

## Math 115 - Midterm 1+2 Theorems

1. **Corollary.** Let  $a = \prod_p p^{\alpha(p)}$ ,  $b = \prod_p p^{\beta(p)}$ ,  $c = \prod_p p^{\gamma(p)}$ .
  - (a)  $ab = c \iff \alpha(p) + \beta(p) = \gamma(p) \quad \forall p$ .
  - (b)  $a \mid c \iff \alpha(p) \leq \gamma(p) \quad \forall p$ .
  - (c)  $c$  is a common divisor of  $a$  and  $b$  iff  $\gamma(p) \leq \min(\alpha(p), \beta(p)) \quad \forall p$ .
  - (d)  $\gcd(a, b) = \prod_p p^{\min(\alpha(p), \beta(p))}$ .
  - (e)  $\text{lcm}(a, b) = \prod_p p^{\max(\alpha(p), \beta(p))}$ .
  - (f)  $c$  is the square of an integer iff  $\gamma(p)$  is even for all  $p$ .
2. **Pascal's Identity.**  $\binom{\alpha+1}{k+1} = \binom{\alpha}{k+1} + \binom{\alpha}{k}$ .
3. **Binomial Theorem.**  $(x + y)^n = \sum_{i=0}^n \binom{n}{i} x^{n-i} y^i$ .
4. **Theorem.** If  $a \equiv b \pmod{m}$ , then  $\gcd(a, m) = \gcd(b, m)$ .
5. **Euler's Theorem.** If  $\gcd(a, m) = 1$ , then  $a^{\phi(m)} \equiv 1 \pmod{m}$ .
6. **Fermat's Little Theorem.** Let  $p$  be a prime. Then:
  - (a)  $\forall a \in \mathbb{Z}$  and  $a$  not a multiple of  $p$ , then  $a^{p-1} \equiv 1 \pmod{p}$ .
  - (b)  $\forall a \in \mathbb{Z}$ ,  $a^p \equiv a \pmod{p}$ .
7. **Wilson's Theorem.** If  $p$  is prime, then  $(p-1)! \equiv -1 \pmod{p}$ .
8. **Solvability of  $x^2 \equiv -1 \pmod{p}$ .** Let  $p$  be a prime. Then,  $x^2 \equiv -1 \pmod{p}$  has a solution  $x \in \mathbb{Z}$  iff  $p = 2$  or  $p \equiv 1 \pmod{4}$ .
9. **Fermat's Theorem on Sum of Squares.** Let  $p$  be a prime such that  $p \equiv 1 \pmod{4}$ . Then  $p$  can be written as  $p = a^2 + b^2$  with  $a, b \in \mathbb{Z}$ .
10. **Solving Degree 1 Congruences.** Let  $a, b \in \mathbb{Z}$  and let  $g = \gcd(a, m)$ . Then:
  - (a) The congruence  $ax \equiv b \pmod{m}$  has a solution iff  $g \mid b$ .
  - (b) If (a) is true, then  $\frac{a}{g}x \equiv \frac{b}{g} \pmod{\frac{m}{g}}$  has a solution modulo  $\frac{m}{g}$ .
11. **Chinese Remainder Theorem.** If  $x \equiv a_1 \pmod{m_1}, \dots, x \equiv a_k \pmod{m_k}$  (where the  $m_i$ 's are pairwise relatively prime), then let  $M = m_1 m_2 \cdots m_k$  and  $y_i = \text{inverse} \left( \frac{M}{m_i} \pmod{m_i} \right)$ . Then, a solution to the simultaneous congruence is given by  $x \equiv a_1 \frac{M}{m_1} y_1 + \cdots + a_k \frac{M}{m_k} y_k \pmod{M}$ .
12. **Theorem.** If  $m \in \mathbb{Z}_{>0}$ , then  $\phi(m) = \left( \prod_{p \text{ prime}, p \mid m} \left(1 - \frac{1}{p}\right) \right) \cdot m$ .
13. **RSA Cryptography Lemma.** Suppose  $m \in \mathbb{Z}_{>0}$  and  $\gcd(a, m) = 1$ . Let  $h, h' \in \mathbb{Z}_{>0}$  such that  $hh' \equiv 1 \pmod{\phi(m)}$ . Then  $a^{kh'} \equiv a \pmod{m}$ .
14. **Primality Testing.** If there is an integer  $a$  such that  $0 < a < m$  and  $a^{m-1} \not\equiv 1 \pmod{m}$ , then  $m$  is not prime.

15. **Hensel's Lemma.** To solve the congruence  $f(x) \equiv 0 \pmod{p^k}$ , first find the solutions to  $f(x) \equiv 0 \pmod{p}$ . Then, for each solution  $a_1$  to  $f(x) \equiv 0 \pmod{p}$ , "lift" its solution by the recurrence relation  $a_2 = a_1 - f(a_1)\overline{f'(a_1)}$ , where  $\overline{f'(a_1)}$  is found by solving  $f'(a_1)\overline{f'(a_1)} \equiv 1 \pmod{p}$  for  $\overline{f'(a_1)}$ . To higher powers, we generalize this recurrence relation to  $a_{j+1} = a_j - f(a_j)\overline{f'(a_j)}$ .
16. **Hensel's Lemma (General Case).** Let  $f \in \mathbb{Z}[x]$ ,  $a \in \mathbb{Z}$ ,  $j \in \mathbb{Z}_{>0}$ , and  $\tau \in \mathbb{N}$ . Assume that  $f(a) \equiv 0 \pmod{p^j}$ ,  $p^\tau \parallel f'(a)$  and  $j \geq 2\tau + 1$ . Then:
  - (a) There is a  $\tau \in \mathbb{Z}$ , unique modulo  $p$ , such that  $f(a + tp^{j-\tau}) \equiv 0 \pmod{p^{j+1}}$ .
  - (b) If  $b \equiv a \pmod{p^{j-\tau}}$ , then  $f(b) \equiv f(a) \pmod{p^j}$  and  $p^j \parallel f'(b)$ .
17. **Corollary to Hensel's Lemma.** Let  $f \in \mathbb{Z}[x]$ ,  $p$  be prime,  $a \in \mathbb{Z}$ ,  $\tau \in \mathbb{N}$ , and let  $l \in \mathbb{Z}$ . Assume that  $p^\tau \parallel f'(a)$ ,  $f(a) \equiv 0 \pmod{p^l}$ , and  $l \geq 2\tau + 1$ . Then, for any  $\alpha \geq l$ , there exists a  $b \in \mathbb{Z}$ , unique modulo  $p^{\alpha-\tau}$ , such that  $b \equiv a \pmod{p^{l-\tau}}$  and  $f(b) \equiv 0 \pmod{p^\alpha}$ .
18. **Lemma.** Let  $f \in \mathbb{Z}[x]$  and  $p$  prime. Assume that  $a_1, \dots, a_r$  are roots of  $f \pmod{p}$ , with  $r > 0$  and  $a_i \equiv a_j \pmod{p}$  for all  $i \neq j$ . Then there is a polynomial  $g \in \mathbb{Z}[x]$  such that  $f(x) \equiv (x - a_1)g(x) \pmod{p}$ . Also, for any such  $g$ ,  $a_1, \dots, a_r$  are roots of  $g$  modulo  $p$ .
19. **Theorem.** If  $f(x) \equiv 0 \pmod{p}$  has (at least)  $r$  solutions  $x \equiv a_1, \dots, a_r \pmod{p}$ , with  $a_i \not\equiv a_j \pmod{p}$  (for all  $i \neq j$ ), then there is a polynomial  $q \in \mathbb{Z}[x]$  such that  $f(x) \equiv (x - a_1) \cdots (x - a_r)q(x) \pmod{p}$ .
20. **Theorem 2.26.** The congruence  $f(x) \equiv 0 \pmod{p}$  of degree  $n \geq 0$  has at most  $n$  solutions.
21. **Corollary 2.27.** If  $f \in \mathbb{Z}[x]$  has degree  $n \geq 0$  (thus,  $f \neq 0$ ), and the congruence  $f(x) \equiv 0 \pmod{p}$  has more than  $n$  distinct solutions, then  $f \equiv 0 \pmod{p}$  (as polynomials).
22. **Lemma.** Let  $f \in \mathbb{Z}[x]$  be a monic polynomial of degree  $n$ . If the congruence  $f(x) \equiv 0 \pmod{p}$  has  $n$  solutions,  $x \equiv a_1, \dots, a_n \pmod{p}$ , distinct modulo  $p$ , then  $f(x) \equiv (x - a_1) \cdots (x - a_n) \pmod{p}$ .
23. **Proposition.** Let  $f \in \mathbb{Z}[x]$ . Then there is a well-defined function  $\tilde{f}$  with  $\tilde{f} : \mathbb{Z}/m\mathbb{Z} \rightarrow \mathbb{Z}/m\mathbb{Z}$  given by  $\tilde{f}(\tilde{a}) = \tilde{f(a)}$  for all  $\tilde{a} \in \mathbb{Z}/m\mathbb{Z}$ .
24. **Proposition.** Let  $f, g \in \mathbb{Z}[x]$ . If  $f \equiv g \pmod{m}$  (as polynomials), then  $\tilde{f} = \tilde{g}$  (as functions  $\mathbb{Z}/m\mathbb{Z} \rightarrow \mathbb{Z}/m\mathbb{Z}$ ).
25. **Corollary.** Let  $\psi : \mathbb{Z}/m\mathbb{Z} \rightarrow \mathbb{Z}/m\mathbb{Z}$  be any function. If  $\psi$  can be given by a polynomial (i.e.  $\psi = \tilde{f}$  for some  $f \in \mathbb{Z}[x]$ ), then it can be given by a polynomial of degree less than  $p$ .
26. **Theorem 2.28.** If  $F : \mathbb{Z}/p\mathbb{Z} \rightarrow \mathbb{Z}/p\mathbb{Z}$ , then there is a polynomial  $f \in \mathbb{Z}[x]$  with degree at most  $p - 1$  such that  $F(x) \equiv f(x) \pmod{p}$  for all residue classes  $x$  modulo  $p$ .
27. **Theorem.** The polynomials in Theorem 2.28 are unique modulo  $p$ .
28. **Corollary 2.30.** Suppose  $d > 0$  and  $d \mid (p - 1)$ , then the congruence  $x^d \equiv 1 \pmod{p}$  has exactly  $d$  solutions.
29. **Proposition.** Let  $a$  have order  $h$  modulo  $m$ , and let  $n \in \mathbb{N}$ . Then,  $a^n \equiv 1 \pmod{m}$  iff  $n$  is a multiple of  $h$ .
30. **Corollary.** If  $a$  has order  $h$  (modulo  $m$ ), then  $h \mid \phi(m)$ .
31. **Corollary.** Let  $m, m' \in \mathbb{Z}_{>0}$  and  $a \in \mathbb{Z}$ . Assume that  $a$  has orders  $h$  and  $h'$  modulo  $m$  and  $m'$ , respectively (i.e.  $\gcd(a, m) = \gcd(a, m') = 1$ ). Then, if  $m \mid m'$ , then  $h \mid h'$ .
32. **Proposition.** Suppose  $g$  is a primitive root modulo  $m$ . Then:
  - (a)  $1, g, \dots, g^{\phi(m)-1}$  are distinct modulo  $m$ .

- (b) The above numbers are a reduced residue system modulo  $m$ .
- (c) Let  $a \in \mathbb{Z}$ , with  $\gcd(a, m) = 1$ . Then there exists an  $i \in \mathbb{Z}$  such that for all  $j \in \mathbb{N}$ ,  $g^j \equiv a \pmod{m}$  iff  $j \equiv i \pmod{\phi(m)}$ .
33. If there exists a primitive root  $g$  modulo  $m$ , then you have a theory of discrete logarithms modulo  $m$ .
34. **Generalization of Corollary 2.30.** Assume that there is a primitive root modulo  $m$  and let  $d$  be a positive divisor of  $\phi(m)$ . Then, the congruence  $x^d \equiv 1 \pmod{m}$  has exactly  $d$  solutions.
35. **Generalization of Theorem 2.37.** Assume that there is a primitive root modulo  $m$  and let  $n \in \mathbb{Z}_{>0}$ , and let  $a \in \mathbb{Z}$  coprime to  $m$ . Then the congruence  $x^n \equiv a \pmod{m}$  has  $\gcd(n, \phi(m))$  solutions if  $a^{\phi(m)/\gcd(n, \phi(m))} \equiv 1 \pmod{m}$  or has no solutions otherwise.
36. **Euler's Criterion.** Let  $p$  be an odd prime and let  $a \in \mathbb{Z}$  with  $p \nmid a$ . Assume that there is a primitive root modulo  $p$ . Then,  $x^2 \equiv a \pmod{p}$  has two solutions if  $a^{\frac{p-1}{2}} \equiv 1 \pmod{p}$  or has no solutions otherwise.
37. **Lemma.** Suppose  $a \in \mathbb{Z}$  has order  $h$  modulo  $m$ . Then:
- (a) If  $d > 0$ , and  $d \mid h$ , then  $a^d$  has order  $\frac{h}{d}$  modulo  $m$ .
- (b) For all  $k \in \mathbb{N}$ ,  $a^k$  has order  $\frac{h}{\gcd(h, k)} \pmod{m}$ .
38. **Corollary.** If there is a primitive root modulo  $m$ , then there are  $\phi(\phi(m))$  of them (as residue classes modulo  $m$ ).
39. **Lemma.** Suppose that  $a, b \in \mathbb{Z}$  have order  $h$  and  $k$ , respectively modulo  $m$ , and that  $h$  and  $k$  are coprime. Then,  $ab$  has order  $hk$  modulo  $m$ .
40. If  $p$  is prime, then there exists a primitive root modulo  $p$ .
41. **Lemma.** Let  $m, m' \in \mathbb{Z}_{>0}$  with  $m \mid m'$ . Let  $a \in \mathbb{Z}$ , with  $\gcd(a, m') = 1$ . Then:
- (a)  $\gcd(a, m) = 1$ .
- (b) If  $h, h'$  are the orders of  $a$  and  $m'$  modulo  $m$ , respectively, then  $h \mid h'$ .
42. **Theorem.** Let  $p$  be an odd prime and let  $\alpha \in \mathbb{Z}_{>0}$ . Then there exists a primitive root modulo  $p^\alpha$ .
43. **Diffie-Hellman Key Exchange.** This is a process used in order to initialize the secure line before message transfers occur. Suppose Alice and Bob are the participants. Then:
- (a) They (publicly) agree on a large prime  $p$  (600 digits...) and a primitive root  $g$  modulo  $p$ .
- (b) Alice thinks up a number  $a$ ,  $1 < a < p - 1$ , and sends  $g^a \pmod{p}$  to Bob.
- (c) Bob thinks up a number  $b$ ,  $1 < b < p - 1$ , and sends  $g^b \pmod{p}$  to Alice.
- (d) Alice computes  $(g^b)^a \pmod{p}$  and Bob computes  $(g^a)^b \pmod{p}$ , which becomes their shared key.
44. **Solving Quadratic Congruences Modulo  $p \neq 2$ .** Let  $ax^2 + bx + c \equiv 0 \pmod{p}$  be a quadratic congruence with  $a \not\equiv 0 \pmod{p}$ . First, multiply it by  $\bar{a} \pmod{p}$  to get  $x^2 + \bar{a}bx + \bar{a}c \equiv 0 \pmod{p}$ . Then, complete the square to get  $(x + \frac{\bar{a}b}{2})^2 + \bar{a}c - (\frac{\bar{a}b}{2})^2 \equiv 0 \pmod{p}$ . Then, solve the resulting congruence.
45. **Theorem 3.1.** Let  $a, b \in \mathbb{Z}$ . Then:
- (a)  $\left(\frac{a}{p}\right) \equiv a^{(p-1)/2} \pmod{p}$ .
- (b)  $\left(\frac{ab}{p}\right) = \left(\frac{a}{p}\right) \left(\frac{b}{p}\right)$ .

- (c) If  $a \equiv b \pmod{p}$ , then  $\left(\frac{a}{p}\right) = \left(\frac{b}{p}\right)$ .
- (d) If  $p \nmid a$ , then  $\left(\frac{a^2}{p}\right) = 1$  and  $\left(\frac{a^2 b}{p}\right) = \left(\frac{b}{p}\right)$ .
- (e)  $\left(\frac{1}{p}\right) = 1$  and  $\left(\frac{-1}{p}\right) = (-1)^{(p-1)/2}$ .
46. **Theorem 3.2 (Lemma of Gauss).** Let  $a \in \mathbb{Z}$  be relatively prime to  $p$  and let  $n$  be the number of elements of the set  $\{j \in \{1, 2, \dots, p-1\} \mid ja \pmod{p} > \frac{p}{2}\}$ . Then,  $\left(\frac{a}{p}\right) = (-1)^n$ .
47. **Part of Theorem 3.3.** Let  $a \in \mathbb{Z}$  be relatively prime to  $p$ . Assume also that  $a$  is odd. Let  $t = \sum_{j=1}^{(p-1)/2} \left[\frac{ja}{p}\right]$ . Then,  $\left(\frac{a}{p}\right) = (-1)^t$ .
48. **Quadratic Reciprocity.** We have:
- (a)  $\left(\frac{-1}{p}\right) = 1$  if  $p \equiv 1 \pmod{4}$  and  $-1$  if  $p \equiv -1 \pmod{4}$ .
- (b)  $\left(\frac{2}{p}\right) = 1$  if  $p \equiv \pm 1 \pmod{8}$  and  $-1$  if  $p \equiv \pm 3 \pmod{8}$ .
- (c) For all odd primes  $p, q$  with  $p \neq q$ , we have that  $\left(\frac{p}{q}\right) \left(\frac{q}{p}\right) = (-1)^{\frac{p-1}{2} \cdot \frac{q-1}{2}}$ .
49. **Variation of Theorem 3.4.** If  $p, q$  are odd primes, then  $\left(\frac{q}{p}\right) =$
- (a)  $\left(\frac{p}{q}\right)$  if  $p \equiv 1 \pmod{4}$  or  $q \equiv 1 \pmod{4}$ .
- (b)  $-\left(\frac{p}{q}\right)$  if  $p \equiv q \equiv -1 \pmod{4}$ .
50. **Quadratic Reciprocity for Jacobi Symbols** Let  $Q$  be an odd positive integer. Then:
- (a)  $\left(\frac{-1}{Q}\right) = (-1)^{\frac{Q-1}{2}}$ .
- (b)  $\left(\frac{2}{Q}\right) = (-1)^{\frac{Q^2-1}{8}}$ .
- (c) If  $P$  is an odd positive integer, then  $\left(\frac{P}{Q}\right) = (-1)^{\frac{P-1}{2} \cdot \frac{Q-1}{2}} \left(\frac{Q}{P}\right)$ .
51. **Lemma.** For all odd positive integers  $a$  and  $b$ , we have  $\frac{ab-1}{2} \equiv \frac{a-1}{2} + \frac{b-1}{2} \pmod{2}$ , so therefore,  $(-1)^{\frac{ab-1}{2}} = (-1)^{\frac{a-1}{2}} (-1)^{\frac{b-1}{2}}$ .
52. For all odd positive integers  $a$  and  $b$ , we have  $\frac{(ab)^2-1}{8} \equiv \frac{a^2-1}{8} + \frac{b^2-1}{8} \pmod{2}$ , so therefore,  $(-1)^{\frac{(ab)^2-1}{8}} = (-1)^{\frac{a^2-1}{8}} (-1)^{\frac{b^2-1}{8}}$ .
53. **Theorem 3.10.** Let  $f(x, y) = ax^2 + bxy + cy^2$  be a nonzero binary quadratic form with integer coefficients, and let  $d = b^2 - 4ac$  be its discriminant. Then:
- (a) If  $d$  is a perfect square (including 0), then  $f$  can be factored into two linear factors with integer coefficients.
- (b) If  $d$  is not a perfect square, then  $f$  cannot be factored into linear factors with rational coefficients.
54. **Theorem.** Let  $d \in \mathbb{Z}$ . Then there exists a binary quadratic form of discriminant  $d$  iff  $d \equiv 0 \pmod{4}$  or  $d \equiv 1 \pmod{4}$ .
55. **Theorem 3.13.** Let  $n, d \in \mathbb{Z}$  with  $n \neq 0$ . Then there exists a form of discriminant  $d$  that properly represents  $n$  iff the congruence  $x^2 \equiv d \pmod{4|n|}$  has a solution.

56. **Corollary.** Let  $p$  be an odd prime and  $d \in \mathbb{Z}$ . Then there is a form of discriminant  $d$  that (properly) represents  $p$  iff  $\left(\frac{d}{p}\right) = 0$  or  $1$ .
57. **Corollary.** Let  $p$  be a prime. Then there exists a binary quadratic form of discriminant  $-4$  that represents  $p$  iff  $p$  is represented by  $x^2 + y^2$ .
58. **Theorem.** Let  $f$  be a positive definite quadratic form of discriminant  $-4$ . Then an integer  $n$  is represented by  $f$  iff it is represented by  $x^2 + y^2$ .
59. **Theorem.** Let  $d \in \mathbb{Z}$  and assume  $d \equiv 0 \pmod{4}$  or  $d \equiv 1 \pmod{4}$ . Then there is a finite list  $f_1, \dots, f_n$  of forms of discriminant  $d$  such that for all  $n \in \mathbb{Z}$ ,  $n$  is represented by some form of discriminant  $d$  iff  $f$  is represented by one of  $f_1, \dots, f_n$ .
60. **Theorem.** For any  $d \equiv 0 \pmod{4}$  or  $d \equiv 1 \pmod{4}$ , there are infinitely many forms of discriminant  $d$ .
61. **Theorem.** Let  $a, b, c, d \in \mathbb{R}$  and  $M = \begin{pmatrix} a & b \\ c & d \end{pmatrix}$ . Then:
- (a)  $T_M(\mathbb{Z}^2) \subseteq \mathbb{Z}^2$  (i.e.  $T_M(x, y) \in \mathbb{Z}^2$  for all  $(x, y) \in \mathbb{Z}^2$ ) iff  $a, b, c, d \in \mathbb{Z}$ .
  - (b)  $T_M$  maps  $\mathbb{Z}^2$  bijectively to  $\mathbb{Z}^2$  iff  $a, b, c, d \in \mathbb{Z}$  and  $\det M = \pm 1$ .