Review and Extension — Divisibility and Congruences

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May 14, 2022

1 Exam Review

2 Farey sequences

Let n be a fixed positive integer. Let $\frac{a_1}{b_1}, \ldots, \frac{a_k}{b_k}$ be the rational numbers between 0 and 1 inclusive with denominators at most n, written in increasing order and lowest terms.

- Prove that for each i, $a_{i+1}b_i - a_i b_{i+1} = 1$.
- Prove that the rational number x with smallest denominator such that $\frac{a_i}{b_i} < x < \frac{a_{i+1}}{b_{i+1}}$ is $\frac{a_i+a_{i+1}}{b_i+b_{i+1}}$.
- Which pairs of numbers appear as consecutive b_is?

3 Dirichlet Convolution and Mobius Inversion

Let $f : \mathbb{N} \to \mathbb{R}$ and $g : \mathbb{N} \to \mathbb{R}$ be two functions. We define the *Dirichlet convolution* $f * g$ as

$$(f * g)(n) = \sum_{d|n} f(d) g\left(\frac{n}{d}\right).$$

We define the functions $d,\ \sigma,\ \varphi$ as before and also define the functions

$$\zeta(n) = 1,\ \psi(n) = n.$$

- Prove that $*$ is associative: that is, $(a * b) * c = a * (b * c)$.
- Prove that if a and b are multiplicative then so is $a * b$.
- Find a function δ such that $\delta * a = a$ for all functions a.
- Find a function μ such that $\mu * \zeta = \delta$.
- Prove that $g = f * \zeta \iff f = g * \mu$.
- Find $\zeta * \zeta,\ \psi * \zeta$ and $\varphi * \zeta$.
- Prove that
$$\sum_{i=1}^{n} f(i) \left\lfloor \frac{n}{i} \right\rfloor = \sum_{j=1}^{n} (f * \zeta)(j).$$

4 Homework

1. Given three distinct natural numbers a, b, c, show that

$$\gcd(ab+1, bc+1, ca+1) \leq \frac{a+b+c}{3}.$$

2. Suppose that $(a_1, b_1), (a_2, b_2), \ldots, (a_{100}, b_{100})$ are distinct ordered pairs of nonnegative integers. Let N denote the number of pairs of integers (i, j) satisfying $1 \leq i < j \leq 100$ and $|a_i b_j - a_j b_i| = 1$. Determine the largest possible value of N over all possible choices of the 100 ordered pairs.

3. For a positive integer n, let $f(n)$ be the number of binary strings of length n that can't be expressed as an m-fold repetition of another binary string for any $m > 1$.

   For example, $f(6) = 54$ since the only strings of length 6 that can be expressed as an m-fold repetition of another binary string for some $m > 1$ are 000000, 001001, 010010, 010101, 011011, 100100, 101010, 101101, 110110, 111111.

   (a) Find two functions g and h, in closed form, such that $f = g * h$.

   (b) Prove that $n \mid f(n)$.

   (c) Find all n for which $n \mid \displaystyle\sum_{i=1}^{n} f(i) \left\lfloor \frac{n}{i} \right\rfloor$.