's assume that $k = 3$, then if n is odd:

$$\begin{aligned} &\sigma(n) > n + p_1p_2 + p_1p_3 + p_2p_3 \\ &\geq n + 3 \cdot 5 + 3 \cdot 7 + 5 \cdot 7 = n + 71, \text{ impossible.} \end{aligned}$$

If n is even, $p_1 = 2$, then $\sigma(n) = n + 55$ is odd. Since p_2, p_3 are odd and:

$$\begin{aligned} &\sigma(n) = (1 + \cdots + 2^{\alpha_1 - 1})(1 + \cdots + p_2^{\alpha_2 - 1})(1 + \cdots + p_3^{\alpha_3 - 1}) \Rightarrow \alpha_2, \alpha_3 \text{ are odd.} \\ &\Rightarrow \sigma(n) > n + (1 + 3 + 3^2)(1 + 5 + 5^2) = n + 403, \text{ impossible.} \end{aligned}$$

Now, $k = 2$, we consider the following cases:

$\alpha_1 = \alpha_2 = 1$: then

$$54 = \sigma(n) - n - 1 = p_1 + p_2 \Rightarrow (p_1, p_2) = (7, 47), (11, 43), (13, 41), (17, 37), (23, 31).$$

$\alpha_1 = 2, \alpha_2 = 1$: then

$$55 = \sigma(n) - n = (1 + p_1 + p_1^2)(1 + p_2) - p_1^2 p_2 = (1 + p_1)(1 + p_2) + p_1^2.$$

It is easy to see that the right side is larger than 55 if $p_1 > 5$ and cannot be the left side if $p_1 \in \{2, 3, 5\}$.

$\alpha_1 = \alpha_2 = 2$: then

$$55 = \sigma(n) - n = (1 + p_1)(1 + p_1 + p_1^2) + p_1^2(1 + p_2) \geq (1 + 2)(1 + 3 + 9) + 4(1 + 3) = 55.$$

Thus the only possible solution is $(p_1, p_2) = (2, 3)$.

$\alpha_1 \geq 3$: then

$$55 = \sigma(n) - n \geq (1 + p_2)(1 + p_1 + p_1^2) + p_1^3 > 55, \text{ if } p_1 \geq 3.$$

If $p_1 = 2$, then α_2 must be even for $\sigma(n)$ to be odd, thus

$$55 = \sigma(n) - n \geq (1 + p_1 + p_1^2)(1 + p_2 + p_2^2) \geq 7 \cdot 13 > 55.$$

Therefore the solutions are

$$7 \cdot 47 = \boxed{329}, 11 \cdot 43 = \boxed{473}, 13 \cdot 41 = \boxed{533}, 17 \cdot 37 = \boxed{629}, 23 \cdot 31 = \boxed{713}, 2^2 \cdot 3^2 = \boxed{36}.$$

□

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Problem 9.3.10. $P(x)$ is an odd degree polynomial with real coefficients. The coefficient of x^2 in $P(x)$ is zero. For all real number x:

$$P(P(x)) \leq P(x)^3.$$

(*5 points*) Prove that the degree of $P(x)$ is 3.

(*2 points*) Find the value of the leading coefficient (the coefficient of the highest power of x) in $P(x)$.

(*3 points*) Find all such $P(x)$.

Solution. For the first question, let assume that:

$$P(x) = a_n x^n + a_{n-1}x^{n-1} + \ldots + a_1 x + a_0 \Rightarrow \deg(P(P(x))) = n^2,\ \deg(P(x)^3) = 3n.$$

Now, let $Q(x) = P(P(x)) - P(x)^3$, if $n = 1$ then $Q(x)$ is a third degree polynomial; if $n > 3$ then $Q(x)$ is a $n^2 > 9^{\text{th}}$ degree polynomial; if $n = 3$ but the highest exponents of x in $P(P(x))$ and $P(x)^3$ don't cancel each other, then $Q(x)$ is an *odd* degree polynomial and the inequality

$$Q(x) = P(P(x)) - P(x)^3 \leq 0 \text{ cannot stand when } x \text{ is small- or large enough.}$$

Hence the highest exponents of x in $P(P(x))$ and $P(x)^3$ must cancel each other, thus:

$$n^2 = 3n \Rightarrow n = \boxed{3.}$$
$$a_3(a_3x^3)^3 = (a_3x^3)^3,\ \forall x \in \mathbb{R} \Rightarrow {a_3}^4 = {a_3}^3 \Rightarrow a_3 = \boxed{1.}$$

The coefficient of x^2 in $P(x)$ is zero, so $P(x) = x^3 + ax + b$, for some real numbers a, b :

$$Q(x) = P(P(x)) - P(x)^3 = a(x^3 + ax + b) + b \leq 0,\ \forall x$$

$Q(x)$ is an odd degree polynomial if $a \neq 0$. By the same argument, $a = 0$. Thus $b \leq 0$. Hence $\boxed{P(x) = x^3 + b, b \leq 0.}$ $\square$

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Problem 9.3.11. In $\triangle ABC$, $AB = c, BC = a, CA = b$, m_a, m_b, m_c are medians (connecting A, B, C with midpoints of BC, CA, AB, respectively.)

(*3 point*) Denote $s = \frac{1}{2}(a + b + c)$. Prove that:

$$m_a \geq \sqrt{s(s-a)}$$

(*3 points*) Prove that:

$$m_a m_b \leq \frac{ab}{4} + \frac{c^2}{2}$$

(*4 points*) Prove that

$$cm_c \leq \frac{am_b + bm_a}{2}.$$

Solution. Let M be the midpoint of BC. By the Law of Cosines, and note that $\angle AMB = 180^\circ - \angle AMC$:

$$\cos\angle AMC = \frac{\left(\frac{a}{2}\right)^2 + m_a^2 - b^2}{2m_a\left(\frac{a}{2}\right)}, \quad \cos\angle AMB = \frac{\left(\frac{a}{2}\right)^2 + m_a^2 - c^2}{2m_a\left(\frac{a}{2}\right)}$$

$$\Rightarrow \left(\frac{a}{2}\right)^2 + m_a^2 - b^2 = c^2 - \left(\frac{a}{2}\right)^2 - m_a^2 \Rightarrow {m_a}^2 = \frac{b^2 + c^2}{2} - \frac{a^2}{4}$$

$$\Rightarrow {m_a}^2 \geq \frac{(b+c)^2 - a^2}{4} = s(s-a) \Rightarrow \boxed{m_a \geq \sqrt{s(s-a)}.}$$

Let N be the midpoint of AC. By Ptolemy's inequality for the quadrilateral $ABMN$,

$$m_a m_b \leq c \cdot \frac{c}{2} + \frac{a}{2}\frac{b}{2} \Rightarrow \boxed{m_a m_b \leq \frac{ab}{4} + \frac{c^2}{2}.}$$

Let G be the centroid of $\triangle ABC$, By Ptolemy's inequality for the quadrilateral $GMCN$,

$$\left(\frac{2}{3}m_c \cdot \frac{c}{2}\right) \leq \left(\frac{1}{3}m_a\right) \cdot \frac{b}{2} + \left(\frac{1}{3}m_b\right) \cdot \frac{a}{2} \Rightarrow \boxed{cm_c \leq \frac{am_b + bm_a}{2}.}$$

$\square$

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Problem 9.3.12. You are given a $(2n+1) \times (2n+1)$ board and as many as needed pieces of three kinds shown as below:

(*2 point*) Number the columns left-to-right and rows top-to-bottom from 1 to $2n+1$. Colour in black the squares in odd rows and odd columns. Colour in white the rest. What is the number of black squares? Of white squares?

(*3 point*) Let a be the number of pieces of the first kind (from left to right) that cover *one* black square, b be the number of pieces of the first kind that cover *no* black square, c be the number of pieces of the other two kinds. Express the number of white squares in terms of a, b, and c only.

(*5 point*) Prove that if the given board can be tiled with the pieces above, then at least $4n+3$ pieces of the first kind will be used.

Solution. For the first question, by counting alternate rows $(n+1)$ and columns $(n+1)$, it is easy to see that there are $(n+1)^2 = \boxed{n^2+2n+1}$ black squares.

The number of white squares is $(2n+1)^2 - (n+1)^2 = n(3n+2) = \boxed{3n^2+2n.}$

Now, let a be the number of pieces of the first kind that cover *one* black square, b be the number of pieces of the first kind that cover *no* black square, c be the number of pieces of the other two kinds.

Each of the kinds in c cover exactly three white square, thus counting the white squares results in:

$$\boxed{2a+3b+3c} = 3n^2+2n.$$

It is trivial that the number of black squares is:

$$a+c = n^2+2n+1.$$

Therefore the number of the pieces of the first kind is $a+b$:

$$a+b \geq a-3b = 3(a+c)-(2a+3b+3c) = 3(n^2+2n+1)-(3n^2+2n) = \boxed{4n+3.}$$

□

9.4 Club Championship Team - Test 2

Rules:

You have **60 minutes** to solve **10** problems. Both Middle School and High School Teams solve the same problems. Any team member can choose any problem to work on. Several students can work on the same problem. However for each problem the whole team can submit a single answer. No individual answer is allowed.

The students can use any book, calculator, computer. The students can chat, talk, or use any mean of communications. They can sit next to each other if that is convenient.

No searching on the Internet is allowed. Nobody outside of the team can provide help.

Read carefully what submission (a number, a list of answers, a formula, a diagram, etc) is required by a problem. Each team submit a **single** image, pdf/excel file, or online spreadsheet containing the answers. It is the team responsibility that the answers are readable without any ambiguity. The submission must be done in time (within 60 minutes) and as instructed by the COs.

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Important: Read the rules before proceed!

Problem 9.4.1. In the following, different letters represent different digits.

$$\begin{array}{cccccc} & & & O & N & E \\ + & & F & O & U & R \\ \hline & & F & I & V & E \end{array} \qquad \begin{array}{cccccc} & & & O & N & E \\ \times & & & & & 4 \\ \hline & & F & O & U & R \end{array}$$

(*3 points*) What digit the letter O represents?

(*7 points*) What is the number represented by FIVE?

Solution. It is easy to see that $O \neq 0$. In the first calculation, $O + O$ even without carry over does not change the value of F thus O can only be 1, 2, 3, or 4. In the second calculation, $4 \times O$ and perhaps carry over has a tens digit as F, thus O cannot be 1. If O is 2, then N must be 8 or 9, but $4 \times 2 + 3 = 11$ has a different unit digit than O. If O is 4 then $4 \times 4 = 16$ and no value of N can make the unit digit (even with carry over) to be O. Thus, O is $\boxed{3.}$

For the second question, since O is 3, then F is 1. $E + R$ has a unit digit E, thus R is 0. Since $4 \times E$ has a unit digit 0, therefore E is 5. $4 \times N$ plus carry over of 2 has a unit U, which cannot be 0, 1, 3, or 5, and $U \neq N$. Thus N is 4 and U is 8. Therefore V is 2 and I is 7.

$$\begin{array}{cccccc} & & & 3 & 4 & 5 \\ + & & 1 & 3 & 8 & 0 \\ \hline & & 1 & 7 & 2 & 5 \end{array} \qquad \begin{array}{cccccc} & & & 3 & 4 & 5 \\ \times & & & & & 4 \\ \hline & & 1 & 3 & 8 & 0 \end{array}$$

Hence, FIVE is $\boxed{1725.}$ □

Problem 9.4.2. Each of three coloured cups covers each of three objects.

1. The red cup is somewhere to the left of the white cup.
2. The coin is somewhere left of the bean.
3. The gray cup is somewhere right of the shell.
4. The bean is somewhere right of the gray cup.

(*5 points*) Under which cup is the shell?

(*5 points*) What is the order of the objects from left to right?

Solution. Let R, W, G denote the colours of the cups. According to statement 1, the order of the cups from left to right could be RWG, RGW, GRW. According to statement 3, GRW is imposible. According to statement 4, RWG is imposible. Therefore RGW is the right order. Hence the shell is under $\boxed{\text{the red cup.}}$

The objects from left to right are $\boxed{\text{the shell, the coin, and the bean.}}$ □

Problem 9.4.3. The fraction $\frac{1}{4} = 0.25$ is a decimal written with two decimal places. The fraction $\frac{3}{8} = 0.375$ is a decimal written with three decimal places. Note that the last digit in the decimal must not be a zero.

(*5 points*) Find the number of fractions $\frac{p}{q}$, where p and q are relatively primes, that are decimals written with *two* decimal places, so that

$$\frac{1}{4} \leq \frac{p}{q} \leq \frac{3}{8}.$$

(*5 points*) Find the number of fractions $\frac{p}{q}$ where p and q are relatively primes, that are decimals written with *three* decimal places, so that

$$\frac{1}{4} \leq \frac{p}{q} \leq \frac{3}{8}.$$

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Solution. For the first question, note that if $a = \frac{p}{q}$ is a decimal written with *two* decimal places and

$$0.25 = \frac{1}{4} \leq a = \frac{p}{q} \leq \frac{3}{8} = 0.375 \Rightarrow 0.25 \leq a \leq 0.37$$

There are $37 - 25 + 1 = 13$ such numbers $0.25, 0.26, \ldots, 0.37$. Note that 0.30 cannot be considered as a decimal written with *two* decimal places. Hence there are $13 - 1 = \boxed{12}$ such numbers.

For the second question, note that if $a = \frac{p}{q}$ is a decimal written with *three* decimal places and

$$0.25 = \frac{1}{4} \leq a = \frac{p}{q} \leq \frac{3}{8} = 0.375 \Rightarrow 0.251 \leq a \leq 0.375$$

There are $375 - 251 + 1 = 125$ numbers between 251 and 375, but we have to remove the numbers 260, 270, ..., 370 or $37 - 26 + 1 = 12$ numbers. Thus, there are $125 - 12 = \boxed{113}$ decimals written with *three* decimal places. □

Problem 9.4.4. M, A, B, N are on the circle centred at C such that $\angle MCN = 210°$, $\angle MCA = 40°$. P is a point on CN such that $\angle CAP = \angle CBP = 10°$.

(*10 points*) What is the measure of the arc $\widehat{BN}$ in degrees?

Solution. Note that $\angle ACP = 360° - \angle ACM - \angle MCN = 110°$. Thus $\angle APC = 180° - \angle CAP - \angle ACP = 60°$.

Since $\angle CAP = \angle CBP$, so A, C, P, B are on the same circle, thus $\angle ABC = \angle APC = 60°$. Hence $\triangle ABC$ is equilateral and $\angle CAB = 60°$.

Thus $\widehat{BN} = \angle BCN = \angle PAB = \boxed{50°.}$ □

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Problem 9.4.5. (*10 points*) α is a real number. a and b are the real roots of the equation

$$x^2 + 4x - 480 = \alpha.$$

Find the minimum real root of the equation

$$x^2 - (a+b)x + ab + \alpha = 0.$$

Solution. Since a and b are the real roots of the equation $x^2 + 4x - 480 = \alpha$, therefore

$$\begin{aligned}&(x-a)(x-b) = x^2 + 4x - 480 - \alpha\\ &\Rightarrow x^2 - (a+b)x + ab + \alpha = x^2 + 4x - 480 = (x-20)(x+24)\end{aligned}$$

Hence, the minimum real root is $\boxed{-24.}$ □

Problem 9.4.6. Two ferries carry passengers over a river. They travel across the river on the same route, back and forth.

At 6AM the red ferry starts from the north bank of the river and repeats the following until 9:30PM: (i) it goes from the north bank to the south bank in 90 minutes; then (ii) it spends 30 minutes on the south bank; then (iii) it takes 90 minutes to go to the north bank; and then (iv) it waits 30 minutes at the north bank.

At 6AM the green ferry starts from the south bank of the river and repeats the following until 9PM: (i) it goes from the south bank to the north bank in 60 minutes; then (ii) it spends 60 minutes on the north bank; then (iii) it takes 60 minutes to go to the south bank; and then (iv) it waits 60 minutes at the south bank.

(*5 points*) How many times the two ferries cross each other, i.e. one goes in a direction while the other in the opposite one?

(*5 points*) In total how many minutes the ferries wait at the opposite banks at the same time, i.e. one waits at the north bank while the other at the south bank?

Solution. In the following diagram, the lines represents positions in time relatively to the river banks of the two ferries.

It is easy to see that the two ferries cross each other $\boxed{8}$ times, and in total there are $7 \times 30 = \boxed{210}$ minutes they wait at the opposite banks at the same time. □

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Problem 9.4.7. Let $S = \{1, 2, 3, \ldots, 2024\}$. M is called a *good* $k-$element $(1 < k < 1012)$ subset of S, if:

1. $|M| = k$, in other words M has k elements;
2. For any $a, b \in M$ then $|a - b| \neq 1$, in other words M does not contain two consecutive integers.

(*2 points*) How many distinct *good* $2-$element subsets are there?

(*8 points*) For $1 < k < 1012$, how many distinct *good* $k-$element subsets are there?

Solution. Let $a_1 < a_2 < \cdots < a_k \in M$ be k elements of M. Let $n = 2024$, By the given condition:

$$1 \leq a_1 < a_2 - 1 < a_3 - 2 < \cdots < a_k - (k-1) \leq n - (k-1).$$

Thus $(a_1, a_2 - 1, a_3 - 2, \ldots, a_k - (k-1))$ is a strictly increasing $k - term$ sequence of k elements of:

$$R = \{1, 2, \ldots, n - k + 1\}.$$

Therefore for a set $M = \{a_1, a_2, \cdots, a_k\}$ there is a strictly increasing $k - term$ sequence of $R : (a_1, a_2 - 1, a_3 - 2, \ldots, a_k - (k-1))$.

Now, for a strictly increasing sequence of k elements of $R : (i_1, i_2, \ldots, i_k)$, where $1 \leq i_1 < i_2 < \cdots < i_k \leq n - k + 1$, the subset $M = \{i_1, i_2 + 1, \ldots, i_k + (k-1)\}$ contains no two consecutive integers.

Thus, there is a one-on-one correspondence between the $k-$element subsets and the strictly increasing $k - term$ sequences of R. It is easy to see that the number of such sequences in R is $\binom{n-k+1}{k}$.

For $k = 2, n = 2024$, the desired number is $\binom{2024-2+1}{2} = \boxed{2\ 045\ 253.}$

For any $k, n = 2024$, the desired number is $\binom{2024-k+1}{k} = \boxed{\binom{2025-k}{k}}$. □

Problem 9.4.8. (*10 points*) a, b, c, d, and e are arbitrary real numbers. Find the maximum value of M such that the following inequality always stands:

$$a^2 + b^2 + c^2 + d^2 + e^2 \geq M(ab + bc + cd + de).$$

Solution. Note that, by AM-GM inequality:

$$\left.\begin{aligned}
a^2 + \frac{1}{3}b^2 &\geq 2\sqrt{a^2 \cdot \frac{1}{3}b^2} = \frac{2}{\sqrt{3}}(ab) \\
\frac{2}{3}b^2 + \frac{1}{2}c^2 &\geq 2\sqrt{\frac{2}{3}b^2 \cdot \frac{1}{2}c^2} = \frac{2}{\sqrt{3}}(bc) \\
\frac{1}{2}c^2 + \frac{2}{3}d^2 &\geq 2\sqrt{\frac{1}{2}c^2 \cdot \frac{2}{3}d^2} = \frac{2}{\sqrt{3}}(cd) \\
\frac{1}{3}d^2 + e^2 &\geq 2\sqrt{\frac{1}{3}d^2 \cdot e^2} = \frac{2}{\sqrt{3}}(de)
\end{aligned}\right\} \Rightarrow a^2 + b^2 + c^2 + d^2 + e^2 \geq \frac{2}{\sqrt{3}}(ab + bc + cd + de).$$

Thus $M \leq \frac{2}{\sqrt{3}}$. It is easy to see that for $a = 1, b = \sqrt{3}, c = 2, d = \sqrt{3}, e = 1$, then $M = \boxed{\frac{2}{\sqrt{3}}}$. □

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Problem 9.4.9. (*10 points*) Let p be an odd prime. Find all integers k such that $\sqrt{k^2 - pk}$ is a positive integer.

Solution. Note that $\sqrt{k^2 - pk} = n$, then there exists a positive integer n such that: $k^2 - pk = n^2$. Thus k is a root of the quadratic function $f(k) = k^2 - pk - n^2$, or:

$$k = \frac{p \pm \sqrt{p^2 + 4n^2}}{2}.$$

Hence $p^2 + 4n^2$ is a perfect square, thus there exists a positive integer m such that:

$$p^2 + 4n^2 = m^2 \Rightarrow p^2 = (m - 2n)(m + 2n) \Rightarrow m - 2n = 1, m + 2n = p^2 \Rightarrow n = \frac{p^2 - 1}{4}$$
$$p^2 + 4n^2 = p^2 + 4\left(\frac{p^2 - 1}{4}\right)^2 = \left(\frac{p^2 + 1}{2}\right)^2$$

Hence,

$$k = \frac{p \pm \sqrt{p^2 + 4n^2}}{2} = \frac{p \pm \frac{p^2+1}{2}}{2} \Rightarrow k \in \boxed{\left\{-\left(\frac{p-1}{2}\right)^2, \left(\frac{p+1}{2}\right)^2\right\}}$$

□

Problem 9.4.10. There are m teachers and 2024 students in a school. We know that:

1. Each teacher teaches exactly 100 students;
2. For any two distinct students, there are exactly n teachers teaching them.

(*2 points*) If a teacher t teaches two student $s_1 \neq s_2$ then they form a triples (t, s_1, s_2). How many triples (t, s_1, s_2) are there?

(*8 points*) Find $\frac{m}{n}$.

Solution. If a teacher t teaches two student $s_1 \neq s_2$ then they form a triples (t, s_1, s_2). Let M be the number of all triples.

For any teacher t, since t teaches 100 students, so there are $\binom{100}{2}$ triples (t, s_1, s_2). and there are m such teachers, so the number of triples is $\boxed{m \cdot \binom{100}{2}}$.

On the other hand, for any two students $s_1 \neq s_2$, there are exactly n teachers teaching them. Thus, there are n triples (t, s_1, s_2). Since there are $\binom{2024}{2}$ pairs of students, thus the number of triples is $\boxed{n \cdot \binom{2024}{2}}$.

Therefore

$$m \cdot \binom{100}{2} = n \cdot \binom{2024}{2} \Rightarrow \frac{m}{n} = \frac{\binom{2024}{2}}{\binom{100}{2}} = \boxed{\frac{93058}{225}}.$$

□

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9.5 Club Championship Individual - Test 3

Rules:

You have **60 minutes** to complete the test. You can submit **the answers, partial-, or full solutions**. Each submission is graded accordingly.

For a problem with multiple questions, each of the questions can be answered independently of others. You don't have to use the result of any preceding question(s) to solve the following ones. However if you use the result of the preceding questions to solve the following ones then you have to provide a correct solutions for the preceding questions.

Note that you have to **follow the instructions by the COs** *for submitting the answers.*

- **Intermediate (I) level: Problems 1-4**
- **Advanced (A) level: Problems 5-8**
- **Olympiad (O) level: Problems 9-12**

No coding solution is accepted.

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Problem 9.5.1. (*10 points*) Three aliens and three humans want to get from the moon they are on to another moon close at hand. They must cross between the moons in a space shuttle that will only hold two creatures at a time. Wherever they are, if the aliens outnumber the humans, they will do unspeakable things to them.

How can all three aliens and all three humans cross to the new moon safely?

Solution. Below is a solution:

This moon	Shuttle there	Shuttle back	That moon
HHHAAA			
HHAA	HA		HA
HHHAA		H	A
HHH	AA		AAA
HHHA		A	AA
HA	HH		HHAA
HHAA		HA	HA
AA	HH		HHHA
AAA		A	HHH
A	AA		HHHAA
AA		A	HHHA
	AA		HHHAAA

□

Problem 9.5.2. a, b, c, d are positive real numbers

(*3 points*) Prove that:

$$\frac{a^2}{b} + \frac{b^2}{a} \geq a + b.$$

(*7 points*) Prove that:

$$\frac{a^2}{b} + \frac{b^2}{c} + \frac{c^2}{d} + \frac{d^2}{a} \geq a + b + c + d.$$

Solution. For the first question, by the identity $x^2 + y^2 - 2xy = (x - y)^2$.

$$\frac{a^2}{b} + b - 2a = \left(\frac{a}{\sqrt{b}}\right)^2 + \left(\sqrt{b}\right)^2 - 2 \cdot \frac{a}{\sqrt{b}} \cdot \sqrt{b} = \left(\frac{a}{\sqrt{b}} - \sqrt{b}\right)^2 \geq 0.$$
$$\Rightarrow \frac{a^2}{b} \geq 2a - b, \text{ similarly } \frac{b^2}{a} \geq 2b - a \Rightarrow \frac{a^2}{b} + \frac{b^2}{a} \geq a + b.$$

For the second question, we apply the method in the solution for the first question several times:

$$\left.\begin{array}{l} \frac{a^2}{b} + b \geq 2a \\ \frac{b^2}{c} + c \geq 2b \\ \frac{c^2}{d} + d \geq 2c \\ \frac{d^2}{a} + a \geq 2d \end{array}\right\} \Rightarrow \frac{a^2}{b} + \frac{b^2}{c} + \frac{c^2}{d} + \frac{d^2}{a} \geq (a + b + c + d)$$

□

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Problem 9.5.3. (*2 points*) In an arbitrary $\triangle ABC$, $AB = c, BC = a, CA = b$. Prove that:

$$\frac{a}{b+c} < \frac{2a}{a+b+c}.$$

(*3 points*) In an arbitrary $\triangle ABC$, $AB = c, BC = a, CA = b$. Prove that:

$$\frac{a}{b+c} + \frac{b}{c+a} + \frac{c}{a+b} < 2.$$

(*5 points*) Find a $\triangle ABC$ with side lengths $AB = c, BC = a, CA = b$, such that

$$\frac{a}{b+c} + \frac{b}{c+a} + \frac{c}{a+b} > 1.9$$

Solution. For the first question, since $b + c > a$, so $2(b + c) > a + b + c$, thus:

$$\frac{a}{b+c} < \frac{2a}{a+b+c}$$

Similarly:

$$\frac{b}{c+a} < \frac{2b}{a+b+c}, \ \frac{c}{a+b} < \frac{2c}{a+b+c} \Rightarrow \frac{a}{b+c} + \frac{b}{c+a} + \frac{c}{a+b} < 2.$$

For the last inequality, let $a = 99, b = 100, c = 2$, then

$$\frac{a}{b+c} = \frac{99}{102}, \frac{b}{a+c} = \frac{100}{101} \Rightarrow \frac{a}{b+c} + \frac{b}{c+a} + \frac{c}{a+b} > \frac{99}{102} + \frac{100}{101} \approx 1.96 > 1.9.$$

□

Problem 9.5.4. The numbers $1, 2, \ldots, 10$ are written on a board. In an operation, any two numbers a and b can be erased and replaced with the number $a - b$.

(*2 points*) Is that possible to have only the numbers 1, 2, 3, 4, 5 remain on the board?

(*8 points*) Is that possible to have only the number 0 remains on the board?

Solution. For the first question we can perform the following operations:

$$(1,2) \to 1,\ (2,4) \to 2,\ (3,6) \to 3,\ (4,8) \to 4,\ (5,10) \to 5,\ (7,9) \to 2,\ (1,2) \to 1$$

For the second question, at the beginning the sum of the numbers on the board is $1 + 2 + \cdots + 10 = 55$, which is odd. At every operation the sum is reduced by $(a + b) - (a - b) = 2b$, which is an even number. The sum of the numbers on the board *at any moment* is an odd number. Hence, it $\boxed{\text{cannot be 0.}}$ □

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Problem 9.5.5. (*2 points*) In below there are two subtractions, each with two three-digit numbers.

$$\begin{array}{rccc} & 4 & 0 & 0 \\ - & a & b & 4 \\ \hline \end{array} \qquad \begin{array}{rccc} & 4 & a & b \\ - & 4 & 0 & 0 \\ \hline \end{array}$$

Find digits a, b in the following knowing that the results are the same for both subtractions.

(*8 points*) In below there are two subtractions, each with two 2025-digit numbers.

$$\begin{array}{rccccc} & 4 & 0 & \dots & 0 & 0 \\ - & a_{2023} & a_{2022} & \dots & a_0 & 4 \\ \hline \end{array} \qquad \begin{array}{rccccc} & 4 & a_{2023} & \dots & a_1 & a_0 \\ - & 4 & 0 & \dots & & 0 \\ \hline \end{array}$$

Digits $a_0, a_1, a_2, \dots, a_{2023}$ are such that the results are the same for both subtractions.

Find the sum $a_0 + a_1 + \cdots + a_{2023}$.

Solution. For the first question, note that

$$400 - \overline{ab4} = \overline{4ab} - 400 \Rightarrow 400 - 4 = \overline{ab} + \overline{ab0}$$
$$\Rightarrow 11\overline{ab} = 396 \Rightarrow \overline{ab} = 36 \Rightarrow (a, b) = \boxed{(3, 6)}.$$

Similarly for the second question, let $n = 1012$, $m = \overline{a_{2n-1} \dots a_0}$, then:

$$\underbrace{40\dots0}_{2n \text{ digits } 0} - \overline{a_{2n-1} \dots a_0 4} = \overline{4a_{2n-1} \dots a_0} - \underbrace{40\dots0}_{2n \text{ digits } 0}$$
$$\Rightarrow 11m = 4 \cdot 10^{2n} - 4 = 4 \cdot \underbrace{99\dots9}_{2n \text{ digits } 9}$$
$$\Rightarrow m = 4 \cdot \underbrace{90 \cdots 909}_{n \text{ times } 90} = \underbrace{36 \cdots 36}_{n \text{ times } 36}$$

Thus, $a_{2k} = 6, a_{2k+1} = 3$, $k = 0, 1, \dots, n-1$. Hence $\sum_{k=0}^{2n-1} a_k = 9n$, $\sum_{k=0}^{2023} a_k = 9 \cdot 1012 = \boxed{9108.}$ $\square$

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Problem 9.5.6. (*5 points*) Let $\alpha, \beta, \gamma, \delta \in \left(0, \frac{\pi}{2}\right)$ such that:

$$\sin^2\alpha + \sin^2\beta + \sin^2\gamma + \sin^2\delta = 1.$$

Prove that:

$$\tan\alpha\tan\beta\tan\gamma\tan\delta \leq \frac{1}{9}$$

(*5 points*) a, b, c, d are positive real numbers such that:

$$\frac{a^2}{1+a^2} + \frac{b^2}{1+b^2} + \frac{c^2}{1+c^2} + \frac{d^2}{1+d^2} = 1$$

Prove that:

$$9abcd \leq 1.$$

Solution. For the first question, note that $\alpha, \beta, \gamma, \delta \in \left(0, \frac{\pi}{2}\right)$, therefore:

$$\sin\alpha, \cos\alpha, \sin\beta, \cos\beta, \sin\gamma, \cos\gamma, \sin\delta, \cos\delta \text{ all are positive.}$$

$$\begin{aligned}
&\cos^2\alpha = 1 - \sin^2\alpha = \sin^2\beta + \sin^2\gamma + \sin^2\delta \geq 3\sqrt[3]{\sin^2\beta\sin^2\gamma\sin^2\delta} \\
&\Rightarrow \cos^2\beta \geq 3\sqrt[3]{\sin^2\alpha\sin^2\gamma\sin^2\delta},\ \cos^2\gamma \geq 3\sqrt[3]{\sin^2\alpha\sin^2\beta\sin^2\delta},\ \cos^2\delta \geq 3\sqrt[3]{\sin^2\alpha\sin^2\beta\sin^2\gamma} \\
&\Rightarrow (\cos\alpha\cos\beta\cos\gamma\cos\delta)^2 \geq 81(\sin\alpha\sin\beta\sin\gamma\sin\delta)^2 \\
&\Rightarrow \tan\alpha\tan\beta\tan\gamma\tan\delta \leq \frac{1}{9}
\end{aligned}$$

For the second question, since $a, b, c, d > 0$, there exist $\alpha, \beta, \gamma, \delta \in \left(0, \frac{\pi}{2}\right)$ such that $a = \tan\alpha, b = \tan\beta, c = \tan\gamma, d = \tan\delta$. Note that:

$$\frac{a^2}{1+a^2} = \frac{\tan^2\alpha}{1+\tan^2\alpha} = \sin^2\alpha \Rightarrow \frac{b^2}{1+b^2} = \sin^2\beta, \frac{c^2}{1+c^2} = \sin^2\gamma, \frac{d^2}{1+d^2} = \sin^2\delta.$$

From the answer to the first question

$$\sin^2\alpha + \sin^2\beta + \sin^2\gamma + \sin^2\delta = 1 \Rightarrow \tan\alpha\tan\beta\tan\gamma\tan\delta \leq \frac{1}{9}.$$

Hence $\boxed{9abcd \leq 1.}$ □

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Problem 9.5.7. (*3 points*) $XZYW$ is a convex quadrilateral. Diagonals XZ and YW intersect at O. Let $\angle XOY = \alpha$.

Prove that:

$$-XY^2 + YZ^2 - ZW^2 + WX^2 = 2 \cdot XZ \cdot YW \cdot \cos\alpha.$$

(*3 points*) In $\triangle ABC$, $\angle BAC = 60°$, P is a point inside triangle such that $PA = 6, PB = 7, PC = 10$. D is a point outside of the triangle such that $PD \parallel AB, AD \parallel PB$.

Prove that:

$$CD^2 - 6CD - 183 \leq 0.$$

(*4 points*) Conditions are given in the previous question. Now, prove that

$$[ABC] \leq 36 + 22\sqrt{3}.$$

Solution. For the first question, by the Law of Cosines:

$$\left.\begin{aligned} XY^2 &= OX^2 + OY^2 - 2(OX)(OY)\cos\alpha \\ YZ^2 &= OY^2 + OZ^2 + 2(OY)(OZ)\cos\alpha \\ ZW^2 &= OZ^2 + OW^2 - 2(OZ)(OW)\cos\alpha \\ WX^2 &= OW^2 + OX^2 - 2(OW)(OX)\cos\alpha \end{aligned}\right\} \Rightarrow -XY^2 + YZ^2 - ZW^2 + WX^2 = 2 \cdot XZ \cdot YW \cdot \cos\alpha.$$

For the second question, let E be the intersection of PD and AC. $\angle PEC = 60°$.

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By the result above, and note that $AD = PB = 7$, $PD = AB$,

$$-CP^2 + PA^2 - AD^2 + DC^2 = 2(CA)(DP)\cos 60^\circ \Rightarrow CD^2 = AB \cdot AC + 113$$

Now, by Ptolemy inequality for the quadrilateral $PADC$:

$$AC \cdot PD \leq PC \cdot DA + CD \cdot PA \Rightarrow AB \cdot AC \leq 70 + 6CD$$
$$\Rightarrow CD^2 - 113 \leq 70 + 6CD \Rightarrow CD^2 - 6CD - 183 \leq 0.$$

By solving the inequality and note that $CD \geq 0$:

$$0 \leq CD \leq 3 + 8\sqrt{3}.$$

Thus

$$[ABC] = \frac{1}{2}(AB)(AC)\sin\angle BAC = \frac{\sqrt{3}}{4}(CD^2 - 113) \leq \boxed{36 + 22\sqrt{3}}.$$

□

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Problem 9.5.8. If a_1, a_2, a_3, a_4, a_5 is a permutation of $1, 2, 3, 4, 5$ satisfying that for any $i = 1, 2, 3, 4$, each permutation of $a_1, a_2, \ldots, a_i$ is *not* a permutation of $1, 2, \ldots, i$, then we call $(a_1, a_2, a_3, a_4, a_5)$ a *good* permutation.

(*1 points*) Find the number of good permutations for $a_1 = 5$.

(*2 points*) Find the number of good permutations for $a_1 = 4$.

(*7 points*) Find the number of (all) good permutations.

Solution. For the first question, it is easy to see that if $a_1 = 5$, then for any $i = 1, 2, 3, 4$, each permutation of $a_1, a_2, \ldots, a_i$ is *not* a permutation of $1, 2, \ldots, i$. Thus the number of good permutations in this case is the number of permutations of $1, 2, 3, 4$ which is $4! = \boxed{24.}$

For the second question, note that there are 24 permutations if $a_1 = 4$. Among them, the ones in the following pattern have to be removed:

$$4 \ _ \ _ \ _ \ 5$$

It is easy to see that the number of those is the number of permutations of $1, 2, 3$, which is $3! = 6$. Thus, the number of good permutations for $a_1 = 4$ is $24 - 6 = \boxed{18.}$

For the last question, if we want to have the number of all good permutations, we need to count the number of good permutations in two additional cases.

Case 1: $a_1 = 3$. The number of permutations is 24 and we have to remove the ones with following patterns:

$$3 \ _ \ _ \ _ \ 5 \text{ or } 3 \ _ \ _ \ 5 \ 4.$$

The number of those in first pattern is $3! = 6$. The number of those in the second pattern is $2! = 2$. Thus, the number of good permutations for $a_1 = 3$ is $24 - (6 + 2) = 16$.

Case 2: $a_1 = 2$. The number of permutations is 24 and we have to remove the ones with following patterns:

$$2 \ 1 \ 5 \ _ \ _ \text{ or } 2 \ 1 \ 4 \ 5 \ 3 \text{ or } 2 \ _ \ _ \ 5 \ 4 \text{ or } 2 \ _ \ _ \ _ \ 5$$

The number of those in first pattern is $2! = 2$. The number of those in the second pattern is 1. The number of those in the third pattern is $2! = 2$. The number of those in the fourth pattern is $3! = 6$. Thus, the number of good permutations for $a_1 = 2$ is $24 - (2 + 1 + 2 + 6) = 13$.

Hence, the number of (all) good permutations is $24 + 18 + 16 + 13 = \boxed{71}$. □

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Problem 9.5.9. a, b, c are non-negative real numbers such that $a + b + c = 1$.

(*2 point*) Let $q = ab + bc + ca$, $r = abc$. Prove that:

$$\begin{cases} a^3 = a^2 - qa + r \\ b^3 = b^2 - qb + r \\ c^3 = c^2 - qc + r \end{cases}$$

(*4 point*) Prove that:

$$2 \leq (1 - a^2)^2 + (1 - b^2)^2 + (1 - c^2)^2.$$

(*4 point*) Prove that:

$$(1 - a^2)^2 + (1 - b^2)^2 + (1 - c^2)^2 \leq (1 + a)(1 + b)(1 + c).$$

Solution. Note that a, b, c are roots of the polynomial $P(x) = (x - a)(x - b)(x - c)$, thus:

$$P(x) = (x - a)(x - b)(x - c) = x^3 - (a + b + c)x^2 + (ab + bc + ca)x - abc = x^3 - x^2 + qx - r$$

Thus $0 = P(a) = a^3 - a^2 + qa - r \Rightarrow a^3 = a^2 - qa + r$. Similar results can be obtained for b and c.

For the second question, note that

$$\begin{aligned} &a^4 = a \cdot a^3 = a(a^2 - qa + r) = a^3 - qa^2 + ra = a^2 - qa + r - qa^2 + ra = a^2(1 - q) - a(q - r) + r \\ &\Rightarrow a^4 + b^4 + c^4 = (1 - q)(a^2 + b^2 + c^2) - (a + b + c)(q - r) + 3r = (1 - q)(1 - 2q) - (q - r) + 3r \\ &\Rightarrow (1 - a^2)^2 + (1 - b^2)^2 + (1 - c^2)^2 = 3 - 2(a^2 + b^2 + c^2) + (a^4 + b^4 + c^4) \\ &= 3 - 2(1 - 2q) + (1 - q)(1 - 2q) - (q - r) + 3r = 2q^2 + 4r + 2 \geq 2. \end{aligned}$$

For the third question,

$$\begin{aligned} &(1 + a)(1 + b)(1 + c) = 1 + (a + b + c) + q + r = 2 + q + r \\ &2q^2 + 4r + 2 \leq 2 + q + r \Leftrightarrow 3r \leq q - 2q^2 = q(1 - 2q) \\ &\Leftrightarrow 3abc \leq (ab + bc + ca)(a^2 + b^2 + c^2). \end{aligned}$$

The last inequality is easy to prove using Cauchy inequality. □

Problem 9.5.10. A, B are two points on the circle. A curve through A, B bisects the area of the circle. Prove that the curve is at least as long as a diameter of the circle.

Solution. It is obvious that the curve is at least as long as a diameter of the circle if AB is a diameter. Thus, let's assume that AB is a chord that is shorter than the diameter of the circle. Let CD be the diameter of the circle that is parallel to AB. Let B' be the reflection of B over CD. See the diagram below.

If the curve does not intersect CD, then the curve cannot bisect the area of the circle, thus the curve must intersect CD. Let one of the intersections be E. The length of the curve must be at least as long as $BE + EA$. Now, $BE + EA = B'E + EA \geq B'A$, which is a diameter. Hence, the curve is at least as long as a diameter of the circle. $\square$

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Problem 9.5.11. In $\triangle ABC$, $AB = c, BC = a, CA = b$. r_a, r_b, r_c are radius of the excircles corresponding to sides BC, CA, AB.

(*2 point*) Prove that if $x = -a + b + c, y = a - b + c, z = a + b - c$, then

$$r_a = \frac{1}{2x}\sqrt{(xyz)(x+y+z)}.$$

(*3 points*) Prove that:

$$\frac{(y+z)^2}{y^2+z^2} \geq \frac{2xyz(x+y+z)}{x^2y^2+y^2z^2+z^2x^2}$$

(*5 points*) Prove that

$$\frac{a^2}{r_b^2+r_c^2} + \frac{b^2}{r_c^2+r_a^2} + \frac{c^2}{r_a^2+r_b^2} \geq 2.$$

Solution. For the first question,

$$r_a = \frac{2[ABC]}{b+c-a} = \frac{\sqrt{(a+b+c)(-a+b+c)(a-b+c)(a+b-c)}}{2(b+c-a)} = \frac{1}{2x}\sqrt{(xyz)(x+y+x)}.$$

For the second question,

$$\begin{aligned}
&\frac{(y+z)^2}{y^2+z^2} \geq \frac{2xyz(x+y+z)}{x^2y^2+y^2z^2+z^2x^2} \\
&\Leftrightarrow (y+z)^2(x^2y^2+y^2z^2+z^2x^2) \geq 2xyz(x+y+z)(y^2+z^2) \\
&\Leftrightarrow (y+z)^2x^2(y^2+z^2) + (y+z)^2y^2z^2 \geq 2xyz(x+y+z)(y^2+z^2) \\
&\Leftrightarrow (y^2+z^2)x^2(y^2+z^2) + (y+z)^2y^2z^2 \geq 2xyz(x+y+z)(y^2+z^2) - 2yzx^2(y^2+z^2) \\
&\Leftrightarrow (y^2+z^2)^2x^2 + (y+z)^2y^2z^2 \geq 2xyz(y+z)(y^2+z^2) \\
&\Leftrightarrow ((y^2+z^2)x - (y+z)yz)^2 \geq 0
\end{aligned}$$

For the third question,

$$\begin{aligned}
&\frac{(y+z)^2}{y^2+z^2} \geq \frac{2xyz(x+y+z)}{x^2y^2+y^2z^2+z^2x^2} \Rightarrow \frac{y^2z^2(y+z)^2}{y^2+z^2} \geq \frac{2xyz(x+y+z)y^2z^2}{x^2y^2+y^2z^2+z^2x^2} \\
&\Rightarrow \frac{y^2z^2(y+z)^2}{xyz(x+y+z)(y^2+z^2)} \geq \frac{2y^2z^2}{x^2y^2+y^2z^2+z^2x^2}
\end{aligned}$$

Now,

$$\begin{aligned}
&a = \left(\frac{y+z}{2}\right)^2 = \frac{(y+z)^2}{4}, r_b^2 + r_c^2 = \frac{xyz(x+y+z)}{4y^2} + \frac{xyz(x+y+z)}{4z^2} = xyz(x+y+z)\frac{(y^2+z^2)}{4y^2z^2} \\
&\Rightarrow \frac{a^2}{r_b^2+r_c^2} = \frac{(y+z)^2}{4} \cdot \frac{1}{xyz(x+y+z)}\frac{4y^2z^2}{(y^2+z^2)} = \frac{y^2z^2(y+z)^2}{xyz(x+y+z)(y^2+z^2)} \geq \frac{2y^2z^2}{x^2y^2+y^2z^2+z^2x^2}
\end{aligned}$$

Similarly

$$\frac{b^2}{r_c^2+r_a^2} \geq \frac{2z^2x^2}{x^2y^2+y^2z^2+z^2x^2}, \frac{c^2}{r_a^2+r_b^2} \geq \frac{2x^2y^2}{x^2y^2+y^2z^2+z^2x^2}$$

Hence,

$$\frac{a^2}{r_b^2+r_c^2} + \frac{b^2}{r_c^2+r_a^2} + \frac{c^2}{r_a^2+r_b^2} \geq \frac{2(x^2y^2+y^2z^2+z^2x^2)}{x^2y^2+y^2z^2+z^2x^2} = 2.$$

□

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Problem 9.5.12. Two players Alice and Bob play a game. Alice goes first then Bob and they alternate.

At the beginning there are 101 numbers 1, 2, ..., 101 written on a board. At a turn, the player of that turn deletes 9 numbers among the remaining numbers.

After 11 turns, there are two numbers a and b left. The number of points Alice has is the positive difference of a and b.

Prove that there is a way for Alice to reach at least 55 points at the end of the game, regardless what Bob is doing.

Solution. Alice can delete the numbers $47, 48, \ldots, 55$ and have all the remaining numbers paired in $(i, 55+i)$ pairs. Now, whatever 9 numbers Bob deletes, Alice deletes 9 other numbers so that they form 9 pairs $(i, 55+i)$. At the end it is obvious that the points Alice can get is $\boxed{55.}$ □

9.6 Club Championship Team - Test 3

Rules:

You have **60 minutes** to solve **10** problems. Both Middle School and High School Teams solve the same problems. Any team member can choose any problem to work on. Several students can work on the same problem. However for each problem the whole team can submit a single answer. No individual answer is allowed.

The students can use any book, calculator, computer. The students can chat, talk, or use any mean of communications. They can sit next to each other if that is convenient.

No searching on the Internet is allowed. Nobody outside of the team can provide help.

Read carefully what submission (a number, a list of answers, a formula, a diagram, etc) is required by a problem. Each team submit a **single** image, pdf/excel file, or online spreadsheet containing the answers. It is the team responsibility that the answers are readable without any ambiguity. The submission must be done in time (within 60 minutes) and as instructed by the COs.

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Important: Read the rules before proceed!

Problem 9.6.1. The mice in the Village-of-Cheese are poets. They want to record their poems for later generation. In order to do that with cheap human printers, they use Latin alphabet to invent a written language. Below is a little poem in *mice language* with a translation of each verse:

Am ty my rm	$\rightarrow$	*Giant cat was scary.*
Ty lr dy am	$\rightarrow$	*Mouse saw giant cat.*
Ry lr ty rm	$\rightarrow$	*Scary cat ate mouse.*

(*5 points*) What does *dy* mean?

(*5 points*) What is *giant mouse ate cat* in mice language?

Solution. There is a single English word appear in all three lines: *cat.* Therefore it is *ty.*

The last two sentences share a same word of *mouse*, and that should not be same as cat, thus it is *lr.* By the same logic, from the first two sentences *giant* is *am;* from the first and third sentences *scary* is *rm.*

Finally by elimination, *was* is *my,* $\boxed{saw}$ is *dy*, and *ate* is *ry.*

Therefore, *giant mouse ate cat* is $\boxed{Ry\ ty\ lr\ am.}$ □

Problem 9.6.2. (*10 points*) In the diagram below, $ABCDE$ is a regular pentagon, ABF is an equilateral triangle. G is the center of the circumcircle of $\triangle CEF$. Find the measure of the $\angle EGF$ in degree.

Solution. Note that $\angle BAE = \frac{(5-2)180}{5} = 108°$. Connect EF and CF.

Since $\triangle EAF$ is isosceles, $\angle FAE = 108 + 60 = 168°$, thus $\angle AEF = \frac{180-168}{2} = 6°$.

$\angle CED = \frac{180-108}{2} = 36°$, so $\angle AEC = 108 - 36 = 72°$, thus $\angle FEC = 72 - 6 = 66°$. G is the center of the circumcircle of $\triangle CEF$, thus $\angle EGF = 2\angle ECF = 2\angle FEC = \boxed{132°.}$ □

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Problem 9.6.3. (*10 points*) Find all distinct triples of positive integers (x, y, z), such that

$$xy + yz + zx = xyz + 2$$

Solution. By dividing both side by xyz and let's assume that $0 < x \leq y \leq z$,

$$xy + yz + zx = xyz + 2 \Rightarrow \frac{1}{x} + \frac{1}{y} + \frac{1}{z} = 1 + \frac{2}{xyz}$$
$$0 < x \leq y \leq z \Rightarrow 1 < 1 + \frac{2}{xyz} = \frac{1}{x} + \frac{1}{y} + \frac{1}{z} \leq \frac{3}{x} \Rightarrow x \leq 2.$$

Case 1: $x = 1$.

$$y + yz + z = yz + 2 \Rightarrow y = z = 1 \Rightarrow (x, y, z) = \boxed{(1, 1, 1).}$$

Case 2: $x = 2$.

$$2y + yz + 2z = 2yz + 2 \Rightarrow yz - 2y - 2z + 4 = 2 \Rightarrow (y - 2)(z - 2) = 2$$
$$\Rightarrow \begin{cases} y - 2 = -2, z - 2 = -1 \Rightarrow y = 0, \text{ impossible.} \\ y - 2 = 1, z - 2 = 2 \Rightarrow (x, y, z) = (2, 3, 4) \end{cases}$$

By permuting the values of $(2, 3, 4)$, there are 7 distinct triples:

$$\boxed{\{(1, 1, 1), (2, 3, 4), (2, 4, 3), (3, 2, 4), (3, 4, 2), (4, 2, 3), (4, 3, 2)\}.}$$

□

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Problem 9.6.4. (*3 points*) Show an example of tiling the 12×11 board with 2×2, and 3×3 tiles.

(*3 points*) A 23×23 board is tiled with 1×1, 2×2, and 3×3 tiles, what is the least amount of 1×1 tiles?

(*4 points*) Show an example of such tiling (with that least amount of 1×1 tiles).

Solution. For the first question, first we show that how 12×11 board can be tiled with 2×2, and 3×3 tiles.

For the second, let's assume that no 1×1 tile is needed to tile a 23×23 board. This would mean that the 23×23 board is tile with 2×2 and 3×3 tiles only. Colour all the squares in each of the columns $1^{\text{st}}, 4^{\text{st}}, 7^{\text{st}}, \ldots, 19^{\text{st}}, 22^{\text{st}}$ black. Colour the rest of the squares white.

Now, each of the 2×2 tiles covers two black and two white squares or four white squares; and each of the 3×3 tiles covers exactly three black and six white squares. Thus, the number of white squares covered by these titles is always even. This contradicts the fact that the number of white squares by the two-colouring is 15×23, which is an odd number. Therefore at least $\boxed{1}$ 1×1 tile is needed.

For the last question, we use the tiling in the answer of the first question and show a way of tiling the 23×23 board as follow:

□

Problem 9.6.5. $ABCDEF$ is a hexagon. P is a point inside the hexagon such that

$$PA = 11, PC = 10, PE = 9, \text{ and } \angle PAB = \angle PBA = \angle PCD = \angle PDC = \angle PEF = \angle PFE = 45^\circ.$$

(*5 points*) What is the minimal value of the sum $s = BC + DE + FA$?

(*5 points*) When the sum $s = BC + DE + FA$ is minimal, what is the value of BC?

Solution. Let C' and F' be the reflection of C and F over the lines PB and PA, respectively.

$$\begin{aligned}
&\angle DPE + \angle BPC + \angle APF = 360^\circ - 3 \cdot 90^\circ = 90^\circ \\
&\Rightarrow \angle C'PF' = \angle BPA - \angle BPC - \angle APF = \angle DPE \\
&\Rightarrow \triangle DPE \cong \triangle C'PF' \Rightarrow C'F' = DE \\
&\Rightarrow BC + DE + FA = BC' + C'F' + F'A \geq BA = \boxed{11\sqrt{2}.}
\end{aligned}$$

The minimal value is achievable when C' and F' are points on AB, thus $\angle CBP = 45^\circ$. Let $BC = x$, by the Law of Cosines:

$$CP^2 = CB^2 + PB^2 - 2(CB)(PB)\cos 45^\circ \Rightarrow x^2 - 11x\sqrt{2} + 21 = 0 \Rightarrow x = \boxed{\frac{11 - \sqrt{79}}{\sqrt{2}}.}$$

□

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Problem 9.6.6. On day zero, a single blue bacteria was put into a colony of 2024 red bacteria.

Everyday after day zero, each of the blue bacteria consumes exactly one red bacteria (without sharing that with any other blue bacteria); and at the end of the day, each of blue and (remaining) red bacteria split into two.

On a day when there is no red bacteria left, the colony of blue bacteria dies at the end of the day.

(*5 points*) What is the day when the number of blue bacteria is equal to the number of red bacteria at the end of that day?

(*5 points*) How many red bacteria got eaten in total?

Solution. Let's consider the following: at the end of each day, we move half of the red and half of the blue bacteria into a separate area (not accessible by any other bacteria). Let n be the number of red bacteria on day zero.

At the end day 1, we have a single area, having 2 blue bacteria and $2(n-1)$ red bacteria. we move 1 blue bacteria and $n-1$ red bacteria to a separate area. So we have now two areas, each having 1 blue bacteria and $n-1$ red bacteria.

At the end day 2, after the consumption there are two areas, each having 1 blue bacteria and $n-2$ red bacteria. Each area's population will double into 2 blue bacteria and $2(n-2)$ red bacteria. Now, we move half of each population into a new area. Thus, we have 4 area, each has 1 blue bacteria and $n-2$ red bacteria.

Continue to do so, at the end of day k $(1 \leq k \leq n)$, we have 2^k area with 1 blue bacteria and $n-k$ red bacteria. Easy to see that at the end of day $n-1 = \boxed{2023}$, the numbers of red and blue bacteria are the same.

In day k $(1 \leq k \leq n)$, in each of 2^{k-1} areas, a single red bacteria is consumed, thus, the total number of red bacteria that were eaten is:

$$\sum_{k=1}^{n} 2^{k-1} = 2^n - 1 = \boxed{2^{2024} - 1.}$$

Note that: it is also a good argument to consider that the total number of blue bacteria growth is equal to the number of red bacteria being eaten. □

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Problem 9.6.7. k is an arbitrary positive integer, $k > 1$. (a, b) are positive integers such that:

$$a(a+1) = b(b+k) \quad (*)$$

Find the smallest positive integer k such that the equation (*) has:

(*5 points*) at least *two* distinct solutions (a, b).

(*5 points*) at least *three* distinct solutions (a, b).

Solution. [Solution 1] Note that

$$a(a+1) = b(b+k) \Rightarrow 4a(a+1) = 4b(b+k) \Rightarrow (2a+1)^2 - 1 = (2b+k)^2 - k^2$$
$$\Rightarrow (2b - 2a + k - 1)(2b + 2a + k + 1) = k^2 - 1$$

For the first question, let's investigate a few cases by increasing k from 2 until we find a suitable value.

Case 1: k is even, $k = 2\ell$ (we stop at 8 to investigate the possible solutions.)

$$(2b - 2a + 2\ell - 1)(2b + 2a + 2\ell + 1) = (2\ell - 1)(2\ell + 1).$$

Note that $0 < 2b - 2a + 2\ell - 1 < 2\ell - 1$, and $2b + 2a + 2\ell + 1 > 2\ell + 1$, thus in order for (*) has at least two solutions, there would be at least three ways to factorize $(2\ell - 1)(2\ell + 1)$ as a product of two distinct terms, one is less than $2\ell - 1$ and the other is more than $2\ell + 1$.

$$k = 2 \Rightarrow k^2 - 1 = 3 = 1 \cdot 3 \Rightarrow \text{ so no solution.}$$
$$k = 4 \Rightarrow k^2 - 1 = 15 = 1 \cdot 15 = 3 \cdot 5 \Rightarrow \text{ at most one solution.}$$
$$k = 6 \Rightarrow k^2 - 1 = 35 = 1 \cdot 35 = 5 \cdot 7 \Rightarrow \text{ at most one solution.}$$
$$k = 8 \Rightarrow k^2 - 1 = 63 = 1 \cdot 63 = 3 \cdot 31 = 7 \cdot 9 \Rightarrow \text{ at most two solutions.}$$

$$k = 8: \ (2b - 2a + 7)(2b + 2a + 9) = 63 \Rightarrow \begin{cases} 2b - 2a + 7 = 1, 2b + 2a + 9 = 63 \Rightarrow (a, b) = (15, 12) \\ 2b - 2a + 7 = 3, 2b + 2a + 9 = 21 \Rightarrow (a, b) = (4, 2) \\ 2b - 2a + 7 = 7, 2b + 2a + 9 = 9 \Rightarrow \text{ no solution.} \end{cases}$$

Case 2: k is odd, $k = 2\ell - 1$ (we stop at 7 to investigate the possible solutions.)

$$(2b - 2a + 2\ell - 2)(2b + 2a + 2\ell) = (2\ell - 2)(2\ell) \Rightarrow (b - a + \ell - 1)(b + a + \ell) = (\ell - 1)\ell$$

Note that $0 < b - a + \ell - 1 < \ell - 1$, and $b + a + \ell > \ell$, thus in order for (*) has at least two solutions, there would be at least three ways to factorize $(\ell - 1)\ell$ as a product of two distinct terms, one is less than $2\ell - 1$ and the other is more than ℓ.

$$k = 3 \Rightarrow \ell = 2 \Rightarrow (\ell - 1)\ell = 2 = 1 \cdot 2 \Rightarrow \text{ no solution.}$$
$$k = 5 \Rightarrow \ell = 3 \Rightarrow (\ell - 1)\ell = 6 = 1 \cdot 6 = 2 \cdot 3 \Rightarrow \text{ at most one solution.}$$
$$k = 7 \Rightarrow \ell = 4 \Rightarrow (\ell - 1)\ell = 12 = 1 \cdot 12 = 2 \cdot 6 = 3 \cdot 4 \Rightarrow \text{ at most two solutions.}$$

$$\ell = 4: (b - a + 3)(b + a + 4) = 12 \Rightarrow \begin{cases} b - a + 3 = 1, b + a + 4 = 12 \Rightarrow (a, b) = (5, 3) \\ b - a + 3 = 2, b + a + 4 = 6 \Rightarrow \text{ no solution.} \\ b - a + 3 = 3, b + a + 4 = 4 \Rightarrow \text{ no solution.} \end{cases}$$

Hence, $k = \boxed{8}$ is the smallest positive integer such that (*) has at least *two* distinct solutions.

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For the second question we can investigate two cases:

Case 1: k is odd, $k = 2\ell - 1$ (we stop at 11 to investigate the possible solutions.)

$$k = 9 \Rightarrow \ell = 5 \Rightarrow (\ell - 1)\ell = 20 = 1 \cdot 20 = 2 \cdot 10 = 4 \cdot 5 \text{ at most two solutions.}$$
$$k = 11 \Rightarrow \ell = 6 \Rightarrow (\ell - 1)\ell = 30 = 1 \cdot 30 = 2 \cdot 15 = 3 \cdot 10 = 5 \cdot 6 \Rightarrow \text{ at most three solutions.}$$

$$\ell = 6: \ (b - a + 3)(b + a + 4) = 12 \Rightarrow \begin{cases} b - a + 5 = 1, b + a + 6 = 30 \Rightarrow (a, b) = (14, 10) \\ b - a + 5 = 2, b + a + 6 = 15 \Rightarrow (a, b) = (6, 3) \\ b - a + 5 = 3, b + a + 6 = 10 \Rightarrow (a, b) = (3, 1) \\ b - a + 5 = 5, b + a + 6 = 6 \Rightarrow \text{ no solution.} \end{cases}$$

Case 1: k is even, $k = 2\ell$.

$$k = 10 \Rightarrow k^2 - 1 = 99 = 1 \cdot 99 = 3 \cdot 33 = 9 \cdot 11 \text{ at most two solutions.}$$

Hence, $k = \boxed{11}$ is the smallest positive integer such that (*) has at least *three* distinct solutions. $\square$

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Solution. [Solution 2] Here we show a coding solution. It follows the same reasoning as in the solution above.

```
        def get_divisors(n):
        divisors = []
        d = 1
        while True:
            if n % d == 0:
                divisors.append(d)
            if d * d > n:
                if d != n:
                    divisors.append(n)
                break
            d += 1
        return divisors

    k = 2
    while True:
        found = []
        if k % 2 == 0:
            p = int(k*k - 1)
        else:
            l = (k+1)/2
            p = int(l*(l - 1))

        d_list = get_divisors(p)
        if len(d_list) < 3:
            k += 1
            continue

        for d1 in d_list:
            d2 = int(p/d1)
            if k % 2 == 0:
                if (d2 - d1 - 2) % 4 == 0:
                    a = (d2 - d1 - 2) // 4
                    b = (d2 + d1 - 2*k) // 4
                    if a > 0 and b > 0:
                        found.append((a, b))
            else:
                if (d2 - d1 - 1) % 2 == 0:
                    a = (d2 - d1 - 1) // 2
                    b = (d2 + d1 - 2*l+1) // 2
                    if a > 0 and b > 0:
                        found.append((a, b))

        if len(found) == 2:
            print(f"{k} -- {found}")
            k += 1
        elif len(found) == 3:
            print(f"{k} -- {found}")
            break
        else:
            k += 1
```

The answer is $\boxed{8}$ for first question and $\boxed{11}$ for the second question. □

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Problem 9.6.8. A positive integer n is called *powerful* if it is divisible by all positive integers which are less than or equal to $\sqrt{n}$.

(*2 points*) Find all powerful numbers among $1, 2, \ldots, 10$.

(*8 points*) Find all powerful numbers.

Hint: prove that any positive integer n can be expressed uniquely as $n = q^2 + r,\ 0 \le r \le 2q$.

Solution. Since $3 < sqrt(10) < 4$, it is easy to verify that the powerful numbers not exceeding 10 are: $\boxed{1,\ 2,\ 3,\ 4,\ 6,\ 8.}$

First we prove the following claim:

Claim — Every n positive integer can be uniquely expressed as $n = q^2 + r,\ 0 \le r \le 2q$.

Proof. Note that every positive integer is between two perfect squares, or for any positive integer n there exists q positive integer such that:

$$q^2 \le n \le (q+1)^2 \Rightarrow 0 \le r = n - q^2 < 2q + 1 \Rightarrow 0 \le r \le 2q.$$

Now if $q^2 \le n \le (q+1)^2$, then $q = \lfloor \sqrt{n} \rfloor$. Thus q is uniquely determined by n, similar is r. ■

Let's consider that $n > 10$. let q, r be such that $n = q^2 + r,\ 0 \le r \le 2q$, then since $q \le \sqrt{n}$, so $q \mid n$. Thus $q \mid q^2 + r$, or $q \mid r$, where $0 \le r \le 2q$. Thus, there are there possible cases.

Case 1: $r = 0, n = q^2$. then $q - 1 \ge 2$,

$$q - 1 \mid n = q^2 = q(q-1) + q \Rightarrow q - 1 \mid q \text{ impossible.}$$

Case 2: $r = q, n = q^2 + q$. then $q - 1 \ge 2$,

$$q - 1 \mid n = q^2 + q = q(q-1) + 2q \Rightarrow q - 1 \mid 2q \Rightarrow q - 1 = 2, q = 3 \Rightarrow n = 12$$

Case 3: $r = q, n = q^2 + 2q$. then $q - 1 \ge 2$,

$$q - 1 \mid n = q^2 + 2q = q(q-1) + 3q \Rightarrow q - 1 \mid 3q \Rightarrow q - 1 = 3, q = 4 \Rightarrow n = 24.$$

Hence, the powerful numbers are $\{1, 2, 3, 4, 6, 8, 12, 24.\}$ □

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Problem 9.6.9. $x_1, x_2, \ldots, x_n$ are real numbers, $c_1, c_2, \ldots, c_n$ are also real numbers.

The sum $s = c_1x_1 + c_2x_2 + \ldots c_nx_n$ is called *linear combinations* of $x_1, x_2, \ldots, x_n$. *(an expression constructed from a set of terms by multiplying each term by a constant and adding the results.)*

(*1 point*) Express $a + 3c$ as a linear combination of $a + 2b + c, a + b + 2c$, and $a + b + 3c$.

(*5 points*) Find minimal value of the expression below:

$$S = \frac{a+3c}{a+2b+c} + \frac{4b}{a+b+2c} - \frac{8c}{a+b+3c}.$$

(*4 points*) Suppose that S reaches the minimal value. Find the value of $\frac{b+c}{a}$.

Solution.

$$a + 3c = (-1)(a + 2b + c) + 2(a + b + 2c) + (0)(a + b + 3c)$$

Let $x = a + 2b + c, y = a + b + 2c$, and $z = a + b + 3c$, then:

$$\begin{aligned}
&a + 3c = -x + 2y, 4b = 4x - 8y + 4z, 8c = -8y + 8z \\
&\frac{a+3c}{a+2b+c} + \frac{4b}{a+b+2c} - \frac{8c}{a+b+3c} = \frac{-x+2y}{x} + \frac{4x-8y+4z}{y} - \frac{-8y+8z}{z} \\
&= -1 + 2\frac{y}{x} + 4\frac{x}{y} - 8 + 4\frac{z}{y} + 8\frac{y}{z} - 8 = -17 + 2\left(\frac{y}{x} + 2\frac{x}{y}\right) + 4\left(2\frac{y}{z} + \frac{z}{y}\right) \\
&\geq -17 + 4\sqrt{2} + 8\sqrt{2} = \boxed{-17 + 12\sqrt{2}}
\end{aligned}$$

The equality stands when

$$\frac{y}{x} = 2\frac{x}{y},\ \frac{z}{y} = 2\frac{y}{z} \Rightarrow \begin{cases} a + b + 2c = \sqrt{2}(a + 2b + c) \\ a + b + 3c = \sqrt{2}(a + b + 2c) \end{cases} \Rightarrow \begin{cases} b(1 - 2\sqrt{2}) + c(2 - \sqrt{2}) = a(\sqrt{2} - 1) \\ b(1 - \sqrt{2}) + c(3 - 2\sqrt{2}) = a(\sqrt{2} - 1) \end{cases}$$

$$\begin{aligned}
&\Rightarrow b(1 - 2\sqrt{2}) + c(2 - \sqrt{2}) = b(1 - \sqrt{2}) + c(3 - 2\sqrt{2}) \\
&\Rightarrow c(\sqrt{2} - 1) = b\sqrt{2} \Rightarrow c = b\sqrt{2}(\sqrt{2} + 1) \\
&\Rightarrow b(1 - 2\sqrt{2}) + b\sqrt{2}(\sqrt{2} + 1)(2 - \sqrt{2}) = a(\sqrt{2} - 1) \Rightarrow b = (\sqrt{2} + 1)a,\ c = (4 + 3\sqrt{2})a
\end{aligned}$$

Hence, $\frac{b+c}{a} = \sqrt{2} + 1 + 4 + 3\sqrt{2} = \boxed{5 + 4\sqrt{2}.}$ □

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Problem 9.6.10. (*2 point*) P is a regular heptagon (7-gon). Find the smallest positive integer n such that any choice of n vertices (among the vertices of the heptagon) there are 4 vertices that form a convex quadrilateral whose 3 sides are also sides of P.

(*8 points*) P is a regular 2027-gon. Find the smallest positive integer n such that any choice of n vertices (among the vertices of the heptagon) there are 4 vertices that form a convex quadrilateral whose 3 sides are also sides of P.

Solution. For the first question, the answer is $\boxed{6}$. For any 6 vertices we can choose 4 consecutive vertices which form a convex quadrilateral whose 3 sides are also sides of P. On the opposite, if we choose 5 vertices A_1, A_2, A_3, A_5, A_6, then no selection of 4 vertices can form a convex quadrilateral whose 3 sides are also sides of P.

Based on this idea, we state that the answer for the second question is $\left(\frac{2027-3}{4}+1\right)3 = \boxed{1521}$. First, it is easy to prove that a convex quadrilateral whose 3 sides are also sides of P should contain four consecutive vertices.

Let the set of vertices of the given polygon be $A_1, A_2, \ldots, A_{2027}$. Remove A_{4k}, $(k = 1, 2, \ldots 506)$, and A_{2027} from the set, we obtain

$$S = \{A_1, A_2, A_3, A_5, A_6, A_7, A_9, \ldots, A_{2023}, A_{2025}, A_{2026}\}.$$

Then $|S| = \frac{3\cdot 2024}{4} + 2 = 1520$. It is obvious that there is no 4 consecutive vertices in S, so $n \geq 1521$.

Second, consider the following partition of S into 507 subsets:

$$S_1 = \{A_1, A_2, A_3, A_4\}, S_2 = \{A_5, A_6, A_7, A_8\}, \ldots, S_{506} = \{A_{2021}, A_{2022}, A_{2023}, A_{2024}\},$$
$$S_{507} = \{A_{2025}, A_{2026}, A_{2027}\}$$

Let B an arbitrary set containing $\boxed{1521}$ vertices of P. Assume that B contains no 4 consecutive vertices. Then for each i $(1 \leq i \leq 507)$, B has at most three common elements with S_i. But $3 \cdot 507 = 1521$, thus B has exactly three common elements with each S_i $(1 \leq i \leq 507)$.

Now,

$$S_{507} \subset B \Rightarrow A_1 \notin B \Rightarrow A_2, A_3, A_4 \in B \Rightarrow A_5 \notin B \Rightarrow A_6, A_7, A_8 \notin B \Rightarrow A_9 \notin B$$
$$\Rightarrow A_{13} \notin B, \ldots, A_{2025} \notin B \text{ a contradiction!}$$

Thus B contains 4 consecutive vertices, or there are 4 vertices in B that form a convex quadrilateral whose 3 sides are also sides of P. $\square$

9.7 Club Championship Individual - Test 4

Rules:

You have **60 minutes** to complete the test. You can submit **the answers, partial-, or full solutions**. Each submission is graded accordingly.

For a problem with multiple questions, each of the questions can be answered independently of others. You don't have to use the result of any preceding question(s) to solve the following ones. However if you use the result of the preceding questions to solve the following ones then you have to provide a correct solutions for the preceding questions.

Note that you have to **follow the instructions by the COs** *for submitting the answers.*

- **Intermediate (I) level: Problems 1-4**
- **Advanced (A) level: Problems 5-8**
- **Olympiad (O) level: Problems 9-12**

No coding solution is accepted.

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Problem 9.7.1. (*10 points*) a, b, c, d are real numbers such that

$$\frac{(a-b)(c-d)}{(b-c)(d-a)} = -\frac{5}{3}.$$

(*5 points*) Factor the following expression

$$(a-b)(c-d) - (b-c)(d-a).$$

(*5 points*) Compute

$$\frac{(a-c)(b-d)}{(a-b)(c-d)}.$$

Solution. For the first question,

$$\begin{aligned}&(a-b)(c-d) - (b-c)(d-a) = ac - ad - bc + bd - db + ba + cd - ca\\&= ab - ad + cd - cb = a(b-d) - c(b-d) = (a-c)(b-d).\end{aligned}$$

For the second question:

$$\begin{aligned}&\frac{(a-b)(c-d)}{(b-c)(d-a)} = -\frac{5}{3} \Rightarrow \frac{(b-c)(d-a)}{(a-b)(c-d)} = -\frac{3}{5} \Rightarrow \frac{(b-c)(d-a)}{(a-b)(c-d)} - 1 = -\frac{8}{5}\\&\Rightarrow \frac{(b-c)(d-a) - (a-b)(c-d)}{(a-b)(c-d)} = -\frac{8}{5} \Rightarrow \frac{(a-c)(b-d)}{(a-b)(c-d)} = \boxed{\frac{8}{5}.}\end{aligned}$$

□

Problem 9.7.2. In how many ways the diagram below can be coloured such that adjacent regions (sharing a border like B and C) are in different colours,

(*5 points*) by using four colours.

(*5 points*) by using five colours.

Solution. For the first question, there are 4 ways to choose a colour for A, 3 ways to choose a colour for B, 2 ways to choose a colour for C, and 1 way to choose a colour for D. So there are $4! = 24$ ways for (A, B, C, D).

Now, since there are 4 colours, E must be coloured with the same colour as B or D. If E is same as B then F must be same as C. If E is same as D then F can be same as C or B. Thus there are $1 + 2 = 3$ ways to colour E and F. Hence, the number of ways is $24 \times 3 = \boxed{72.}$

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For the second question, by the same logic, there are $5 \cdot 4 \cdot 3 \cdot 2 = 120$ ways for colouring (A, B, C, D). We consider a few different cases.

Case 1: E is coloured in the same way as B. Then F can be coloured as C or the remaining colour. There are two ways.

Case 2: E is coloured in the same way as D. Then F can be coloured as B, C, or the remaining colour. There are three ways.

Case 3: E is coloured by the remaining colour. Then F can be coloured as B or C. There are two ways.

Hence, there are $120 \cdot (2 + 3 + 2) = \boxed{840}$ ways of colourings in this case. □

Problem 9.7.3. (*10 points*) $ABCD$ is a trapezoid: $AB \parallel CD$, $AD \perp AC$, $AD = 6$, $AB = BC = 7$. Find BD.

Solution. Extend DA and CB to meet at P. Let E be the foot of the perpendicular from B.

$AB \parallel DC \Rightarrow \angle BAC = \angle DCA$. $AB = BC \Rightarrow \angle BCA = \angle BAC = \angle DCA$

$AC = AC, \angle DCA = \angle PCA, \angle DAC = \angle PAC \Rightarrow \triangle DAC \cong \triangle PAC$

$PA = AD = 6 \Rightarrow PB = BC = 7 \Rightarrow PC = PB + BC = 14 \Rightarrow AC = \sqrt{PC^2 - PA^2} = 4\sqrt{10}$

E is midpoint of $AP \Rightarrow BE = 2\sqrt{10} \Rightarrow BD = \sqrt{AE^2 + BE^2} = \sqrt{\left(\frac{3}{4}PD\right)^2 + 40} = \boxed{11.}$

□

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Problem 9.7.4. A a positive integer is called a composite number if it has a divisor which is not 1 and not the number itself. For example $6 = 2 \cdot 3$ is a composite number, while $7 = 1 \cdot 7$ is not a composite number.

(*5 points*) Prove that any multiple of 6 which is larger than or equal to 18, can be expressed as a sum of two *odd* composite numbers.

(*5 points*) Find the largest even positive integer that *cannot be expressed* as a sum of two odd composite numbers.

Solution. For the first question, let $6n$ be a multiple of 6, which is larger than or equal to 18. Thus $n \geq 3$. Then,

$$6n = 9 + (6n - 9) = 3 \cdot 3 + 3(2n - 3).$$

It is easy to see that $9 = 3 \cdot 3$ is a composite number. Since $1 < 2n - 3 < 3(2n - 3)$ so $3(2n - 3)$ is also a composite number. Thus, any multiple of 6 which is larger than or equal to 18, can be expressed as a sum of two *odd* composite numbers.

For the second question, a positive integer that is a sum of two odd composite numbers is an even number. Let $2m$ be the number. There are three different cases for the remainder of m when divided by 3.

Case 1: m is divisible by 3, then there exists a positive integer n such that $m = 3n$. From the result above, any multiple of 6 from 18 can be expressed as a sum of two odd composite numbers.

Case 2: there exists a positive integer n such that $m = 3n+1$. Then for $n \geq 7$, $6n+2 = 5 \cdot 7+3(2n-11) \geq 44$ is a sum of two odd composite numbers.

Case 3: there exists a positive integer n such that $m = 3n+2$. Then for $n \geq 5$, $6n+4 = 5 \cdot 5+3(2n-7) \geq 34$ is a sum of two odd composite numbers.

Thus $\boxed{38}$ is the largest positive integer that cannot be expressed as a sum of two odd composite numbers. □

Problem 9.7.5. (*5 points*) Let a, b, c be real numbers. Factor the following expression:

$$(bc)^2 - 4(a)(b^3 + c^3 - 4abc).$$

(*5 points*) Let a, b, c be real numbers such that $a > 0$, and the polynomial

$$P_3(x) = ax^2 + bcx + b^3 + c^3 - 4abc \text{ has no real roots.}$$

Prove that exactly one of the polynomials

$$P_1(x) = ax^2 + bx + c \quad \text{and} \quad P_2(x) = ax^2 + cx + b \quad \text{has only positive values.}$$

Solution. First,

$$(bc)^2 - 4(a)(b^3 + c^3 - 4abc) = b^2(c^2 - 4ab) - 4ac(c^2 - 4ab) = (b^2 - 4ac)(c^2 - 4ab)$$

Now, $P_3(x)$ has no real roots, thus its discriminant is negative, or:

$$\Delta_{P_3} = (bc)^2 - 4(a)(b^3 + c^3 - 4abc) = (b^2 - 4ac)(c^2 - 4ab) < 0.$$

This means that exactly one of $b^2 - 4ac$ and $c^2 - 4ab$ is negative. These are the discriminants of P_1 and P_2, respectively. Both P_1 and P_2 have the same leading coefficient $a > 0$, and the one with negative discriminant is the one having only positive values. □

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Problem 9.7.6. Find the number of triples of integers (x, y, z) such that $x + y + z = 10$, and

(*5 points*) $x > 0$, $y > 0$, and $z \geq 0$. Note that $(1, 2, 1) \neq (2, 1, 1)$.

(*5 points*) $x \leq y$, $y > 2$ and $z \geq 0$.

Solution. We draw line $x + y = 10$ on the plane. It is easy to see that the desired pairs corresponding to the points within the region defined by two axes above the line $x = 0$, right of the line $y = 0$, and under or on the line $x + y = 10$.

Note that $z = 10 - x - y \geq 0$, thus the problem is equivalent to find the number of pairs (x, y) such that$x + y \leq 10$. There are 9 grid points on the grid line where $x = 1$, 8 grid points on the grid line where $x = 2, \ldots,$ 1 grid points on the grid line where $x = 9$. In total $\frac{9 \cdot 10}{2} = \boxed{45.}$

Since there is no lower limit for x, thus there are $\boxed{\text{there are infinitely many}}$ of triples. □

Problem 9.7.7. $ABCD$ is a quadrilateral such that the triangles DAB, CDA, BCD, and ABC are similar to one another. (note that DAB, CDA are similar does not necessarily mean that $\angle DAB = \angle CDA$.)

(*5 points*) Prove that $ABCD$ is not a concave quadrilateral, for example D cannot lie inside $\triangle ABC$.

(*5 points*) Determine all such quadrilaterals $ABCD$.

Solution. For the first question, let's assume that $ABCD$ is concave. WLOG let's assume that D is inside $\triangle ABC$. Furthermore, WLOG, $\angle ABC$ is the largest in $\triangle ABC$, then (see the diagram below on the left):

$$\angle ADC = \angle ABC + \angle BAD + \angle BCD > \angle ABC.$$

This means that $\angle ADC$ is (strictly) larger than any of the angles in $\triangle ABC$, so $\triangle CDA$ and $\triangle ABC$ cannot be similar, a contradiction. Thus, $ABCD$ is a $\boxed{\text{convex}}$ quadrilateral.

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Now, let $ABCD$ be a convex quadrilateral. WLOG let $\angle ABC$ be the largest internal angle in the quadrilateral. Then (see the diagram above on the right):

$$\angle ABC > \angle DBC,\ \angle ABC \geq \angle ADC > \angle BCD.$$

Since $\triangle ABC$ and $\triangle BCD$ are similar, so $\angle ABC = \angle BCD$. Continuing this reasoning in similar way, all internal angles if the quadrilateral are equal. Thus it is a $\boxed{\text{rectangle.}}$ □

Problem 9.7.8. (a, b) are positive integer solutions for the equation $54^a = a^b$.

(*5 points*) Find the smallest value of b.

(*5 points*) Find the second smallest value of b.

Solution. Note that, $(54)^a = 2^a \cdot 3^{3a} \Rightarrow 2 \mid a, 3 \mid a$, thus there exist α, β positive integers such that:

$$\begin{aligned}
&a = 2^\alpha 3^\beta \Rightarrow (54)^a = 2^{2^\alpha 3^\beta} 3^{2^\alpha 3^{\beta+1}},\ a^b = 2^{\alpha b} 3^{\beta b} \\
&\Rightarrow 2^\alpha 3^\beta = \alpha b,\ 2^\alpha 3^{\beta+1} = \beta b \Rightarrow 3 = \frac{\beta}{\alpha} \\
&\Rightarrow a = 2^\alpha 3^{3\alpha} = 54^\alpha, b = \frac{54^\alpha}{\alpha}.
\end{aligned}$$

For the first question, the smallest value for a is $54^\alpha = 54$, where $\alpha = 1$, thus $b = \boxed{54.}$

For the second question, we can easily prove by induction that:

Claim — For any positive integer $\alpha : 54^\alpha > 1 + 53\alpha$.

Now, we prove that:

Claim — If α increases, then a increases, thus b also increases.

Proof. Let $\alpha_1 > \alpha_2$ be positive integers:

$$\begin{aligned}
&(53\alpha_2 - 1)(\alpha_1 - \alpha_2) > 0 \Rightarrow 1 + 53(\alpha_1 - \alpha_2) > \frac{\alpha_1}{\alpha_2} \\
&\Rightarrow 54^{\alpha_1 - \alpha_2} > 1 + 53(\alpha_1 - \alpha_2) > \frac{\alpha_1}{\alpha_2} \\
&\Rightarrow \frac{54^{\alpha_1}}{\alpha_1} > \frac{54^{\alpha_2}}{\alpha_2} \text{ or } b \text{ increases when } \alpha \text{ increases.}
\end{aligned}$$

■

Therefore the second smallest value of b is $\frac{54^2}{2} = \boxed{1458.}$ □

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Problem 9.7.9. Let $h(x)$ be a polynomial of degree 100: $h(x) = c_{100}x^{100} + c_{99}x^{99} + \cdots + c_1x + c_0$, where

$$c_{100} + c_{99} + \cdots + c_1 + c_0 = 0.$$

$f(x)$ and $g(x)$ are two polynomials of degree 100:

$$\begin{aligned}
&f(x) = a_{100}x^{100} + a_{99}x^{99} + \cdots + a_1x + a_0,\ g(x) = b_{100}x^{100} + b_{99}x^{99} + \cdots + b_1x + b_0\\
&b_0 = 2, b_1 = b_0 + c_0, b_2 = b_0 + c_0 + c_1, \ldots, b_{100} = b_0 + c_0 + c_1 + \cdots + c_{99}\\
&a_0 = b_1, a_1 = b_2, \ldots, a_{99} = b_{100}, a_{100} = b_0.
\end{aligned}$$

(*5 point*) Prove that $f(x) - g(x) = h(x)$.

(*5 point*) Prove that there exists such $h(x)$ that $f(x) \geq g(x),\ \forall x$.

Solution. Note that $b_{100} = b_0 + c_0 + c_1 + \cdots + c_{99} = b_0 - c_{100}$, thus:

$$\left.\begin{aligned}
&a_0 - b_0 = b_1 - b_0 = c_0\\
&a_1 - b_1 = b_2 - b_1 = c_1\\
&\ldots\\
&a_{99} - b_{99} = b_{100} - b_{99} = c_{99}\\
&a_{100} - b_{100} = b_0 - b_{100} = c_{100}
\end{aligned}\right\} \Rightarrow \boxed{f(x) - g(x) = h(x).}$$

For the second question, let $\boxed{h(x) = (x-1)^{100}}$, then

$$h(1) = c_{100} + c_{99} + \cdots + c_1 + c_0 = 0 \Rightarrow f(x) - g(x) = h(x) = (x-1)^{100} \geq 0,\ \forall x$$

□

Problem 9.7.10. Let $\mathbb{Z}^+ = \{1, 2, 3, \ldots\}$ be the set of positive integers. For positive real number a and positive integer n, the tuple $(A_1, A_2, \ldots, A_n)$ is called a *good $a-$partition* of $\mathbb{Z}^+$, if:

- each of the sets has infinite number of elements: $|A_i| = +\infty, \forall i \in \{1, 2, \ldots, n\}$;
- the sets are disjoint: $A_i \cup A_j = \emptyset, \forall i \neq j \in \{1, 2, \ldots, n\}$;
- the sets form a partition of $\mathbb{Z}^+ : \cup_{i=1}^n A_i = \mathbb{Z}^+$;
- for each of the sets, $u, v \in A_i, u \neq v \Rightarrow |u - v| \geq a^i, \forall i \in \{1, 2, \ldots, n\}$.

(*2 points*) Prove that for an arbitrary $0 < a < 2$, there exists positive integer n such that $2^{n-1} > a^n$.

(*3 points*) Let a be a real number: $0 < a < 2$. Let n be a positive integer such that $2^{n-1} > a^n$.

$$\text{Let } A_i = \{2^{i-1}m \mid m \text{ is odd}\}, \forall i \in \{1, 2, \ldots, n-1\},\ A_n = \{m \mid 2^{n-1} \text{ is a divisor of } m\}$$

Prove that $(A_1, A_2, \ldots, A_n)$ is a *good* $a-$partition of $\mathbb{Z}^+$.

(*5 points*) Let a be arbitrary real number $a \geq 2$. Prove that for any positive integer n there does not exist a *good $a-$ partition* of $\mathbb{Z}^+$.

Solution. For the first question,

$$2^{n-1} > a^n \Rightarrow \frac{1}{2} > \left(\frac{a}{2}\right)^n \Rightarrow \log_{\frac{a}{2}} \frac{1}{2} > n \Rightarrow \frac{\log(2)}{log(2) - log(a)} > n.$$

Since $0 < a < 2$ thus $\log(2) > log(2) - log(a) > 0$, thus, $n = \boxed{\left\lfloor \frac{\log(2)}{log(2) - log(a)} \right\rfloor}$ is a solution.

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For the second question, it is easy to verify the first three properties of a *good $a-$partition*. For the last one, we look at two cases:

$\forall i \in \{1, 2, \ldots, n-1\}$, $\forall a \neq b \in A_i = \{2^{i-1}m \mid m \text{ is odd}\}$, thus there exist $\ell_1 \neq \ell_2$:

$$a = 2^{i-1}(2\ell_1 + 1), b = 2^{i-1}(2\ell_2 + 1) \Rightarrow |a - b| = 2^i|\ell_1 - \ell_2| \geq 2^i > a^i.$$

$\forall a \neq b \in A_n = \{m \mid 2^{n-1} \text{ is a divisor of } m\}$, so $a = 2^{n-1}\ell_1, b = 2^{n-1}\ell_2$, thus $|a - b| \geq 2^{n-1} > a^n$.

For the last question, let's assume that for $a \geq 2$, there exists a positive integer n such that $(A_1, A_2, \ldots, A_n)$ is a *good $a-$partition*. Let $S = \{1, 2, \ldots, 2^n\}$. Let $B_i = A_i \cap S$, $\forall i \in \{1, 2, \ldots, n\}$. Now, for an arbitrary $i \in \{1, 2, \ldots, n\}$, let $B_i = \{b_1, b_2, \ldots, b_m\}$:

$$\begin{aligned}
&\text{WLOG } b_1 < b_2 < \cdots < b_m \Rightarrow 2^n > b_m - b_1 = (b_m - b_m{-}1) + \cdots + (b_2 - b_1) \geq (m-1)2^i \\
&\Rightarrow 2^{n-i} > m - 1 \Rightarrow 2^{n-i} \geq m \Rightarrow |B_i| \geq 2^{n-i} \\
&\Rightarrow 2^n = |S| = |B_1| + |B_2| + \cdots + |B_n| \leq \sum_{i=1}^{n} 2^{n-i} = 2^n - 1, \text{ impossible.}
\end{aligned}$$

Hence, if $a \geq 2$ then there does not exist a *good $a-$ partition* of $\mathbb{Z}^+$ for any positive integer n. □

Problem 9.7.11. ABC is an isosceles right triangle: $CA = CB = 1$, $\angle ACB = 90°$.

(*5 points*) Prove that if P is a point on AC then:

$$PA \cdot PB \cdot PC < \frac{\sqrt{2}}{4}.$$

(*5 points*) P is a point on the perimeter of $\triangle ABC$. What is maximal value of $PA \cdot PB \cdot PC$. What is the position of P when the maximal value is reached.

Solution. If P is a point on AC then:

$$\left.\begin{aligned} PA \cdot PC \leq \frac{1}{4}(PA + PC)^2 = \frac{1}{4}AC^2 = \frac{1}{4} \\ PB \leq AB = \sqrt{2} \end{aligned}\right\} \Rightarrow PA \cdot PB \cdot PC \leq \frac{\sqrt{2}}{4}$$

The equality cannot stand since P cannot be both midpoint of AC and A at the same time.

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For the second question, let P be a point on AB, let $x = PA$, then $PB = \sqrt{2} - x$, and by the Law of Cosines:

$$PC^2 = AC^2 + PA^2 - 2(AC)(PA)\cos 45^\circ = x^2 + 1 - x\sqrt{2}.$$

Let $t = x(\sqrt{2} - x)$, then:

$$0 \le t \le \frac{1}{4}(x + (\sqrt{2} - x))^2 = \frac{1}{2} \Rightarrow t \in \left[0, \frac{1}{2}\right]$$

Now, consider function $f(t) = PA^2 \cdot PB^2 \cdot PC^2 = x^2(\sqrt{2} - x)^2(x^2 + 1 - x\sqrt{2}) = t^2(1 - t)$. The first derivate of f is

$$f'(t) = 2t - 3t^2 = t(2 - 3t) \Rightarrow f \text{ increases on } \left[0, \frac{1}{2}\right] \Rightarrow f(t) \le f\left(\frac{1}{2}\right) = \frac{1}{8}.$$

Thus $PA \cdot PB \cdot PC \le \sqrt{\frac{1}{8}} = \boxed{\frac{\sqrt{2}}{4}.}$ The equality stands if $t = \frac{1}{2}$, $PA = PB$, so P is midpoint of AB. $\square$

Problem 9.7.12. (*3 points*) a, b, c, d are four pair-wise relatively prime numbers from $\{1, 2, \ldots, 24\}$. Prove that at least one of them is a prime number.

(*7 points*) Find the smallest positive integer k such that there is a prime number in any $k-$element subset of the set $S = \{1, 2, \ldots, n\}$ whose elements are pair-wise relatively primes.

Solution. For the first question, let's assume that none of a, b, c, d is a prime number. At most one of them can be 1, and at least three of them are composite numbers. Let $2 \le p < q < r$ be the smallest prime factors of these three composite numbers, then the composite number that divides r must be at least $r^2 \ge 5^2 = 25$, which is impossible. Hence $\boxed{\text{at least one of them is a prime number.}}$

For the second question, let's number the prime numbers as follow:

$$2 = p_1, 3 = p_2, 5 = p_3, \ldots$$

Let $p_0 = 1$, for every positive integer $n \ge 4$, there exists a positive integer $k \ge 1$ such that $p_{k-1}^2 \le n < p_k^2$. Now, let $A = \{1, p_1^2, p_2^2, \ldots, p_{k-1}^2\}$, then A is a subset of $\{1, 2, \ldots, n\}$, A contains k pair-wise relatively prime numbers and none of them is a prime number.

Let assume that $B \subset \{1, 2, \ldots, n\}$, $|B| = k + 1$, and all elements of B are pair-wise relatively prime numbers and none of them is a prime number. At most one element of B can be 1, at least k elements of B are composite numbers. Let $2 \le q_1 < q_2 < q_k$ be the smallest prime factors of these k composite numbers, then the composite number that divides q_k must be at least $q_k^2 \ge p_k^2 > n$, which is impossible.

Thus, k is the smallest positive integer such that there is no prime number in any $(k+1)-$element subset of S whose elements are pair-wise relatively primes. $\square$

9.8 Club Championship Team - Test 4

Rules:

You have **60 minutes** to solve **10** problems. Both Middle School and High School Teams solve the same problems. Any team member can choose any problem to work on. Several students can work on the same problem. However for each problem the whole team can submit a single answer. No individual answer is allowed.

The students can use any book, calculator, computer. The students can chat, talk, or use any mean of communications. They can sit next to each other if that is convenient.

No searching on the Internet is allowed. Nobody outside of the team can provide help.

Read carefully what submission (a number, a list of answers, a formula, a diagram, etc) is required by a problem. Each team submit a **single** image, pdf/excel file, or online spreadsheet containing the answers. It is the team responsibility that the answers are readable without any ambiguity. The submission must be done in time (within 60 minutes) and as instructed by the COs.

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Important: Read the rules before proceed!

Problem 9.8.1. (*10 points*) Find the value of:

$$\left(4+2\sqrt{3}\right)^{\frac{3}{2}}-\left(4-2\sqrt{3}\right)^{\frac{3}{2}}$$

Solution. Note that

$$4+2\sqrt{3}=(\sqrt{3})^2-2(\sqrt{3})(1)+1^2=(\sqrt{3}+1)^2,\ 4-2\sqrt{3}=(\sqrt{3}-1)^2$$
$$\Rightarrow\left(4+2\sqrt{3}\right)^{\frac{3}{2}}=(\sqrt{3}+1)^3,\ \left(4-2\sqrt{3}\right)^{\frac{3}{2}}=(\sqrt{3}-1)^3$$

Now, it is easy to see that for any real number a :

$$(a+1)^3-(a-1)^3=(a^3+3a^2+3a+1)-(a^3-3a^2+3a-1)=6a^2+2$$
$$\Rightarrow(\sqrt{3}+1)^3-(\sqrt{3}-1)^3=6(\sqrt{3})^2+2=\boxed{20.}$$

□

Problem 9.8.2. (*10 points*) Minh, Ha-Anh, and Julie were having a snowball fight. Ha-Anh threw the first snowball. Then in response to every snowball that hit her, Minh threw six snowballs. Similarly, each time she was hit by a snowball, Julie threw five. Ha-Anh threw four each time she was hit. After a certain amount of time the game ended. If in total 13 snowballs missed their targets, how many snowballs each one of the players threw?

(*You can't throw a snowball at yourself and one snowball cannot hit two people.*)

Solution. Let the amounts of snowballs that hit Minh, Ha-Anh, and Julie be m, h, and j, respectively, then $13+m+h+j$ is the total amount of snowballs. Thus, the number of ball they throw is $6m+(4h+1)+5j$, (note that Ha-Anh threw the first snowball). Therefore:

$$13+m+h+j=6m+(4h+1)+5j\Rightarrow 5m+3h+4j=12\Rightarrow m\in\{0,1,2\}$$

Case 1: $m=0$ then $3h+4j=12$, h is even. If $h=0, j=3$, only Ha-Anh was the only other player who threw some balls, and she threw a single snowball, it is impossible to hit Julie three times. If $h=4, j=0$, then Ha-Anh was the only who threw some balls, she threw a fives snowballs, and hit herself four times. It's impossible.

Case 2: $m=1$ then $3h+4j=7$. It is easy to see that $h=1, j=1$. So how did it happen? The first snowball threw by Ha-Anh hit one of the other two girls (says A, B). That girl (A) one threw some balls: (i) one of them hit both Ha-Anh and another hit the remaining girl (B), triggering the responses from both girls that hit no one; (ii) one of them hit only Ha-Anh, Ha-Anh threw some snowballs that hit the remaining girl (B), triggering her response that hit no one; (ii) one of them hit only the remaining girl (B), B threw some snowballs that hit Ha-Anh, triggering her response that hit no one. The game is ended in any case.

It is easy to see that the numbers of snowballs were the same in every case: $\boxed{6,5,5}$ (3 hits and 13 misses.)

Case 3: $m=2$ then $3h+4j=2$. There is no solution for this case. □

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Problem 9.8.3. (*10 points*) $CBDE$ is a quadrilateral. $BD = 4$, $CE = 5$. BE and CD meet at F such that $BF = 2FE$ and $CF = 2FD$. Furthermore

$$\angle FEC - \angle FBD = \angle FDB - \angle FCE = 90^\circ.$$

Find the area of $\triangle CEF$.

Solution. Extend BD and CE to meet at A. $\angle BAC = \angle FEC - \angle FBD = \angle FDB - \angle FCE = 90^\circ$.

Let $s = [CEF], u = [AEF], v = [ADF]$, then

$$[BDF] = \frac{1}{2}(FD)(FB)\sin\angle DFB = \frac{1}{2}(x)(2y)\sin\angle DFB = \frac{1}{2}(FC)(FE)\sin\angle EFC = s$$

$$[AEF] = \frac{1}{2}[AFB] \Rightarrow u = \frac{1}{2}(v+s),\ [ADF] = \frac{1}{2}[AFC] \Rightarrow v = \frac{1}{2}(u+s) \Rightarrow u = v = s$$

$$\Rightarrow D, E \text{ are midpoints of } AB, AC \text{ respectively} \Rightarrow DA = 8, AE = 10$$

$$[BCF] = 2[FCE] = 2s \Rightarrow [ABC] = 6s \Rightarrow s = \frac{1}{6}[ABC] = \frac{40}{6} = \boxed{\frac{20}{3}.}$$

□

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Problem 9.8.4. (*1 point*) Find one pair of positive integers x, y such that $x^2 + 3y$ are $y^2 + 3x$ are perfect squares.

(*9 points*) Find all pairs of integers (x, y) such that $x^2 + 3y$ and $y^2 + 3x$ are perfect squares.

Solution. For the first question it is easy to see that $\boxed{x = y = 1}$ is a solution.

Note that since x, y are positive integers

$$(x^2 + 3y) + (y^2 + 3x) < x^2 + 4x + 4 + y^2 + 4y + 4 = (x + 2)^2 + (y + 2)^2$$

Thus one of the following is true: $x^2 + 3y < (x + 2)^2$ or $y^2 + 3x < (y + 2)^2$. WLOG, $x^2 + 3y < (x + 2)^2$, then since $x^2 + 3y > x^2$, thus:

$$x^2 + 3y = (x + 1)^2 \Rightarrow 3y = 2x + 1 \Rightarrow y \text{ is odd} \Rightarrow \exists k \geq 0 : \ y = 2k + 1 \Rightarrow x = 3k + 1$$

$$y^2 + 3x = (2k + 1)^2 + 3(3k + 1) = 4k^2 + 13k + 4 \Rightarrow \begin{cases} 4k^2 + 13k + 4 - (2k + 3)^2 = k - 5 > 0, \text{ if } k \geq 6 \\ 4k^2 + 13k + 4 - (2k + 4)^2 = -3k - 12 < 0, \ \forall k \end{cases}$$

Case 1: there are no solution if $k \geq 6$.

Case 2: if $k = 5$, then $x = 16, y = 11, x^2 + 3y = 289 = 17^2$, $y^2 + 3x = 169 = 13^2$.

Case 3: $0 < k < 5$, it is easy to verify that there is no solution.

Case 4: $k = 0$, $x^2 + 3y = 4 = 2^2$, $y^2 + 3x = 4 = 2^2$.

Thus, there are three solutions $\boxed{(1, 1), (11, 16), (16, 11).}$ □

Problem 9.8.5. (*10 points*) a, b are arbitrary positive real numbers. x, y are real numbers such that

$$ax^2 + by^2 = ab.$$

What is the value of $x + y$ when xy reaches maximal value?

Solution. Note that

$$\begin{aligned} &ax^2 + by^2 = ab \Rightarrow (\sqrt{a}x)^2 + (\sqrt{b}y)^2 - 2(\sqrt{a}x)(\sqrt{b}y) = ab - 2(\sqrt{a}x)(\sqrt{b}y) \\ &\Rightarrow 2xy\sqrt{ab} = ab - (\sqrt{a}x - \sqrt{b}y)^2 \leq ab. \end{aligned}$$

xy reaches the maximal value of $\frac{\sqrt{ab}}{2}$, when $\sqrt{a}x = \sqrt{b}y$. It is obvious that $x \neq 0, y \neq 0$, so:

$$y\frac{\sqrt{a}}{\sqrt{b}}x \Rightarrow ax^2 + b\left(\frac{\sqrt{a}}{\sqrt{b}}x\right)^2 = ab \Rightarrow 2ax^2 = ab \Rightarrow x = \pm\sqrt{\frac{b}{2}}, y = \pm\sqrt{\frac{a}{2}}$$

Hence there are two values for $x + y$: $\boxed{(\sqrt{\frac{b}{2}}, \sqrt{\frac{a}{2}}), \ (-\sqrt{\frac{b}{2}}, -\sqrt{\frac{a}{2}}).}$ □

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Problem 9.8.6. (*2 points*) Find the minimal value of the following expression

$$|x-1|+|x-2|.$$

(*8 points*) Find the minimal value of the following expression

$$|x-1|+|x-2|+|x-4|+\ldots+|x-2^{2024}|.$$

Solution. It is easy to prove the following claim:

Claim — $|x-a|+|x-b| \geq |a-b|$, the equality stands if x is between a and b.

For the first question,

$$|x-1|+|x-2| \geq |1-2| = \boxed{1.}$$

The equality stands when $x \in [1,2]$.

Now,

$$|x-2^i|+|x-2^{2024-i}| \geq |2^{2024-i}-2^i| = 2^{2024-i}-2^i,\ \forall i \in \{0,1,\ldots,1011\}$$
$$|x-2^{2012}| \geq 0.$$

Thus, the minimal value of the expression is:

$$\sum_{i=0}^{1011}(2^{2024-i}-2^i) = (2^{1013}-1)(\sum_{i=0}^{1011}2^i) = \boxed{(2^{1013}-1)(2^{2012}-1).}$$

This, indeed, is reached when $x = 2^{2012}$. □

Problem 9.8.7. (*10 points*) $ABCD$ is a rectangle where $AB = a$, $AD = b$, and $b > a$. P and Q are points on BD and BC, respectively. Find the minimal value of $CP + PQ$.

Solution. Let C' be the reflection of C over BD. Let E be the foot of the perpendicular from C' to BC.

Then $CP + PQ = C'P + PQ \geq C'E$.

$$CC' \perp BD \Rightarrow C'C \cdot BD = 4[BCD] = 2 \cdot BC \cdot CD \Rightarrow CC' = \frac{2ab}{\sqrt{a^2+b^2}}$$

$$\triangle CEC' \sim \triangle DCB \Rightarrow \frac{C'E}{CC'} = \frac{BC}{DB} \Rightarrow C'E = \frac{CC' \cdot BC}{BD} = \boxed{\frac{2ab^2}{a^2+b^2}.}$$

□

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Problem 9.8.8. (*3 points*) Find the maximal value of $2\sin^4 x\cos^2 x$.

(*7 points*) Find the maximal value of $\cos^3 x + \sin^2 x - \cos x$.

Solution. For the first question, by AM-GM:

$$2\sin^4 x\cos^2 x = (\sin^2 x)(\sin^2 x)(2\cos^2 x) \le \left(\frac{(\sin^2 x) + (\sin^2 x) + (2\cos^2 x)}{3}\right)^3 = \boxed{\frac{8}{27}.}$$

For the second question, let:

$$f(x) = \cos^3 x + \sin^2 x - \cos x = \sin^2 x - \cos x(1 - \cos^2 x) = \sin^2 x(1 - \cos x)$$
$$4\sin^2\frac{x}{2}\cos^2\frac{x}{2}\cdot 2\sin^2\frac{x}{2} = 8\sin^2\frac{x}{2}\sin^2\frac{x}{2}\cos^2\frac{x}{2}$$

By result of the first part, $f(x) \le 4\frac{8}{27} = \boxed{\frac{32}{27}.}$ □

Problem 9.8.9. A, B, P are points on the perimeter of the unit circle centred at O such that $\angle APB = \angle AOB$. Find the length of the chord AB.

Solution. Let C be point on the major arc AB.

It is easy to see that:

$$\widehat{APB} = \angle AOB = \angle APB = \frac{1}{2}\widehat{ACB} = \frac{1}{2}(360^\circ - \widehat{APB}) \Rightarrow \widehat{APB} = 120^\circ.$$

By the Law of Cosines: $AB^2 = OA^2 + OB^2 - 2(OA)(OB)\cos\angle AOB = 3 \Rightarrow AB = \boxed{\sqrt{3}.}$ □

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Problem 9.8.10. The sequence (a_n) is defined as follow:

$$a_0 = 2,\ a_{n+1} = 5a_n + \sqrt{24a_n^2 - 96},\ \forall n \geq 0.$$

Find a_{2024}.

Solution. First, by isolating the square root and squaring both sides:

$$a_{n+1} = 5a_n + \sqrt{24a_n^2 - 96} \Rightarrow (a_{n+1} - 5a_n)^2 = 24a_n^2 - 96 \Rightarrow a_{n+1}^2 - 10a_na_{n+1} + a_n^2 = -96 \quad (*)$$

Similarly:

$$a_{n+2}^2 - 10a_{n+1}a_{n+2} + a_{n+1}^2 = -96 \quad (**)$$

Now, it is easy to see that $a_0 = 2 > 0, a_{n+1} \geq 5a_n > a_n$, thus (a_n) is a strictly increasing sequence or $a_{n+2} > a_n$. Thus by (*) and (**), a_{n+2} and a_n are the two roots of:

$$x^2 - 10a_{n+1}a + a_{n+1}^2 + 96 = 0 \Rightarrow a_n + a_{n+2} = 10a_{n+1} \Rightarrow a_{n+2} - 10a_{n+1} + a_n = 0, \forall n \geq 0.$$

Thus the characteristic polynomial of the sequence (a_n) is $x^2 - 10x + 1 = 0$, whose roots are $5 \pm 2\sqrt{6}$, thus the generic term can be expressed as:

$$a_n = c_1(5 + 2\sqrt{6})^n + c_2(5 - 2\sqrt{6})^n,\ \text{where } c_1, c_2 \text{ are some constants.}$$
$$a_0 = 2, a_1 = 10 \Rightarrow c_1 = c_2 = 1 \Rightarrow a_n = (5 + 2\sqrt{6})^n + (5 - 2\sqrt{6})^n.$$

Therefore $a_{2024} = \boxed{(5 + 2\sqrt{6})^{2024} + (5 - 2\sqrt{6})^{2024}.}$ □

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9.9 IC Test for Level 2

Problem 9.9.1. I am thinking of a two-digit number. If the digits of my number are reversed, the new number is 36 greater than my original number. If the tens digit of my original number is doubled and the units digit is halved, the new number is 17 greater than my original number. What is my original number?

Solution. Let t be the tens digit and u be the units digit of my number. So, the value of my number is $10t + u$. When the digits of my number are reversed, then u is the tens digit and t is the units digit. This number has value $10u + t$. So, we have $10u + t - (10t + u) = 36$, or $9u - 9t = 36$. Dividing this equation by 9 gives $u - t = 4$.

If the tens digit of my original number is doubled and the units digit is halved, then the new tens digit is $2t$ and the new units digit is $u/2$. This number has value $2t(10) + u/2$, or $20t + u/2$. This number is 17 more than my original number, so $(20t + u/2) - (10t + u) = 17$, or $10t - u/2 = 17$.

From $u - t = 4$, we have $t = u - 4$. Substituting this into $10t - u/2 = 17$ gives

$$10(u-4) - \frac{u}{2} = 17 \Rightarrow 10u - 40 - \frac{u}{2} = 17 \Rightarrow \frac{19u}{2} = 57 \Rightarrow u = 6.$$

So, we have $t = 6 - 4 = 2$, and my original number was $\boxed{26}$. □

Problem 9.9.2. How many triangles can be formed using the vertices of a regular dodecagon (a 12-sided polygon)?

Solution. No three vertices are collinear, so any combination of 3 vertices will make a triangle. This means that choosing 3 out of 12 vertices will form a triangle (!) and the number of them is $\binom{12}{3} = \boxed{220}$. □

Problem 9.9.3. Find the vertex angle of an isosceles triangle if one base angle is $6°$ less than half the vertex angle.

Solution. Let the measure of the vertex angle be x. Therefore, each base angle has measure $x/2 - 6°$ as given in the problem. Together, the three angles sum to $180°$, so we have $x + 2(x/2 - 6°) = 180°$. Therefore, $x = \boxed{96°}$. □

Problem 9.9.4. Mr. Namm baked 252 cookies, Mrs. Clancy baked 105 cookies, and Mr. Palavas baked 168 cookies. Each baker packaged them with the same number of cookies in each package. What is the greatest number of cookies that could be in each package?

Solution. The number of cookies in each package must be a divisor of each of 252, 105, and 168. Since $\gcd(252, 105) = 21$, we check to see if 21 is also a divisor of 168. It is, so $\boxed{21}$ is the greatest possible number of cookies in each package. □

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9.10 IC Test for Level 3

Problem 9.10.1. I have 2 cartons of eggs. 20% of the eggs in the first carton are red, while 25% of the eggs in the second carton are red. If the second carton has 3 times as many eggs as the first, what percentage of my eggs are red?

Solution. Suppose there are x eggs in the first carton, so there are $3x$ eggs in the second. Since 20% of the eggs in the first carton are red, $0.2x$ eggs in the first carton are red. Since 25% of the eggs in the second carton are red, and the second carton has $3x$ eggs, there are $0.25(3x) = 0.75x$ red eggs in the second carton. Therefore, out of the total of $x + 3x = 4x$ eggs in the two cartons, we have $0.2x + 0.75x = 0.95x$ red eggs, for a total percentage of

$$\frac{0.95x}{4x} = \frac{0.95}{4} = 0.2375 = \boxed{23.75\%}.$$

We can quickly check our answer by pretending there are 100 eggs in the first carton, so 20 of them are red. There are then $3(100) = 300$ eggs in the second carton, of which $(0.25)(300) = 75$ are red, for a total of 95 red eggs out of 400 total. So, $95/400 = 23.75\%$ of the eggs are red. □

Problem 9.10.2. I have tiled my square bathroom wall with congruent square tiles. All the tiles are red, except those along the two diagonals, which are all blue (i.e. the corners are blue and all the tiles along the diagonals between each pair of opposite corners are blue). If I used 121 blue tiles, how many red ones did I use?

Solution. The square has dimensions $n \times n$. Each diagonal has n tiles.

If n is even, then the total number of blue tiles is $2n$, since the two diagonals don't intersect.

If n is odd, then the total number of blue tiles is $n + n - 1 = 2n - 1$; we must subtract 1 because the center tile is counted twice, once for each diagonal.

But we know that there are 121 blue tiles, which is an odd number, so $121 = 2n - 1$. This gives that the dimension of the square is $n = 61$, meaning there are $n \times n = 3721$ total tiles.

Since all the other tiles are red, there are $3721 - 121 = \boxed{3600}$ red tiles. □

Problem 9.10.3. Find DE in the diagram below.

Solution. Since $AB/AE = 6/20 = 3/10$ and $AC/AD = 9/30 = 3/10$, we have $AB/AE = AC/AD$. This, combined with $\angle BAC = \angle EAD$ gives us $\triangle ABC \sim \triangle AED$. Therefore, $ED/BC = DA/AC$, so $DE/13 = 30/9$. Finally, we have $DE = 13(30/9) = \boxed{130/3}$. □

Problem 9.10.4. How many positive divisors do 8400 and 7560 have in common?

Solution.

$$\gcd(7560, 8400) = 840 = 2^3 \cdot 3^1 \cdot 5^1 \cdot 7^1.$$

The common divisors of 7560 and 8400 are the divisors of their GCD:

$$t(840) = (3+1)(1+1)(1+1)(1+1) = \boxed{32}.$$

□

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9.11 IC Test for Level 4

Problem 9.11.1. A is a constant such that the graph of the equation $Ax - 3y = 6$ passes through the point $(1, -3)$. Find A.

Solution. Because $(1, -3)$ is on the graph of $Ax - 3y = 6$, the equation must be true when $x = 1$ and $y = -3$. Therefore, we have

$$A(1) - 3(-3) = 6 \Rightarrow A + 9 = 6 \Rightarrow A = \boxed{-3.}$$

□

Problem 9.11.2. Two fair 6-sided dice are rolled. What is the probability that at least one of the dice shows a 1?

Solution. There are 6 ways that the first roll can be a 1: (1,1), (1,2), ..., (1,6), and there are 6 ways that the second roll can be a 1: (1,1), (2,1), ..., (6,1). However, we counted twice when they are both 1, so the number of ways that one of the two dice is 1 is $6 + 6 - 1 = 11$. This means that the probability that at least one of the dice is 1 is $\boxed{\frac{11}{36}}$. □

Problem 9.11.3. In triangle ABC, $\angle A = 100°$, $\angle B = 50°$, and $\angle C = 30°$. H is on $\overline{BC}$ and M on $\overline{AC}$ such that $\overline{AH}$ is an altitude and $\overline{BM}$ is a median. Find $\angle MHC$.

Solution. Since $\overline{AH}$ is an altitude of $\triangle ABC$, $\triangle AHC$ is a right triangle. M is the midpoint of hypotenuse $\overline{AC}$ of this triangle, so $HM = MC = AM$. Since $MH = MC$, we have $\angle MHC = \angle MCH$. From $\triangle ABC$, we have $\angle MHC = \angle C = \boxed{30°}$. □

Problem 9.11.4. What is the greatest three-digit number divisible by both 7 and 8?

Solution. In order to identify the greatest three-digit number that is divisible by both 7 and 8, we first need to determine what kinds of integers are divisible by both 7 and 8. Any common multiple of 7 and 8 must be a multiple of their LCM:

$$\text{lcm}[7, 8] = 2^3 \cdot 7 = 56,$$

so common multiples of 7 and 8 can be written as $56n$ for integer values of n.

Now we translate the problem into the language of math. We want the largest value of $56n$ such that

$$56n < 1000.$$

If we can find the largest value of n for which the inequality is true, then we will know the largest value of $56n$. We can isolate n in the inequality by dividing both sides by 56:

$$n < \frac{1000}{56} = \frac{125}{7} = 17\,\frac{6}{7}.$$

The largest value of n less than the fraction on the right is 17. Our answer is $56 \cdot 17 = \boxed{952}$. □

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9.12 IC Test for Level 5

Problem 9.12.1. Let w and z be complex numbers. Show that $\overline{w+z} = \overline{w} + \overline{z}$ and $\overline{w \cdot z} = \overline{w} \cdot \overline{z}$.

Solution. Let $w = a + bi$ and $z = c + di$, so that

$$\begin{aligned} w + z &= a + bi + c + di \\ &= (a + c) + (b + d)i, \end{aligned}$$

$$\begin{aligned} wz &= (a + bi)(c + di) \\ &= ac + adi + bci + bdi^2 \\ &= (ac - bd) + (ad + bc)i. \end{aligned}$$

We also have $\overline{w} = a - bi$ and $\overline{z} = c - di$. So, we have

$$\begin{aligned} \overline{w+z} &= \overline{(a + c) + (b + d)i} \\ &= (a + c) - (b + d)i, \end{aligned}$$

$$\begin{aligned} \overline{w} + \overline{z} &= a - bi + c - di \\ &= a + c - bi - di \\ &= (a + c) - (b + d)i. \end{aligned}$$

Therefore, $\overline{w+z} = \overline{w} + \overline{z}$.

We also have

$$\begin{aligned} \overline{wz} &= \overline{(ac - bd) + (ad + bc)i} \\ &= (ac - bd) - (ad + bc)i, \end{aligned}$$

$$\begin{aligned} \overline{w} \cdot \overline{z} &= (a - bi)(c - di) \\ &= ac - adi - bci + bdi^2 \\ &= (ac - bd) - (ad + bc)i. \end{aligned}$$

So, $\overline{wz} = \overline{w} \cdot \overline{z}$. □

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Problem 9.12.2. A line segment with length 1 is broken at two random points along its length. What is the probability that the three new segments form a triangle?

Solution. Three lengths a, b, c can be the sides of the triangle if and only if they satisfy the Triangle Inequality in every possible way; that is, if $a+b > c$, $b+c > a$, and $c+a > b$. Since our line segment is the unit interval, and we are breaking it at points x and y with $0 < x < y < 1$. Then the three resulting segments will form a triangle if and only if $x < \frac{1}{2}$, $y > \frac{1}{2}$, and $y - x < \frac{1}{2}$.

So the "possible" region is the triangle with vertices $(0,0)$, $(0,1)$, and $(1,1)$, and the "successful" region is as shaded in the diagram above. Therefore the probability of success is $\frac{\frac{1}{8}}{\frac{1}{2}} = \boxed{\frac{1}{4}}$. □

Problem 9.12.3. If the numbers denoting the perimeter and area of a square are equal, what is the length of its diagonal?

Solution. Let the side length of the square be x. Then the perimeter is $4x$ and the area is x^2, so $4x = x^2$, or $x = 4$. The length of a diagonal is then $\boxed{4\sqrt{2}}$. □

Problem 9.12.4. Find the value of the base b such that the following addition problem is correct: $\overline{6651_b} + \overline{115_b} = \overline{10066_b}$.

Solution. In the two rightmost columns of addition, there is no carrying, but in the third, there is, so $6_b + 1_b = 10_b$ and $b = \boxed{7}$. □