

Number Theory: Example Sheet 2 of 4

1. Evaluate the following Jacobi symbols (in fact, they are Legendre symbols):

$$\left(\frac{20964}{1987}\right), \quad \left(\frac{741}{9283}\right), \quad \left(\frac{5}{160465489}\right), \quad \left(\frac{3083}{3911}\right).$$

Did it help to know that they are Legendre symbols?

2. Find all odd primes p for which 21 is a quadratic residue modulo p .
3. Prove that 3 is a quadratic non-residue modulo any Mersenne prime $2^n - 1$, with $n > 2$.
4. Let p be a prime with $p \equiv 1 \pmod{4}$. Prove that the sum of the quadratic residues in the interval $[1, p-1]$ is equal to the sum of the quadratic non-residues in this interval. Does this hold if $p \equiv 3 \pmod{4}$?
5. Let p be an odd prime and $\zeta = e^{2\pi i/p}$. Let

$$\tau = \sum_{a=1}^{p-1} \left(\frac{a}{p}\right) \zeta^a.$$

Show that $\tau^2 = \pm p$, and determine how the sign depends on p .

6. Let a be a positive integer that is not a square. Prove that there are infinitely many odd primes p such that $\left(\frac{a}{p}\right) = -1$.
7. Let p be a prime with $p \equiv 3 \pmod{8}$. Show that

$$\sum_{a=1}^{p-1} a \left(\frac{a}{p}\right) = \sum_{a=1}^{(p-1)/2} (2a-p) \left(\frac{a}{p}\right)$$

and

$$\sum_{a=1}^{p-1} a \left(\frac{a}{p}\right) = \sum_{a=1}^{(p-1)/2} (p-4a) \left(\frac{a}{p}\right).$$

Deduce that if $p > 3$ then

$$\sum_{a=1}^{(p-1)/2} \left(\frac{a}{p}\right) \equiv 0 \pmod{3}.$$

8. Are the forms $3x^2 + 2xy + 23y^2$ and $2x^2 + 4xy + 5y^2$ equivalent (under the action of $\text{SL}_2(\mathbb{Z})$)? Are the forms $15x^2 - 15xy + 4y^2$ and $3x^2 + 9xy + 8y^2$ equivalent?

9. Prove that equivalence of binary quadratic forms is an equivalence relation.
10. Make a list of all reduced positive definite binary quadratic forms of discriminant $-d$, where $d = 8, 11, 12, 16, 19, 23, 163$.
11. Find the smallest positive integer that can be represented by the form $4x^2 + 17xy + 20y^2$. What is the next largest? And the next?
12. Find congruence conditions for a prime p to be represented by the form $x^2 + 3y^2$.
13. Is there a positive definite binary quadratic form that represents 2 and the primes congruent to 1 or 3 modulo 8, but no other primes? Is there such a form representing the primes congruent to 1 modulo 4 only?
14. Find congruence conditions for a positive integer n to be properly represented by at least one of the two forms $x^2 + xy + 4y^2$ and $2x^2 + xy + 2y^2$.
Assume that n is coprime to 15, and properly represented by at least one of the forms. Show that congruence conditions modulo 15 allow one to decide which form represents n .
15. (Optional, for enthusiasts of group theory) Let G be a group, and H a subgroup of finite index $(G : H) = m$. Write G as the union of cosets $x_i H$ ($1 \leq i \leq m$). Then if $g \in G$, $gx_i H = x_j H$ for some j (depending on g). Write \bar{g} for the mapping $i \mapsto j$. Recall from the proof of Cayley's Theorem that $g \mapsto \bar{g}$ is a permutation of $\{1, \dots, m\}$ and that the map $g \mapsto \bar{g}$ is a homomorphism from G to the symmetric group S_m .

From now on, assume that H is abelian.

(i) Show that for every $g \in G$, the product

$$T(g) = \prod_{i=1}^m x_{\bar{g}(i)}^{-1} g x_i$$

belongs to H , and that T is a homomorphism from G to H (called the *transfer* homomorphism). Does T depend on the choice of coset representatives?

(ii) Show that if G is abelian, then $T(g) = g^m$.

(iii) Explain why, when $G = (\mathbb{Z}/p\mathbb{Z})^\times$ and $H = \{\pm 1\}$, (ii) is just Gauss's Lemma.