Lecture 1 (1/5/2009)

Notation 1.1 *Introduce* $\mathbb{N} := \{0, 1, 2, \dots\}$, $\mathbb{Z}$, $\mathbb{Q}$, $\mathbb{R}$, *and* $\mathbb{C}$. *Also let* $\mathbb{Z}_+ := \mathbb{N} \setminus \{0\}$.

- Set notations.
- Recalled basic notions of a function being one to one, onto, and invertible. Think of functions in terms of a bunch of arrows from the domain set to the range set. To find the inverse function you should reverse the arrows.
- Some example of groups without the definition of a group:
  1. $GL_2(\mathbb{R}) = \left\{ g := \begin{bmatrix} a & b \\ c & d \end{bmatrix} : \det g = ad - bc \neq 0 \right\}$.
  2. Vector space with "group" operation being addition.
  3. The permutation group of invertible functions on a set S like $S = \{1, 2, \dots, n\}$.

1.1 A Little Number Theory

Axiom 1.2 (Well Ordering Principle) *Every non-empty subset, S, of $\mathbb{N}$ contains a smallest element.*

We say that a subset $S \subset \mathbb{Z}$ is **bounded below** if $S \subset [k, \infty)$ for some $k \in \mathbb{Z}$ and **bounded above** if $S \subset (-\infty, k]$ for some $k \in \mathbb{Z}$.

Remark 1.3 (Well ordering variations). The well ordering principle may also be stated equivalently as:

1. any subset $S \subset \mathbb{Z}$ which is bounded from below contains a smallest element or
2. any subset $S \subset \mathbb{Z}$ which is bounded from above contains a largest element.

To see this, suppose that $S \subset [k, \infty)$ and then apply the well ordering principle to $S - k$ to find a smallest element, $n \in S - k$. That is $n \in S - k$ and $n \leq s - k$ for all $s \in S$. Thus it follows that $n + k \in S$ and $n + k \leq s$ for all $s \in S$ so that $n + k$ is the desired smallest element in S.

For the second equivalence, suppose that $S \subset (-\infty, k]$ in which case $-S \subset [-k, \infty)$ and therefore there exist a smallest element $n \in -S$, i.e. $n \leq -s$ for all $s \in S$. From this we learn that $-n \in S$ and $-n \geq s$ for all $s \in S$ so that $-n$ is the desired largest element of S.

Theorem 1.4 (Division Algorithm). *Let $a \in \mathbb{Z}$ and $b \in \mathbb{Z}_+$, then there exists unique integers $q \in \mathbb{Z}$ and $r \in \mathbb{N}$ with $r < b$ such that*

$$a = bq + r.$$

(For example,

$$5 \overline{)\,12}^{\,2} \quad \begin{matrix} \underline{10} \\ 2 \end{matrix} \quad \text{so that } 12 = 2 \cdot 5 + 2.)$$

Proof. Let

$$S := \{k \in \mathbb{Z} : a - bk \geq 0\}$$

which is bounded from above. Therefore we may define,

$$q := \max \{k : a - bk \geq 0\}.$$

As q is the largest element of S we must have,

$$r := a - bq \geq 0 \text{ and } a - b(q + 1) < 0.$$

The second inequality is equivalent to $r - b < 0$ which is equivalent to $r < b$. This completes the existence proof.

To prove uniqueness, suppose that $a = bq' + r'$ in which case, $bq' + r' = bq + r$ and hence,

$$b > |r' - r| = |b(q - q')| = b|q - q'|. \tag{1.1}$$

Since $|q - q'| \geq 1$ if $q \neq q'$, the only way Eq. (1.1) can hold is if $q = q'$ and $r = r'$. ■

Axiom 1.5 (Strong form of mathematical induction) *Suppose that $S \subset \mathbb{Z}$ is a non-empty set containing an element a with the property that; if $[a, n) \cap \mathbb{Z} \subset S$ then $n \in \mathbb{Z}$, then $[a, \infty) \cap \mathbb{Z} \subset S$.*

Axiom 1.6 (Weak form of mathematical induction) *Suppose that $S \subset \mathbb{Z}$ is a non-empty set containing an element a with the property that for every $n \in S$ with $n \geq a$, $n + 1 \in S$, then $[a, \infty) \cap \mathbb{Z} \subset S$.*

Remark 1.7. In Axioms 1.5 and 1.6 it suffices to assume that $a = 0$. For if $a \neq 0$ we may replace S by $S - a := \{s - a : s \in S\}$. Then applying the axioms with $a = 0$ to $S - a$ shows that $[0, \infty) \cap \mathbb{Z} \subset S - a$ and therefore,

$$[a, \infty) \cap \mathbb{Z} = [0, \infty) \cap \mathbb{Z} + a \subset S.$$

Theorem 1.8 (Equivalence of Axioms). *Axioms 1.2 – 1.6 are equivalent. (Only partially covered in class.)*

Proof. We will prove 1.2 $\iff$ 1.5 $\iff$ 1.6 $\implies$ 1.2.

1.2 $\implies$ 1.5 Suppose $0 \in S \subset \mathbb{Z}$ satisfies the assumption in Axiom 1.5. If $\mathbb{N}_0$ is not contained in S, then $\mathbb{N}_0 \setminus S$ is a non empty subset of $\mathbb{N}$ and therefore has a smallest element, n. It then follows by the definition of n that $[0, n) \cap \mathbb{Z} \subset S$ and therefore by the assumed property on S, $n \in S$. This is a contradiction since n can not be in both S and $\mathbb{N}_0 \setminus S$.

1.5 $\implies$ 1.2 Suppose that $S \subset \mathbb{N}$ does not have a smallest element and let $Q := \mathbb{N} \setminus S$. Then $0 \in Q$ since otherwise $0 \in S$ would be the minimal element of S. Moreover if $[1, n) \cap \mathbb{Z} \subset Q$, then $n \in Q$ for otherwise n would be a minimal element of S. Hence by the strong form of mathematical induction, it follows that $Q = \mathbb{N}$ and hence that $S = \emptyset$.

1.5 $\implies$ 1.6 Any set, $S \subset \mathbb{Z}$ satisfying the assumption in Axiom 1.6 will also satisfy the assumption in Axiom 1.5 and therefore by Axiom 1.5 we will have $[a, \infty) \cap \mathbb{Z} \subset S$.

1.6 $\implies$ 1.5 Suppose that $0 \in S \subset \mathbb{Z}$ satisfies the assumptions in Axiom 1.5. Let $Q := \{n \in \mathbb{N} : [0, n) \subset S\}$. By assumption, $0 \in Q$ since $0 \in S$. Moreover, if $n \in Q$, then $[0, n) \subset S$ by definition of Q and hence $n + 1 \in Q$. Thus Q satisfies the restrictions on the set, S, in Axiom 1.6 and therefore $Q = \mathbb{N}$. So if $n \in \mathbb{N}$, then $n + 1 \in \mathbb{N} = Q$ and thus $n \in [0, n + 1) \subset S$ which shows that $\mathbb{N} \subset S$. As $0 \in S$ by assumption, it follows that $\mathbb{N}_0 \subset S$ as desired.

■

Lecture 2 (1/7/2009)

Definition 2.1. *Given* $a, b \in \mathbb{Z}$ *with* $a \neq 0$ *we say that* a ***divides*** b *or* a *is a* ***divisor*** *of* b *(write* $a|b$*) provided* $b = ak$ *for some* $k \in \mathbb{Z}$.

Definition 2.2. *Given* $a, b \in \mathbb{Z}$ *with* $|a| + |b| > 0$, *we let*

$$\gcd(a,b) := \max\{m : m|a \text{ and } m|b\}$$

be the ***greatest common divisor*** *of* a *and* b. *(We do not define* $\gcd(0,0)$ *and we have* $\gcd(0,b) = |b|$ *for all* $b \in \mathbb{Z}\setminus\{0\}$ *.) If* $\gcd(a,b) = 1$, *we say that* a *and* b *are* ***relatively prime***.

Remark 2.3. Notice that $\gcd(a,b) = \gcd(|a|,|b|) \geq 0$ and $\gcd(a,0) = 0$ for all $a \neq 0$.

Lemma 2.4. *Suppose that* $a, b \in \mathbb{Z}$ *with* $b \neq 0$. *Then* $\gcd(a + kb, b) = \gcd(a,b)$ *for all* $k \in \mathbb{Z}$.

Proof. Let S_k denote the set of common divisors of $a + kb$ and b. If $d \in S_k$, then $d|b$ and $d|(a+kb)$ and therefore $d|a$ so that $d \in S_0$. Conversely if $d \in S_0$, then $d|b$ and $d|a$ and therefore $d|b$ and $d|(a+kb)$, i.e. $d \in S_k$. This shows that $S_k = S_0$, i.e. $a + kb$ and b and a and b have the same common divisors and hence the same greatest common divisors. ■

This lemma has a very useful corollary.

Lemma 2.5 (Euclidean Algorithm). *Suppose that* a, b *are positive integers with* $a < b$ *and let* $b = ka + r$ *with* $0 \leq r < a$ *by the division algorithm. Then* $\gcd(a,b) = \gcd(a,r)$ *and in particular if* $r = 0$, *we have*

$$\gcd(a,b) = \gcd(a,0) = a.$$

Example 2.6. Suppose that $a = 15 = 3 \cdot 5$ and $b = 28 = 2^2 \cdot 7$. In this case it is easy to see that $\gcd(15, 28) = 1$. Nevertheless, lets use Lemma 2.5 repeatedly as follows;

$$28 = 1 \cdot 15 + 13 \text{ so } \gcd(15,28) = \gcd(13,15), \tag{2.1}$$
$$15 = 1 \cdot 13 + 2 \text{ so } \gcd(13,15) = \gcd(2,13), \tag{2.2}$$
$$13 = 6 \cdot 2 + 1 \text{ so } G\gcd(2,13) = \gcd(1,2), \tag{2.3}$$
$$2 = 2 \cdot 1 + 0 \text{ so } \gcd(1,2) = \gcd(0,1) = 1. \tag{2.4}$$

Moreover making use of Eqs. (2.1–2.3) in reverse order we learn that,

$$\begin{aligned} 1 &= 13 - 6 \cdot 2 \\ &= 13 - 6 \cdot (15 - 1 \cdot 13) = 7 \cdot 13 - 6 \cdot 15 \\ &= 7 \cdot (28 - 1 \cdot 15) - 6 \cdot 15 = 7 \cdot 28 - 13 \cdot 15. \end{aligned}$$

Thus we have also shown that

$$1 = s \cdot 28 + t \cdot 15 \text{ where } s = 7 \text{ and } t = -13.$$

The choices for s and t used above are certainly not unique. For example we have,

$$0 = 15 \cdot 28 - 28 \cdot 15$$

which added to

$$1 = 7 \cdot 28 - 13 \cdot 15$$

implies,

$$\begin{aligned} 1 &= (7 + 15) \cdot 28 - (13 + 28) \cdot 15 \\ &= 22 \cdot 28 - 41 \cdot 15 \end{aligned}$$

as well.

Example 2.7. Suppose that $a = 40 = 2^3 \cdot 5$ and $b = 52 = 2^2 \cdot 13$. In this case we have $\gcd(40, 52) = 4$. Working as above we find,

$$\begin{aligned} 52 &= 1 \cdot 40 + 12 \\ 40 &= 3 \cdot 12 + 4 \\ 12 &= 3 \cdot 4 + 0 \end{aligned}$$

so that we again see $\gcd(40, 52) = 4$. Moreover,

$$4 = 40 - 3 \cdot 12 = 40 - 3 \cdot (52 - 1 \cdot 40) = 4 \cdot 40 - 3 \cdot 52.$$

So again we have shown $\gcd(a,b) = sa + tb$ for some $s, t \in \mathbb{Z}$, in this case $s = 4$ and $t = 3$.

Example 2.8. Suppose that $a = 333 = 3^2 \cdot 37$ and $b = 459 = 3^3 \cdot 17$ so that $\gcd(333, 459) = 3^2 = 9$. Repeated use of Lemma 2.5 gives,

$$459 = 1 \cdot 333 + 126 \text{ so } \gcd(333, 459) = \gcd(126, 333), \tag{2.5}$$
$$333 = 2 \cdot 126 + 81 \text{ so } \gcd(126, 333) = \gcd(81, 126), \tag{2.6}$$
$$126 = 81 + 45 \text{ so } \gcd(81, 126) = \gcd(45, 81), \tag{2.7}$$
$$81 = 45 + 36 \text{ so } \gcd(45, 81) = \gcd(36, 45), \tag{2.8}$$
$$45 = 36 + 9 \text{ so } \gcd(36, 45) = \gcd(9, 36), \text{ and} \tag{2.9}$$
$$36 = 4 \cdot 9 + 0 \text{ so } \gcd(9, 36) = \gcd(0, 9) = 9. \tag{2.10}$$

Thus we have shown that

$$\gcd(333, 459) = 9.$$

We can even say more. From Eq. (2.10) we have, $9 = 45 - 36$ and then from Eq. (2.10),

$$9 = 45 - 36 = 45 - (81 - 45) = 2 \cdot 45 - 81.$$

Continuing up the chain this way we learn,

$$\begin{aligned} 9 &= 2 \cdot (126 - 81) - 81 = 2 \cdot 126 - 3 \cdot 81 \\ &= 2 \cdot 126 - 3 \cdot (333 - 2 \cdot 126) = 8 \cdot 126 - 3 \cdot 333 \\ &= 8 \cdot (459 - 1 \cdot 333) - 3 \cdot 333 = 8 \cdot 459 - 11 \cdot 333 \end{aligned}$$

so that

$$9 = 8 \cdot 459 - 11 \cdot 333.$$

The methods of the previous two examples can be used to prove Theorem 2.9 below. However, we will two different variants of the proof.

Theorem 2.9. *If $a, b \in \mathbb{Z} \setminus \{0\}$, then there exists (not unique) numbers, $s, t \in \mathbb{Z}$ such that*

$$\gcd(a, b) = sa + tb. \tag{2.11}$$

Moreover if $m \neq 0$ is any common divisor of both a and b then $m | \gcd(a, b)$.

Proof. If m is any common divisor of a and b then m is also a divisor of $sa + tb$ for any $s, t \in \mathbb{Z}$. (In particular this proves the second assertion given the truth of Eq. (2.11).) In particular, $\gcd(a, b)$ is a divisor of $sa + tb$ for all $s, t \in \mathbb{Z}$. Let $S := \{sa + tb : s, t \in \mathbb{Z}\}$ and then define

$$d := \min(S \cap \mathbb{Z}_+) = sa + tb \text{ for some } s, t \in \mathbb{Z}. \tag{2.12}$$

By what we have just said if follows that $\gcd(a, b) | d$ and in particular $d \geq \gcd(a, b)$. If we can snow d is a common divisor of a and b we must then have $d = \gcd(a, b)$. However, using the division algorithm,

$$a = kd + r \text{ with } 0 \leq r < d. \tag{2.13}$$

As
$$r = a - kd = a - k(sa + tb) = (1 - ks) a - ktb \in S \cap \mathbb{N},$$
if r were greater than 0 then $r \geq d$ (from the definition of d in Eq. (2.12) which would contradict Eq. (2.13). Hence it follows that $r = 0$ and $d | a$. Similarly, one shows that $d | b$. ■

Lemma 2.10 (Euclid's Lemma). *If $\gcd(c, a) = 1$, i.e. c and a are relatively prime, and $c | ab$ then $c | b$.*

Proof. We know that there exists $s, t \in \mathbb{Z}$ such that $sa + tc = 1$. Multiplying this equation by b implies,
$$sab + tcb = b.$$
Since $c | ab$ and $c | cb$, it follows from this equation that $c | b$. ■

Corollary 2.11. *Suppose that $a, b \in \mathbb{Z}$ such that there exists $s, t \in \mathbb{Z}$ with $1 = sa + tb$. Then a and b are relatively prime, i.e. $\gcd(a, b) = 1$.*

Proof. If $m > 0$ is a divisor of a and b, then $m | (sa + tb)$, i.e. $m | 1$ which implies $m = 1$. Thus the only positive common divisor of a and b is 1 and hence $\gcd(a, b) = 1$. ■

2.1 Ideals (Not covered in class.)

Definition 2.12. *As non-empty subset $S \subset \mathbb{Z}$ is called an **ideal** if S is closed under addition (i.e. $S + S \subset S$) and under multiplication by **any** element of $\mathbb{Z}$, i.e. $\mathbb{Z} \cdot S \subset S$.*

Example 2.13. For any $n \in \mathbb{Z}$, let

$$(n) := \mathbb{Z} \cdot n = n\mathbb{Z} := \{kn : k \in \mathbb{Z}\}.$$

I is easily checked that (n) is an ideal. The next theorem states that this is a listing of all the ideals of $\mathbb{Z}$.

Theorem 2.14 (Ideals of $\mathbb{Z}$). *If $S \subset \mathbb{Z}$ is an ideal then $S = (n)$ for some $n \in \mathbb{Z}$. Moreover either $S = \{0\}$ in which case $n = 0$ for $S \neq \{0\}$ in which case $n = \min(S \cap \mathbb{Z}_+)$.*

Proof. If $S = \{0\}$ we may take $n = 0$. So we may assume that S contains a non-zero element a. By assumption that $\mathbb{Z} \cdot S \subset S$ it follows that $-a \in S$ as well and therefore $S \cap \mathbb{Z}_+$ is not empty as either a or $-a$ is positive. By the well ordering principle, we may define n as, $n := \min S \cap \mathbb{Z}_+$.

Since $\mathbb{Z} \cdot n \subset \mathbb{Z} \cdot S \subset S$, it follows that $(n) \subset S$. Conversely, suppose that $s \in S \cap \mathbb{Z}_+$. By the division algorithm, $s = kn + r$ where $k \in \mathbb{N}$ and $0 \leq r < n$. It now follows that $r = s - kn \in S$. If $r > 0$, we would have to have $r \geq n = \min S \cap \mathbb{Z}_+$ and hence we see that $r = 0$. This shows that $s = kn$ for some $k \in \mathbb{N}$ and therefore $s \in (n)$. If $s \in S$ is negative we apply what we have just proved to $-s$ to learn that $-s \in (n)$ and therefore $s \in (n)$. ■

Remark 2.15. Notice that $a|b$ iff $b = ak$ for some $k \in \mathbb{Z}$ which happens iff $b \in (a)$.

Proof. Second Proof of Theorem 2.9. Let $S := \{sa + tb : s, t \in \mathbb{Z}\}$. One easily checks that $S \subset \mathbb{Z}$ is an ideal and therefore $S = (d)$ where $d := \min S \cap \mathbb{Z}_+$. Notice that $d = sa + tb$ for some $s, t \in \mathbb{Z}$ as $d \in S$. We now claim that $d = \gcd(a, b)$. To prove this we must show that d is a divisor of a and b and that it is the maximal such divisor.

Taking $s = 1$ and $t = 0$ or $s = 0$ and $t = 1$ we learn that both $a, b \in S = (d)$, i.e. $d|a$ and $d|b$. If $m \in \mathbb{Z}_+$ and $m|a$ and $m|b$, then

$$\frac{d}{m} = s\frac{a}{m} + t\frac{b}{m} \in \mathbb{Z}$$

from which it follows that so that $m|d$. This shows that $d = \gcd(a, b)$ and also proves the last assertion of the theorem.

Alternate proof of last statement. If $m|a$ and $m|b$ there exists $k, l \in \mathbb{Z}$ such that $a = km$ and $b = lm$ and therefore,

$$d = sa + tb = (sk + tl)\, m$$

which again shows that $m|d$. ■

Remark 2.16. As a second proof of Corollary 2.11, if $1 \in S$ (where S is as in the second proof of Theorem 2.9)), then $\gcd(a, b) = \min(S \cap \mathbb{Z}_+) = 1$.

Lecture 3 (1/9/2009)

3.1 Prime Numbers

Definition 3.1. *A number, $p \in \mathbb{Z}$, is* ***prime*** *iff $p \geq 2$ and p has no divisors other than 1 and p. Alternatively put, $p \geq 2$ and $\gcd(a, p)$ is either 1 or p for all $a \in \mathbb{Z}$.*

Example 3.2. The first few prime numbers are $2, 3, 5, 7, 11, 13, 17, 19, 23, \ldots$.

Lemma 3.3 (Euclid's Lemma again). *Suppose that p is a prime number and $p|ab$ for some $a, b \in \mathbb{Z}$ then $p|a$ or $p|b$.*

Proof. We know that $\gcd(a, p) = 1$ or $\gcd(a, p) = p$. In the latter case $p|a$ and we are done. In the former case we may apply Euclid's Lemma 2.10 to conclude that $p|b$ and so again we are done. ■

Theorem 3.4 (The fundamental theorem of arithmetic). *Every $n \in \mathbb{Z}$ with $n \geq 2$ is a prime or a product of primes. The product is unique except for the order of the primes appearing the product. Thus if $n \geq 2$ and $n = p_1 \ldots p_n = q_1 \ldots q_m$ where the p's and q's are prime, then $m = n$ and after renumbering the q's we have $p_i = q_i$.*

Proof. Existence: This clearly holds for $n = 2$. Now suppose for every $2 \leq k \leq n$ may be written as a product of primes. Then either $n+1$ is prime in which case we are done or $n + 1 = a \cdot b$ with $1 < a, b < n + 1$. By the induction hypothesis, we know that both a and b are a product of primes and therefore so is $n + 1$. This completes the inductive step.

Uniqueness: You are asked to prove the uniqueness assertion in 0.#25. Here is the solution. Observe that $p_1|q_1 \ldots q_m$. If p_1 does not divide q_1 then $\gcd(p_1, q_1) = 1$ and therefore by Euclid's Lemma 2.10, $p_1|(q_2 \ldots q_m)$. It now follows by induction that p_1 must divide one of the q_i, by relabeling we may assume that $q_1 = p_1$. The result now follows by induction on $n \vee m$. ■

Definition 3.5. *The least common multiple of two non-zero integers, a, b, is the smallest positive number which is both a multiple of a and b and this number will be denoted by $\operatorname{lcm}(a, b)$. Notice that $m = \min((a) \cap (b) \cap \mathbb{Z}_+)$.*

Example 3.6. Suppose that $a = 12 = 2^2 \cdot 3$ and $b = 15 = 3 \cdot 5$. Then $\gcd(12, 15) = 3$ while

$$\operatorname{lcm}(12, 15) = \left(2^2 \cdot 3\right) \cdot 5 = 2^2 \cdot (3 \cdot 5) = \left(2^2 \cdot 3 \cdot 5\right) = 60.$$

Observe that

$$\gcd(12, 15) \cdot \operatorname{lcm}(12, 15) = 3 \cdot \left(2^2 \cdot 3 \cdot 5\right) = \left(2^2 \cdot 3\right) \cdot (3 \cdot 5) = 12 \cdot 15.$$

This is a special case of Chapter 0.#12 on p. 23 which can be proved by similar considerations. In general if

$$a = p_1^{n_1} \cdot \ldots \cdot p_k^{n_k} \text{ and } b = p_1^{m_1} \ldots p_k^{m_k} \text{ with } n_j, m_l \in \mathbb{N}$$

then

$$\gcd(a, b) = p_1^{n_1 \wedge m_1} \cdot \ldots \cdot p_k^{n_k \wedge m_k} \text{ and } \operatorname{lcm}(a, b) = p_1^{n_1 \vee m_1} \cdot \ldots \cdot p_k^{n_k \vee m_k}.$$

Therefore,

$$\begin{aligned} \gcd(a, b) \cdot \operatorname{lcm}(a, b) &= p_1^{n_1 \wedge m_1 + n_1 \vee m_1} \cdot \ldots \cdot p_k^{n_k \wedge m_k + n_k \vee m_k} \\ &= p_1^{n_1 + m_1} \cdot \ldots \cdot p_k^{n_k + m_k} = a \cdot b. \end{aligned}$$

3.2 Modular Arithmetic

Definition 3.7. *Let n be a positive integer and let $a = q_a n + r_a$ with $0 \leq r_a < n$. Then we define $a \bmod n := r_a$. (Sometimes we might write $a = r_a \bmod n$ – but I will try to stick with the first usage.)*

Lemma 3.8. *Let $n \in \mathbb{Z}_+$ and $a, b, k \in \mathbb{Z}$. Then:*

1. $(a + kn) \bmod n = a \bmod n$.
2. $(a + b) \bmod n = (a \bmod n + b \bmod n) \bmod n$.
3. $(a \cdot b) \bmod n = ((a \bmod n) \cdot (b \bmod n)) \bmod n$.

Proof. Let $r_a = a \bmod n$, $r_b = b \bmod n$ and $q_a, q_b \in \mathbb{Z}$ such that $a = q_a n + r_a$ and $b = q_b n + r_b$.

1. Then $a + kn = (q_a + k)\, n + r_a$ and therefore,
$$(a + kn) \bmod n = r_a = a \bmod n.$$
2. $a + b = (q_a + q_b)\, n + r_a + r_b$ and hence by item 1 with $k = q_a + q_b$ we find,
$$(a + b) \bmod n = (r_a + r_b) \bmod n. = (a \bmod n + b \bmod n) \bmod n.$$
3. For the last assertion,
$$a \cdot b = [q_a n + r_a] \cdot [q_b n + r_b] = (q_a q_b n + r_a q_b + r_b q_a)\, n + r_a \cdot r_b$$
and so again by item 1. with $k = (q_a q_b n + r_a q_b + r_b q_a)$ we have,
$$(a \cdot b) \bmod n = (r_a \cdot r_b) \bmod n = ((a \bmod n) \cdot (b \bmod n)) \bmod n.$$

■

Example 3.9. Take $n = 4$, $a = 18$ and $b = 7$. Then $18 \bmod 4 = 2$ and $7 \bmod 4 = 3$. On one hand,
$$(18 + 7) \bmod 4 = 25 \bmod 4 = 1 \text{ while on the other,}$$
$$(2 + 3) \bmod 4 = 1.$$
Similarly, $18 \cdot 7 = 126 = 4 \cdot 31 + 2$ so that
$$(18 \cdot 7) \bmod 4 = 2 \text{ while}$$
$$(2 \cdot 3) \bmod 4 = 6 \bmod 4 = 2.$$

Remark 3.10 (Error Detection). Companies often add extra digits to identification numbers for the purpose of detecting forgery or errors. For example the United Parcel Service uses a mod 7 check digit. Hence if the identification number were $n = 354691332$ one would append
$$n \bmod 7 = 354691332 \bmod 7 = 2 \text{ to the number to get}$$
$$354691332\_2 \text{ (say).}$$
See the book for more on this method and other more elaborate check digit schemes. Note,
$$354691332 = 50\,670\,190 \cdot 7 + 2.$$

Remark 3.11. Suppose that $a, n \in \mathbb{Z}_+$ and $b \in \mathbb{Z}$, then it is easy to show (you prove)
$$(ab) \bmod (an) = a \cdot (b \bmod n).$$

Example 3.12 (Computing mod 10*).* We have,
$$\begin{aligned} 123456 \bmod 10 &= 6 \\ 123456 \bmod 100 &= 56 \\ 123456 \bmod 1000 &= 456 \\ 123456 \bmod 10000 &= 3456 \\ 123456 \bmod 100000 &= 23456 \\ 123456 \bmod 1000000 &= 123456 \end{aligned}$$
so that
$$a_n \ \ldots a_2\ a_1 \bmod 10^k = a_k \ \ldots a_2\ a_1 \text{ for all } k \le n.$$

Solution to Exercise (0.52). As an example, here is a solution to Problem 0.52 of the book which states that $\overbrace{111\ldots1}^{k \text{ times}}$ is not the square of an integer except when $k = 1$.

As 11 is prime we may assume that $k \ge 3$. By Example 3.12, $111\ldots1 \bmod 10 = 1$ and $111\ldots1 \bmod 100 = 11$. Hence $1111\ldots1 = n^2$ for some integer n, we must have
$$n^2 \bmod 10 = 1 \text{ and } \left(n^2 - 1\right) \bmod 100 = 10.$$
The first condition implies that $n \bmod 10 = 1$ or 9 as $1^2 = 1$ and $9^2 \bmod 10 = 81 \bmod 10 = 1$. In the first case we have, $n = k \cdot 10 + 1$ and therefore we must require,
$$\begin{aligned} 10 &= \left(n^2 - 1\right) \bmod 100 = \left[(k \cdot 10 + 1)^2 - 1\right] \bmod 100 = \left(k^2 \cdot 100 + 2k \cdot 10\right) \bmod 100 \\ &= (2k \cdot 10) \bmod 100 = 10 \cdot (2k \bmod 10) \end{aligned}$$
which implies $1 = (2k \bmod 10)$ which is impossible since $2k \bmod 10$ is even.

For the second case we must have,
$$\begin{aligned} 10 &= \left(n^2 - 1\right) \bmod 100 \bmod 100 = \left[(k \cdot 10 + 9)^2 - 1\right] \bmod 100 \\ &= \left(k^2 \cdot 100 + 18k \cdot 10 + 81 - 1\right) \bmod 100 \\ &= ((10 + 8)\, k \cdot 10 + 8 \cdot 10) \bmod 100 \\ &= (8\,(k + 1) \cdot 10) \bmod 100 \\ &= 10 \cdot 8k \bmod 10 \end{aligned}$$
which implies which $1 = (8k \bmod 10)$ which again is impossible since $8k \bmod 10$ is even.

Solution to Exercise (0.52 Second and better solution). Notice that $111\ldots 11 = 111\ldots 00 + 11$ and therefore,

$$111\ldots 11 \bmod 4 = 11 \bmod 4 = 3.$$

On the other hand, if $111\ldots 11 = n^2$ we must have,

$$(n \bmod 4)^2 \bmod 4 = 3.$$

There are only four possibilities for $r := n \bmod 4$, namely $r = 0, 1, 2, 3$ and these are not allowed since $0^2 \bmod 4 = 0 \neq 3$, $1^2 \bmod 4 = 1 \neq 3, 2^2 \bmod 4 = 0 \neq 3$, and $3^2 \bmod 4 = 1 \neq 3$.

3.3 Equivalence Relations

Definition 3.13. *A* ***equivalence relation*** *on a set S is a subset, $R \subset S \times S$ with the following properties:*

1. *R* ***is reflexive:*** *$(a, a) \in R$ for all $a \in S$*
2. *R* ***is symmetric:*** *If $(a, b) \in R$ then $(b, a) \in R$.*
3. *R* ***is transitive:*** *If $(a, b) \in R$ and $(b, c) \in R$ then $(a, c) \in R$.*

*We will usually write $a \sim b$ to mean that $(a, b) \in R$ and pronounce this as a is equivalent to b. With this notation we are assuming $a \sim a$, $a \sim b \implies b \sim a$ and $a \sim b$ and $b \sim c \implies a \sim c$. (**Note well:** the book write aRb rather than $a \sim b$.)*

Example 3.14. If $S = \{1, 2, 3, 4, 5\}$ then:

1. $R = \{1, 2, 3\}^2 \cup \{4, 5\}^2$ is an equivalence relation.
2. $R = \{(1, 1), (2, 2), (3, 3), (4, 4), (5, 5), (1, 2), (2, 1), (2, 3), (3, 2)\}$ is not an equivalence relation. For example, $1 \sim 2$ and $2 \sim 3$ but 1 is not equivalent to 3, so R is not transitive.

Example 3.15. Let $n \in \mathbb{Z}_+$, $S = \mathbb{Z}$ and say $a \sim b$ iff $a \bmod n = b \bmod n$. This is an equivalence relation. For example, when $s = 2$ we have $a \sim b$ iff both a and b are odd or even. So in this case $R = \{\text{odd}\}^2 \cup \{even\}^2$.

Example 3.16. Let $S = \mathbb{R}$ and say $a \sim b$ iff $a \geq b$. Again not symmetric so is not an equivalence relation.

Definition 3.17. *A* ***partition*** *of a set S is a decomposition, $\{S_\alpha\}_{\alpha \in I}$, by disjoint sets, so S_α is a non-empty subset of S such that $S = \cup_{\alpha \in I} S_\alpha$ and $S_\alpha \cap S_\beta = \emptyset$ if $\alpha \neq \beta$.*

Example 3.18. If $\{S_\alpha\}_{\alpha \in I}$ is a partition of S, then $R = \cup_{\alpha \in I} S_\alpha^2$ is an equivalence relation. The next theorem states this is the general type of equivalence relation.

Lecture 4 (1/12/2009)

Theorem 4.1. *Let R or $\sim$ be an equivalence relation on S and for each $a \in S$, let*

$$[a] := \{x \in S : a \sim x\}$$

be the ***equivalence class*** *of a.. Then S is partitioned by its distinct equivalence classes.*

Proof. Because $\sim$ is reflexive, $a \in [a]$ for all a and therefore every element $a \in S$ is a member of its own equivalence class. Thus to finish the proof we must show that distinct equivalence classes are disjoint. To this end we will show that if $[a] \cap [b] \neq \emptyset$ then in fact $[a] = [b]$. So suppose that $c \in [a] \cap [b]$ and $x \in [a]$. Then we know that $a \sim c$, $b \sim c$ and $a \sim x$. By reflexivity and transitivity of $\sim$ we then have,

$$x \sim a \sim c \sim b, \text{ and hence } b \sim x,$$

which shows that $x \in [b]$. Thus we have shown $[a] \subset [b]$. Similarly it follows that $[b] \subset [a]$. ■

Exercise 4.1. Suppose that $S = \mathbb{Z}$ with $a \sim b$ iff $a \bmod n = b \bmod n$. Identify the equivalence classes of $\sim$. Answer,

$$\{[0], [1], \dots, [n-1]\}$$

where

$$[i] = i + n\mathbb{Z} = \{i + ns : s \in \mathbb{Z}\}.$$

Exercise 4.2. Suppose that $S = \mathbb{R}^2$ with $\mathbf{a} = (a_1, a_2) \sim \mathbf{b} = (b_1, b_2)$ iff $|\mathbf{a}| = |\mathbf{b}|$ where $|\mathbf{a}| := a_1^2 + a_2^2$. Show that $\sim$ is an equivalence relation and identify the equivalence classes of $\sim$. Answer, the equivalence classes consists of concentric circles centered about the origin $(0,0) \in S$.

4.1 Binary Operations and Groups – a first look

Definition 4.2. *A* ***binary operation*** *on a set S is a function, $* : S \times S \to S$. We will typically write $a * b$ rather than $*(a,b)$.*

Example 4.3. Here are a number of examples of binary operations.

1. $S = \mathbb{Z}$ and $* =$ "$+$"
2. $S = \{\text{odd integers}\}$ and $* =$ "$+$" is **not** an example of a binary operator since $3 * 5 = 3 + 5 = 8 \notin S$.
3. $S = \mathbb{Z}$ and $* =$"$\cdot$"
4. $S = \mathbb{R} \setminus \{0\}$ and $* =$"$\cdot$"
5. $S = \mathbb{R} \setminus \{0\}$ with $* =$ "$\backslash$" $=$ "$\div$".
6. Let S be the set of 2×2 real (complex) matrices with $A * B := AB$.

Definition 4.4. *Let $*$ be a binary operation on a set S. Then;*

1. *$*$ is* ***associative*** *if $(a * b) * c = a * (b * c)$ for all $a, b, c \in S$.*
2. *$e \in S$ is an* ***identity element*** *if $e * a = a = a * e$ for all $a \in S$.*
3. *Suppose that $e \in S$ is an identity element and $a \in S$. We say that $b \in S$ is an* ***inverse*** *to a if $b * a = e = a * b$.*
4. *$*$ is* ***commutative*** *if $a * b = b * a$ for all $a, b \in S$.*

Definition 4.5 (Group). *A* ***group*** *is a triple, $(G, *, e)$ where $*$ is an associative binary operation on a set, G, $e \in G$ is an identity element, and each $g \in G$ has an inverse in G. (Typically we will simply denote $g * h$ by gh.)*

Definition 4.6 (Commutative Group). *A group, (G, e), is commutative if $gh = hg$ for all $h, g \in G$.*

Example 4.7 ($(\mathbb{Z}, +)$). One easily checks that $(\mathbb{Z}, * = +)$ is **a commutative group** with $e = 0$ and the inverse to $a \in \mathbb{Z}$ is $-a$. Observe that $e * a = e + a = a$ for all a iff $e = 0$.

Example 4.8. $S = \mathbb{Z}$ and $* =$"$\cdot$" is an associative, commutative, binary operation with $e = 1$ being the identity. Indeed $e \cdot a = a$ for all $a \in \mathbb{Z}$ implies $e = e \cdot 1 = 1$. This is **not** a group since there are no inverses for any $a \in \mathbb{Z}$ with $|a| \geq 2$.

Example 4.9 ($(\mathbb{R} \setminus \{0\}, \cdot)$). $G = \mathbb{R} \setminus \{0\} =: \mathbb{R}^*$, and $* =$"$\cdot$" is a commutative group, $e = 1$, an inverse to a is $1/a$.

Example 4.10. $S = \mathbb{R} \setminus \{0\}$ with $* =$ "$\backslash$" $=$ "$\div$". In this case $*$ is not associative since

$$a*(b*c) = a/(b/c) = \frac{ac}{b} \text{ while}$$
$$(a*b)*c = (a/b)/c = \frac{a}{bc}.$$

It is also not commutative since $a/b \neq b/a$ in general. There is no identity element $e \in S$. Indeed, $e*a = a = a*e$, we would imply $e = a^2$ for all $a \neq 0$ which is impossible, i.e. $e = 1$ and $e = 4$ at the same time.

Example 4.11. Let S be the set of 2×2 real (complex) matrices with $A*B := AB$. This is a non-commutative binary operation which is associative and has an identity, namely

$$e := \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}.$$

It is however not a group only those $A \in S$ with $\det A \neq 0$ admit an inverse.

Example 4.12 ($GL_2(\mathbb{R})$). Let $G := GL_2(\mathbb{R})$ be the set of 2×2 real (complex) matrices such that $\det A \neq 0$ with $A*B := AB$ is a group with $e := \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ and the inverse to A being A^{-1}. This group is non-abeliean for example let

$$A := \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \text{ and } B = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix},$$

then

$$AB = \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -1 & -1 \end{bmatrix} \text{ while}$$
$$BA = \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix} = \begin{bmatrix} -1 & 1 \\ -1 & 0 \end{bmatrix} \neq AB.$$

Example 4.13 ($SL_2(\mathbb{R})$). Let $SL_2(\mathbb{R}) = \{A \in GL_2(\mathbb{R}) : \det A = 1\}$. This is a group since $\det(AB) = \det A \cdot \det B = 1$ if $A, B \in SL_2(\mathbb{R})$.

Lecture 5 (1/14/2009)

5.1 Elementary Properties of Groups

Let $(G, \cdot)$ be a group.

Lemma 5.1. *The identity element in G is unique.*

Proof. Suppose that e and e' both satisfy $ea = ae = a$ and $e'a = ae' = a$ for all $a \in G$, then $e = e'e = e'$. ∎

Lemma 5.2. *Left and right cancellation holds. Namely, if $ab = ac$ then $b = c$ and $ba = ca$ then $b = c$.*

Proof. Let d be an inverse to a. If $ab = ac$ then $d(ab) = d(ac)$. On the other hand by associativity,

$$d(ab) = (da)b = eb = b \text{ and similarly, } d(ac) = c.$$

Thus it follows that $b = c$. The right cancellation is proved similarly. ∎

Example 5.3 (No cross cancellation in general). Let $G = GL_2(\mathbb{R})$,

$$A := \begin{bmatrix} 0 & 1 \\ -1 & 0 \end{bmatrix}, \ B := \begin{bmatrix} 1 & 1 \\ 0 & 1 \end{bmatrix} \text{ and } C := \begin{bmatrix} 1 & 0 \\ -1 & 1 \end{bmatrix}.$$

Then

$$AB = \begin{bmatrix} 0 & 1 \\ -1 & -1 \end{bmatrix} = CA$$

yet $B \neq C$. In general, all we can say if $AB = CA$ is that $C = ABA^{-1}$.

Lemma 5.4. *Inverses in G are unique.*

Proof. Suppose that b and b' are both inverses to a, then $ba = e = b'a$. Hence by cancellation, it follows that $b = b'$. ∎

Notation 5.5 *If $g \in G$, let g^{-1} denote the unique inverse to g. (If we are in an abelian group and using the symbol, "+" for the binary operation we denote g^{-1} by $-g$ instead.*

Example 5.6. Let G be a group. Because of the associativity law it makes sense to write $a_1a_2a_3$ and $a_1a_2a_3a_4$ where $a_i \in G$. Indeed, we may either interpret $a_1a_2a_3$ as $(a_1a_2)a_3$ or as $a_1(a_2a_3)$ which are equal by the associativity law. While we might interpret $a_1a_2a_3a_4$ as one of the following expressions;

$$\begin{aligned} c_1 &:= (a_1a_2)(a_3a_4) \\ c_2 &:= ((a_1a_2)a_3)a_4 \\ c_3 &:= (a_1(a_2a_3))a_4 \\ c_4 &:= a_1((a_2a_3)a_4) \\ c_5 &:= a_1(a_2(a_3a_4)). \end{aligned}$$

Using the associativity law repeatedly these are all seen to be equal. For example,

$$\begin{aligned} c_1 &= (a_1a_2)(a_3a_4) = ((a_1a_2)a_3)a_4 = c_2, \\ c_3 &= (a_1(a_2a_3))a_4 = a_1((a_2a_3)a_4) = c_4 \\ &= a_1(a_2(a_3a_4)) = (a_1a_2)(a_3a_4) = c_1 \end{aligned}$$

and

$$c_5 := a_1(a_2(a_3a_4)) = (a_1a_2)(a_3a_4) = c_1.$$

More generally we have the following proposition.

Proposition 5.7. *Suppose that G is a group and $g_1, g_2, \dots, g_n \in G$, then it makes sense to write $g_1g_2 \dots g_n \in G$ which is interpreted to mean: do the pairwise multiplications in any of the possible allowed orders without rearranging the orders of the g's.*

Proof. Sketch. The proof is by induction. Let us begin by defining $\{M_n : G^n \to G\}_{n=2}^{\infty}$ inductively by $M_2(a,b) = ab$, $M_3(a,b,c) = (ab)c$, and $M_n(g_1, \dots, g_n) := M_{n-1}(g_1, \dots, g_{n-1}) \cdot g_n$. We wish to show that $M_n(g_1, \dots, g_n)$ may be expressed as one of the products described in the proposition. For the base case, $n = 2$, there is nothing to prove. Now assume that the assertion holds for $2 \leq k \leq n$. Consider an expression for $g_1 \dots g_n g_{n+1}$. We now do another induction on the number of parentheses appearing on the right of this expression, $\dots g_n \overbrace{) \dots)}^{k}$. If $k = 0$, we have

$$(\text{brackets involving } g_1 \dots g_n) \cdot g_{n+1} = M_n (g_1, \dots, g_n) \, g_{n+1} = M_{n+1} (g_1, \dots, g_{n+1}) \, ,$$

wherein we used induction in the first equality and the definition of M_{n+1} in the second. Now suppose the assertion holds for some $k \geq 0$ and consider the case where there are $k+1$ parentheses appearing on the right of this expression, i.e. $\dots g_n \overbrace{) \dots)}^{k+1}$. Using the associativity law for the last bracket on the right we can transform this expression into one with only k parentheses appearing on the right. It then follows by the induction hypothesis, that $\dots g_n \overbrace{) \dots)}^{k+1} = M_{n+1} (g_1, \dots, g_{n+1})$. ■

Notation 5.8 *For $n \in \mathbb{Z}$ and $g \in G$, let $g^n := \overbrace{g \dots g}^{n \text{ times}}$ and $g^{-n} := \overbrace{g^{-1} \dots g^{-1}}^{n \text{ times}} = (g^{-1})^n$ if $n \geq 1$ and $g^0 := e$.*

Observe that with this notation that $g^m g^n = g^{m+n}$ for all $m, n \in \mathbb{Z}$. For example,

$$g^3 g^{-5} = gggg^{-1}g^{-1}g^{-1}g^{-1}g^{-1} = ggg^{-1}g^{-1}g^{-1}g^{-1} = gg^{-1}g^{-1}g^{-1} = g^{-1}g^{-1} = g^{-2}.$$

5.2 More Examples of Groups

Example 5.9. Let G be the set of 2×2 real (complex) matrices with $A * B := A + B$. This is a group. In fact any vector space under addition is an abelian group with $e = 0$ and $v^{-1} = -v$.

Example 5.10 ($\mathbb{Z}_n$). For any $n \geq 2$, $G := \mathbb{Z}_n = \{0, 1, 2, \dots, n-1\}$ with $a * b = (a + b) \bmod n$ is a commutative group with $e = 0$ and the inverse to $a \in \mathbb{Z}_n$ being $n - a$. Notice that $(n - a + a) \bmod n = n \bmod n = 0$.

Example 5.11. Suppose that $S = \{0, 1, 2, \dots, n-1\}$ with $a * b = ab \bmod n$. In this case $*$ is an associative binary operation which is commutative and $e = 1$ is an identity for S. In general it is not a group since not every element need have an inverse. Indeed if $a, b \in S$, then $a * b = 1$ iff $1 = ab \bmod n$ which we have seen can happen iff $\gcd(a, n) = 1$ by Lemma 9.8. For example if $n = 4$, $S = \{0, 1, 2, 3\}$, then

$$2 * 1 = 2, \; 2 * 2 = 0, \quad 2 * 0 = 0, \quad \text{and} \quad 2 * 3 = 2,$$

none of which are 1. Thus, 2 is not invertible for this operation. (Of course 0 is not invertible as well.)

6

Lecture 6 (1/16/2009)

Theorem 6.1 (The groups, $U(n)$). *For $n \geq 2$, let*

$$U(n) := \{a \in \{1, 2, \ldots, n-1\} : \gcd(a, n) = 1\}$$

and for $a, b \in U(n)$ let $a * b := (ab) \bmod n$. Then $(U(n), *)$ is a group.

Proof. First off, let $a * b := ab \bmod n$ for all $a, b \in \mathbb{Z}$. Then if $a, b, c \in \mathbb{Z}$ we have

$$\begin{aligned}(abc) \bmod n &= ((ab)\,c) \bmod n = ((ab) \bmod n \cdot c \bmod n) \bmod n \\ &= ((a*b) \cdot c \bmod n) \bmod n = ((a*b) \cdot c) \bmod n \\ &= (a*b)*c.\end{aligned}$$

Similarly one shows that

$$(abc) \bmod n = a * (b * c)$$

and hence $*$ is associative. It should be clear also that $*$ is commutative.

Claim: an element $a \in \{1, 2, \ldots, n-1\}$ is in $U(n)$ iff there exists $r \in \{1, 2, \ldots, n-1\}$ such that $r * a = 1$.

$(\Longrightarrow)$ $a \in U(n) \iff \gcd(a, n) = 1 \iff$ there exists $s, t \in \mathbb{Z}$ such that $sa + tn = 1$. Taking this equation $\bmod n$ then shows,

$$(s \bmod n \cdot a) \bmod n = (s \bmod n \cdot a \bmod n) \bmod n = (sa) \bmod n = 1 \bmod n = 1$$

and therefore $r := s \bmod n \in \{1, 2, \ldots, n-1\}$ and $r * a = 1$.

$(\Longleftarrow)$ If there exists $r \in \{1, 2, \ldots, n-1\}$ such that $1 = r * a = ra \bmod n$, then $n | (ra - 1)$, i.e. there exists t such that $ra - 1 = kt$ or $1 = ra - kt$ from which it follows that $\gcd(a, n) = 1$, i.e. $a \in U(n)$.

The claim shows that to each element, $a \in U(n)$, there is an inverse, $a^{-1} \in U(n)$. Finally if $a, b \in U(n)$ let $k := b^{-1} * a^{-1} \in U(n)$, then

$$k * (a * b) = b^{-1} * a^{-1} * a * b = 1$$

and so by the claim, $a * b \in U(n)$, i.e. the binary operation is really a binary operation on $U(n)$. ■

Example 6.2 ($U(10)$). $U(10) = \{1, 3, 7, 9\}$ with multiplication or Cayley table given by

$a\backslash b$	1	3	7	9
1	1	3	7	9
3	3	9	1	7
7	7	1	9	3
9	9	7	3	1

where the element of the (a, b) row indexed by $U(10)$ itself is given by $a * b = ab \bmod 10$.

Example 6.3. If p is prime, then $U(p) = \{1, 2, \ldots, p\}$. For example $U(5) = \{1, 2, 3, 4\}$ with Cayley table given by,

$a\backslash b$	1	2	3	4
1	1	2	3	4
2	2	4	1	3
3	3	1	4	2
4	4	3	2	1

Exercise 6.1. Compute 23^{-1} inside of $U(50)$.

Solution to Exercise. We use the division algorithm (see below) to show $1 = 6 \cdot 50 - 13 \cdot 23$. Taking this equation mod 50 shows that $23^{-1} = (-13) = 37$. As a check we may show directly that $(23 \cdot 37) \bmod 50 = 1$.

Here is the division algorithm calculation:

$$\begin{aligned}50 &= 2 \cdot 23 + 4 \\ 23 &= 5 \cdot 4 + 3 \\ 4 &= 3 + 1.\end{aligned}$$

So working backwards we find,

$$\begin{aligned}1 &= 4 - 3 = 4 - (23 - 5 \cdot 4) = 6 \cdot 4 - 23 = 6 \cdot (50 - 2 \cdot 23) - 23 \\ &= 6 \cdot 50 - 13 \cdot 23.\end{aligned}$$

6.1 $O(2)$ – reflections and rotations in $\mathbb{R}^2$

Definition 6.4 (Sub-group). *Let $(G, \cdot)$ be a group. A non-empty subset, $H \subset G$, is said to be a subgroup of G if H is also a group under the multiplication law in G. We use the notation, $H \leq G$ to summarize that H is a subgroup of G and $H < G$ to summarize that H is a* ***proper*** *subgroup of G.*

In this section, we are interested in describing the subgroup of $GL_2(\mathbb{R})$ which corresponds to reflections and rotations in the plane. We define these operations now.

As in Figure 6.1 let

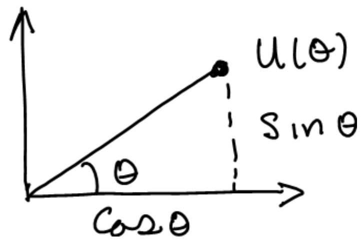

Fig. 6.1. The unit vector, $u(\theta)$, at angle θ to the x – axis.

$$u(\theta) := \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix}.$$

We also let R_α denote rotation by α degrees counter clockwise so that $R_\alpha u(\theta) = u(\theta + \alpha)$ as in Figure 6.2. We may represent R_α as a matrix, namely

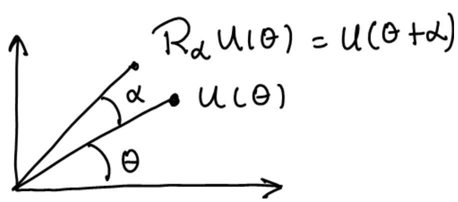

Fig. 6.2. Rotation by α degrees in the counter clockwise direction.

$$\begin{aligned} R_\alpha &= [R_\alpha e_1 | R_\alpha e_2] = [R_\alpha u(0) \,|R_\alpha u(\pi/2)] = [u(\alpha) \,|u(\alpha + \pi/2)] \\ &= \begin{bmatrix} \cos\alpha & \cos(\alpha + \pi/2) \\ \sin\alpha & \sin(\alpha + \pi/2) \end{bmatrix} = \begin{bmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{bmatrix}. \end{aligned}$$

We also define reflection, S_α, across the line determined by $u(\alpha)$ as in Figure 6.3 so that $S_\alpha u(\theta) := u(2\alpha - \theta)$. We may compute the matrix representing S_α

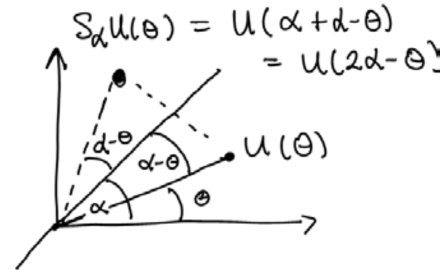

Fig. 6.3. Computing S_α.

as,

$$\begin{aligned} S_\alpha &= [S_\alpha e_1 | S_\alpha e_2] = [S_\alpha u(0) \,|S_\alpha u(\pi/2)] = [u(2\alpha) \,|u(2\alpha - \pi/2)] \\ &= \begin{bmatrix} \cos 2\alpha & \cos(2\alpha - \pi/2) \\ \sin 2\alpha & \sin(2\alpha - \pi/2) \end{bmatrix} = \begin{bmatrix} \cos 2\alpha & \sin 2\alpha \\ \sin 2\alpha & -\cos 2\alpha \end{bmatrix}. \end{aligned}$$

Lecture 7 (1/21/2009)

Definition 7.1 (Sub-group). *Let $(G,\cdot)$ be a group. A non-empty subset, $H\subset G$, is said to be a subgroup of G if H is also a group under the multiplication law in G. We use the notation, $H\leq G$ to summarize that H is a subgroup of G and $H<G$ to summarize that H is a* ***proper*** *subgroup of G.*

Theorem 7.2 (Two-step Subgroup Test). *Let G be a group and H be a non-empty subset. Then $H\leq G$ if*

1. *H is* ***closed*** *under $\cdot$, i.e. $hk\in H$ for all $h,k\in H$,*
2. *H is* ***closed*** *under taking inverses, i.e. $h^{-1}\in H$ if $h\in H$.*

Proof. First off notice that $e=h^{-1}h\in H$. It also clear that H contains inverses and the multiplication law is associative, thus $H\leq G$. ■

Theorem 7.3 (One-step Subgroup Test). *Let G be a group and H be a non-empty subset. Then $H\leq G$ iff $ab^{-1}\in H$ whenever $a,b\in H$.*

Proof. If $a\in H$, then $e=a\,a^{-1}\in H$ and hence so is $a^{-1}=ae^{-1}\in H$. Thus it follows that for $a,b\in H$, that $ab=a\left(b^{-1}\right)^{-1}\in H$ and hence $H\leq G$. and the result follows from Theorem 7.2. ■

Example 7.4. Here are some examples of sub-groups and not sub-groups.

1. $2\mathbb{Z}<\mathbb{Z}$ while $3\mathbb{Z}\subset\mathbb{Z}$ but is not a sub-group.
2. $\mathbb{Z}_n=\{0,1,2,\dots,n-1\}\subset\mathbb{Z}$ is not a subgroup of $\mathbb{Z}$ since they have different group operations.
3. $\{e\}\leq G$ is the trivial subgroup and $G\leq G$.

Example 7.5. Let us find the smallest sub-group, H containing $7\in U(15)$. Answer,

$$7^2 \bmod 15=4,\ 7^3 \bmod 15=13,\ 7^4 \bmod 15=1$$

so that H must contain, $\{1,7,4,13\}$. One may easily check this is a subgroup and we have $|7|=4$.

Proposition 7.6. *The elements, $O(2):=\{S_\alpha,R_\alpha:\alpha\in\mathbb{R}\}$ form a subgroup $GL_2(\mathbb{R})$, moreover we have the following multiplication rules:*

$$R_\alpha R_\beta=R_{\alpha+\beta},\quad S_\alpha S_\beta=R_{2(\alpha-\beta)}, \tag{7.1}$$
$$R_\beta S_\alpha=S_{\alpha+\beta/2},\quad \text{and } S_\alpha R_\beta=S_{\alpha-\beta/2}. \tag{7.2}$$

for all $\alpha,\beta\in\mathbb{R}$. Also observe that

$$R_\alpha=R_\beta \iff \alpha=\beta \bmod 360 \tag{7.3}$$

while,

$$S_\alpha=S_\beta \iff \alpha=\beta \bmod 180. \tag{7.4}$$

Proof. Equations (7.1) and (7.2) may be verified by direct computations using the matrix representations for R_α and S_β. Perhaps a more illuminating way is to notice that all linear transformations on $\mathbb{R}^2$ are determined by there actions on $u(\theta)$ for all θ (actually for two θ is typically enough). Using this remark we find,

$$\begin{aligned}
R_\alpha R_\beta u(\theta)&=R_\alpha u(\theta+\beta)=u(\theta+\beta+\alpha)=R_{\alpha+\beta}u(\theta)\\
S_\alpha S_\beta u(\theta)&=S_\alpha u(2\beta-\theta)=u(2\alpha-(2\beta-\theta))=u(2(\alpha-\beta)+\theta)=R_{2(\alpha-\beta)}u(\theta),\\
R_\beta S_\alpha u(\theta)&=R_\beta u(2\alpha-\theta)=u(2\alpha-\theta+\beta)=u(2(\alpha+\beta/2)-\theta)=S_{\alpha+\beta/2}u(\theta),\\
&\text{and}\\
S_\alpha R_\beta u(\theta)&=S_\alpha u(\theta+\beta)=u(2\alpha-(\theta+\beta))=u(2(\alpha-\beta/2)-\theta)=S_{\alpha-\beta/2}u(\theta)
\end{aligned}$$

which verifies equations (7.1) and (7.2). From these it is clear that H is a closed under matrix multiplication and since $R_{-\alpha}=R_\alpha^{-1}$ and $S_\alpha^{-1}=S_\alpha$ it follows H is closed under taking inverses.

To finish the proof we will now verify Eq. (7.4) and leave the proof of Eq. (7.3) to the reader. The point is that $S_\alpha=S_\beta$ iff

$$u(2\alpha-\theta)=S_\alpha u(\theta)=S_\beta u(\theta)=u(2\beta-\theta)\ \text{ for all }\theta$$

which happens iff

$$[2\alpha-\theta] \bmod 360=[2\beta-\theta] \bmod 360$$

which is equivalent to $\alpha=\beta \bmod 180$. ■

Lecture 8 (1/23/2009)

Notation 8.1 *The* ***order of a group,*** *G, is the number of elements in G which we denote by $|G|$.*

Example 8.2. We have $|\mathbb{Z}| = \infty$, $|\mathbb{Z}_n| = n$ for all $n \geq 2$, and $|D_3| = 6$ and $|D_4| = 8$.

Definition 8.3 (Euler Phi – function). *For $n \in \mathbb{Z}_+$, let*

$$\varphi(n) := |U(n)| = \#\{1 \leq k \leq n : \gcd(k,n) = 1\}.$$

This function, φ, is called the ***Euler Phi – function.***

Example 8.4. If p is prime, then $U(p) = \{1,2,\dots,p-1\}$ and $\varphi(p) = p-1$. More generally $U(p^n)$ consists of $\{1,2,\dots,p^n\} \setminus \{\text{multiples of } p \text{ in } \{1,2,\dots,p^n\}\}$. Therefore,

$$\varphi(p^n) = |U(p^n)| = p^n - \#\{\text{multiples of } p \text{ in } \{1,2,\dots,p^n\}\}$$

Since

$$\{\text{multiples of } p \text{ in } \{1,2,\dots,p^n\}\} = \left\{kp : k = 1,2,\dots,p^{n-1}\right\}$$

it follows that $\#\{\text{multiples of } p \text{ in } \{1,2,\dots,p^n\}\} = p^{n-1}$ and therefore,

$$\varphi(p^n) = p^n - p^{n-1} = p^{n-1}(p-1)$$

valid for all primes and $n \geq 1$.

Example 8.5 ($\varphi(p^m q^n)$). Let $N = p^m q^n$ with $m,n \geq 1$ and p and q being distinct primes. We wish to compute $\varphi(N) = |U(N)|$. To do this, let let $\Omega := \{1,2,\dots,N-1,N\}$, A be the multiples of p in Ω and B be the multiples of q in Ω. Then $A \cap B$ is the subset of common multiples of p and q or equivalently multiples of pq in Ω so that;

$$\begin{aligned}\#(A) &= N/p = p^{m-1}q^n, \\ \#(B) &= N/q = p^m q^{n-1} \text{ and} \\ \#(A \cap B) &= N/(pq) = p^{m-1}q^{n-1}.\end{aligned}$$

Therefore,

$$\begin{aligned}\varphi(N) &= \#(\Omega \setminus (A \cup B)) = \#(\Omega) - \#(A \cup B) \\ &= \#(\Omega) - [\#(A) + \#(B) - \#(A \cap B)] \\ &= N - \left[\frac{N}{p} + \frac{N}{q} - \frac{N}{p \cdot q}\right] \\ &= p^m \cdot q^n - p^{m-1} \cdot q^n - p^m \cdot q^{n-1} + p^{m-1} \cdot q^{n-1} \\ &= \left(p^m - p^{m-1}\right)\left(q^n - q^{n-1}\right).\end{aligned}$$

which after a little algebra shows,

$$\varphi(p^m q^n) = \left(p^m - p^{m-1}\right)\left(q^n - q^{n-1}\right) = N\left(1 - \frac{1}{p}\right)\left(1 - \frac{1}{q}\right).$$

The next theorem generalizes this example.

Theorem 8.6 (Euler Phi function). *Suppose that $N = p_1^{k_1} \dots p_n^{k_n}$ with $k_i \geq 1$ and p_i being distinct primes. Then*

$$\varphi(N) = \varphi\left(p_1^{k_1} \dots p_n^{k_n}\right) = \prod_{i=1}^n \left(p_i^{k_i} - p_i^{k_i - 1}\right) = N \cdot \prod_{i=1}^n \left(1 - \frac{1}{p_i}\right).$$

Proof. (Proof was not given in class!) Let $\Omega := \{1,2,\dots,N\}$ and $A_i := \{m \in \Omega : p_i | m\}$. It then follows that $U(N) = \Omega \setminus (\cup_{i=1}^n A_i)$ and therefore,

$$\varphi(N) = \#(\Omega) - \#(\cup_{i=1}^n A_i) = N - \#(\cup_{i=1}^n A_i).$$

To compute the later expression we will make use of the inclusion exclusion formula which states,

$$\#(\cup_{i=1}^n A_i) = \sum_{l=1}^n (-1)^{l+1} \sum_{1 \leq i_1 < i_2 < \dots < i_l \leq n} \#(A_{i_1} \cap \dots \cap A_{i_l}). \tag{8.1}$$

Here is a way to see this formula. For $A \subset \Omega$, let $1_A(k) = 1$ if $k \in A$ and 0 otherwise. We now have the identity,

$$1 - 1_{\cup_{i=1}^n A_i} = \prod_{i=1}^n (1 - 1_{A_i}) = 1 - \sum_{l=1}^n (-1)^l \sum_{1 \le i_1 < i_2 < \dots < i_l \le n} 1_{A_{i_1} \cap \dots \cap A_{i_l}}.$$

Summing this identity on $k \in \Omega$ then shows,

$$N - \# (\cup_{i=1}^n A_i) = N - \sum_{l=1}^n (-1)^l \sum_{1 \le i_1 < i_2 < \dots < i_l \le n} \# (A_{i_1} \cap \dots \cap A_{i_l})$$

which gives Eq. (8.1).

Since $A_{i_1} \cap \dots \cap A_{i_l}$ consists of those $k \in \Omega$ which are common multiples of $p_{i_1}, p_{i_2}, \dots, p_{i_l}$ or equivalently multiples of $p_{i_1} \cdot p_{i_2} \cdot \dots \cdot p_{i_l}$, it follows that

$$\# (A_{i_1} \cap \dots \cap A_{i_l}) = \frac{N}{p_{i_1} \cdot p_{i_2} \cdot \dots \cdot p_{i_l}}.$$

Thus we arrive at the formula,

$$\varphi (N) = N - \sum_{l=1}^n (-1)^{l+1} \sum_{1 \le i_1 < i_2 < \dots < i_l \le n} \frac{N}{p_{i_1} \cdot p_{i_2} \cdot \dots \cdot p_{i_l}} = N + \sum_{l=1}^n (-1)^l \sum_{1 \le i_1 < i_2 < \dots < i_l \le n} \frac{N}{p_{i_1} \cdot p_{i_2} \cdot \dots \cdot p_{i_l}}$$

Let us now break up the sum over those terms with $i_l = n$ and those with $i_l < n$ to find,

$$\varphi (N) = \left[N + \sum_{l=1}^{n-1} (-1)^l \sum_{1 \le i_1 < i_2 < \dots < i_l < n} \frac{N}{p_{i_1} \cdot p_{i_2} \cdot \dots \cdot p_{i_l}} \right] + \left[\sum_{l=1}^n (-1)^l \sum_{1 \le i_1 < i_2 < \dots < i_{l-1} < i_l = n} \frac{N}{p_{i_1} \cdot p_{i_2} \cdot \dots \cdot p_{i_l}} \right].$$

We may factor out $p_n^{k_n}$ in the first term to find,

$$\varphi (N) = p_n^{k_n} \varphi \left(p_1^{k_1} \dots p_{n-1}^{k_{n-1}} \right) + \sum_{l=1}^n (-1)^l \sum_{1 \le i_1 < i_2 < \dots < i_{l-1} < i_l = n} \frac{N}{p_{i_1} \cdot p_{i_2} \cdot \dots \cdot p_{i_l}}.$$

Similarly the second term is equal to:

$$p_n^{k_n - 1} \left[-p_1^{k_1} \dots p_{n-1}^{k_{n-1}} + \sum_{l=2}^n (-1)^l \sum_{1 \le i_1 < i_2 < \dots < i_{l-1} < n} \frac{p_1^{k_1} \dots p_{n-1}^{k_{n-1}}}{p_{i_1} \cdot p_{i_2} \cdot \dots \cdot p_{i_{l-1}}} \right]$$
$$= p_n^{k_n - 1} \left[-p_1^{k_1} \dots p_{n-1}^{k_{n-1}} - \sum_{l=1}^{n-1} (-1)^l \sum_{1 \le i_1 < i_2 < \dots < i_l < n} \frac{p_1^{k_1} \dots p_{n-1}^{k_{n-1}}}{p_{i_1} \cdot p_{i_2} \cdot \dots \cdot p_{i_l}} \right]$$
$$= -p_n^{k_n - 1} \varphi \left(p_1^{k_1} \dots p_{n-1}^{k_{n-1}} \right).$$

Thus we have shown

$$\varphi (N) = p_n^{k_n} \varphi \left(p_1^{k_1} \dots p_{n-1}^{k_{n-1}} \right) - p_n^{k_n - 1} \varphi \left(p_1^{k_1} \dots p_{n-1}^{k_{n-1}} \right) = \left(p_n^{k_n} - p_n^{k_n - 1} \right) \varphi \left(p_1^{k_1} \dots p_{n-1}^{k_{n-1}} \right)$$

and so the result now follows by induction. ■

Corollary 8.7. *If $m, n \ge 1$ and $\gcd (m, n) = 1$, then $\varphi (mn) = \varphi (m) \varphi (n)$.*

Notation 8.8 *For $g \in G$, let $\langle g \rangle := \{ g^n : n \in \mathbb{Z} \}$. We call $\langle g \rangle$ the* ***cyclic subgroup generated by*** *g (as justified by the next proposition).*

Proposition 8.9 (Cyclic sub-groups). *For all $g \in G$, $\langle g \rangle \le G$.*

Proof. For $m, n \in \mathbb{Z}$ we have $g^n (g^m)^{-1} = g^{n-m} \in \langle g \rangle$ and therefore by the one step subgroup test, $\langle g \rangle \le G$. ■

Notation 8.10 *The* ***order of an element,*** *$g \in G$, is*

$$|g| := \min \{ n \ge 1 : g^n = e \}$$

with the convention that $|g| = \infty$ if $\{ n \ge 1 : g^n = e \} = \emptyset$.

Lemma 8.11. *Let $g \in G$. Then $|g| = \infty$ iff no two elements in the list,*

$$\{ g^n : n \in \mathbb{Z} \} = \left\{ \dots, g^{-2}, g^{-1}, g^0 = e, g^1 = g, g^2, \dots \right\}$$

are equal.

Theorem 8.12. *Suppose that g is an element of a group, G. Then either:*

1. *If $|g| = \infty$ then all elements in the list, $\{ g^n : n \in \mathbb{Z} \}$, defining $\langle g \rangle$ are distinct. In particular $|\langle g \rangle| = \infty = |g|$.*
2. *If $n := |g| < \infty$, then $g^m = g^{m \bmod n}$ for all $m \in \mathbb{Z}$,*
$$\langle g \rangle = \left\{ e, g, g^2, \dots, g^{n-1} \right\} \tag{8.2}$$
with all elements in the list being distinct and $|\langle g \rangle| = n = |g|$. We also have,
$$g^k g^l = g^{(k+l) \bmod n} \text{ for all } k, l \in \mathbb{Z}_n \tag{8.3}$$
which shows that $\langle g \rangle$ is "equivalent" to $\mathbb{Z}_n$.

So in all cases $|g| = |\langle g \rangle|$.

Proof. 1. If $g^i = g^j$ for some $i < j$, then

$$e = g^i g^{-i} = g^j g^{-i} = g^{j-i}$$

so that $g^m = e$ with $m = j - i \in \mathbb{Z}_+$ from which we would conclude that $|g| < \infty$. Thus if $|g| = \infty$ it must be that all elements in the list, $\{g^n : n \in \mathbb{Z}\}$, are distinct. In particular $\langle g \rangle = \{g^n : n \in \mathbb{Z}\}$ has an infinite number of elements and therefore $|\langle g \rangle| = \infty$.

2. Now suppose that $n = |g| < \infty$. Since $g^n = e$, it also follows that $g^{-n} = (g^n)^{-1} = e^{-1} = e$. Therefore if $m \in \mathbb{Z}$ and $m = sn + r$ where $r := m \mod n$, then $g^m = (g^n)^s g^r = g^r$, i.e. $g^m = g^{m \bmod n}$ for all $m \in \mathbb{Z}$. Hence it follows that $\langle g \rangle = \{e, g, g^2, \dots, g^{n-1}\}$. Moreover if $g^i = g^j$ for some $0 \le i \le j < n$, then $g^{j-i} = e$ with $j - i < n$ and hence $j = i$. Thus the list in Eq. (8.2) consists of distinct elements and therefore $|\langle g \rangle| = n$. Lastly, if $k, l \in \mathbb{Z}_n$, then

$$g^k g^l = g^{k+l} = g^{(k+l) \bmod n}.$$

■

Lecture 9 (1/26/2009)

Corollary 9.1. *Let $a \in G$. Then $a^i = a^j$ iff $|a|$ divides $(j - i)$. Here we use the convention that ∞ divides m iff $m = 0$. In particular, $a^k = e$ iff $|a|\,|k$.*

Corollary 9.2. *For all $g \in G$ we have $|g| \le |G|$.*

Proof. This follows from the fact that $|g| = |\langle g\rangle|$ and $\langle g\rangle \subset G$. ∎

Theorem 9.3 (Finite Subgroup Test). *Let H be a non-empty finite subset of a group G which is closed under the group law, then $H \le G$.*

Proof. To each $h \in H$ we have $\{h^k\}_{k=1}^{\infty} \subset H$ and since $\#(H) < \infty$, it follows that $h^k = h^l$ for some $k \neq l$. Thus by Theorem 8.12, $|h| < \infty$ for all $h \in H$ and $\langle h\rangle = \{e, h, h^2, \dots, h^{|h|-1}\} \subset H$. In particular $h^{-1} \in \langle h\rangle \subset H$ for all $h \in H$. Hence it follows by the two step subgroup test that $H \le G$. ∎

Definition 9.4 (Centralizer of a in G). *The **centralizer** of $a \in G$, denoted $C(a)$, is the set of $g \in G$ which commute with a, i.e.*

$$C(a) := \{g \in G : ga = ag\}.$$

More generally if $S \subset G$ is any non-empty set we define

$$C(S) := \{g \in G : gs = sg \text{ for all } s \in S\} = \cap_{s\in S} C(s).$$

Lemma 9.5. *For all $a \in G$, $\langle a\rangle \le C(a) \le G$.*

Proof. If $g \in C(a)$, then $ga = ag$. Multiplying this equation on the right and left by g^{-1} then shows,

$$ag^{-1} = g^{-1}gag^{-1} = g^{-1}agg^{-1} = g^{-1}a$$

which shows $g^{-1} \in C(a)$. Moreover if $g, h \in C(a)$, then $gha = gah = agh$ which shows that $gh \in C(a)$ and therefore $C(a) \le G$. ∎

Example 9.6. If G is abelian, then $C(a) = G$ for all $a \in G$.

Example 9.7. Let $G = GL_2(\mathbb{R})$ we will compute $C(A_1)$ and $C(A_2)$ where

$$A_1 = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \text{ and } A_2 := \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}.$$

1. We have $B = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \in C(A_1)$ iff,

$$\begin{bmatrix} b & a \\ d & c \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix}\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}\begin{bmatrix} a & b \\ c & d \end{bmatrix} = \begin{bmatrix} c & d \\ a & b \end{bmatrix}$$

which means that $b = c$ and $a = d$, i.e. B must be of the form,

$$B = \begin{bmatrix} a & b \\ b & a \end{bmatrix}$$

and therefore,

$$C(A_1) = \left\{\begin{bmatrix} a & b \\ b & a \end{bmatrix} : a^2 - b^2 \neq 0\right\}.$$

2. We have $B = \begin{bmatrix} a & b \\ c & d \end{bmatrix} \in C(A_2)$ iff,

$$\begin{bmatrix} a & -b \\ c & -d \end{bmatrix} = \begin{bmatrix} a & b \\ c & d \end{bmatrix}\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}\begin{bmatrix} a & b \\ c & d \end{bmatrix} = \begin{bmatrix} a & b \\ -c & -d \end{bmatrix}$$

which happens iff $b = c = 0$. Thus we have,

$$C(A_2) = \left\{\begin{bmatrix} a & 0 \\ 0 & d \end{bmatrix} : ad \neq 0\right\}.$$

Lemma 9.8. *If $\{H_i\}$ is a collection of subgroups of G then $H := \cap_i H_i \le G$ as well.*

Proof. If $h, k \in H$ then $h, k \in H_i$ for all i and therefore $hk^{-1} \in H_i$ for all i and hence $hk^{-1} \in H$. ∎

Corollary 9.9. *$C(S) \le G$ for any non-empty subset $S \subset G$.*

Definition 9.10 (Center of a group). *Center of a group, denoted $Z(G)$, is the centralizer of G, i.e.*

$$Z(G) = C(G) := \{a \in G : ax = xa \text{ for all } x \in G\}$$

By Corollary 9.9, $Z(G) = C(G)$ is a group. Alternatively, if $a \in Z(G)$, then $ax = xa$ implies $a^{-1}x^{-1} = x^{-1}a^{-1}$ which implies $xa^{-1} = a^{-1}x$ for all $x \in G$ and therefore $a^{-1} \in Z(G)$. If $a, b \in Z(G)$, then $abx = axb = xab \implies ab \in Z(G)$, which again shows $Z(G)$ is a group.

Example 9.11. G is a abelian iff $Z(G) = G$, thus $Z(\mathbb{Z}_n) = \mathbb{Z}_n$, $Z(U(n)) = U(n)$, etc.

Example 9.12. Using Example 9.7 we may easily show $Z(GL_2(\mathbb{R})) = \{\lambda I : \lambda \in \mathbb{R}\setminus\{0\}\}$. Indeed,

$$Z(GL_2(\mathbb{R})) \subset C(A_1) \cap C(A_2) = \left\{ \begin{bmatrix} a & 0 \\ 0 & a \end{bmatrix} : a^2 \neq 0 \right\} = \{\lambda I : \lambda \in \mathbb{R}\setminus\{0\}\}.$$

As the latter matrices commute with every matrix we also have,

$$Z(GL_2(\mathbb{R})) \subset \{\lambda I : \lambda \in \mathbb{R}\setminus\{0\}\} \subset Z(GL_2(\mathbb{R})).$$

Remark 9.13. If $S \subset G$ is a non-empty set we let $\langle S \rangle$ denote the smallest subgroup in G which contains S. This subgroup may be constructed as finite products of elements from S and $S^{-1} := \{s^{-1} : s \in S\}$. It is not too hard to prove that

$$C(S) = C(\langle S \rangle).$$

Let us also note that if $S \subset T \subset G$, then $C(T) \subset C(S)$ as there are more restrictions on $x \in G$ to be in $C(T)$ than there are for $x \in G$ to be in $C(S)$.

9.1 Dihedral group formalities and examples

Definition 9.14 (General Dihedral Groups). *For $n \geq 3$, the **dihedral group**, D_n, is the symmetry group of a regular n – gon. To be explicit this may be realized as the sub-groups $O(2)$ defined as*

$$D_n = \left\{ R_{k\frac{2\pi}{n}}, S_{k\frac{\pi}{n}} : k = 0, 1, 2, \dots, n-1 \right\},$$

see the Figures below. Notice that $|D_n| = 2n$.

See the book and the demonstration in class for more intuition on these groups. For computational purposes, we may present D_n in terms of generators and relations as follows.

Theorem 9.15 (A presentation of D_n). *Let $n \geq 3$ and $r := R_{\frac{2\pi}{n}}$ and $f = S_0$. Then*

$$D_n = \{r^k, r^k f : k = 0, 1, 2, \dots, n-1\} \tag{9.1}$$

and we have the relations, $r^n = 1$, $f^2 = 1$, and $frf = r^{-1}$. We say that r and f are generators for D_n.

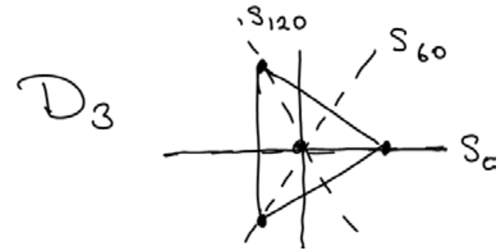

Fig. 9.1. The 3 reflection symmetries axis of a regular 3 – gon,. i.e. a equilateral triangle.

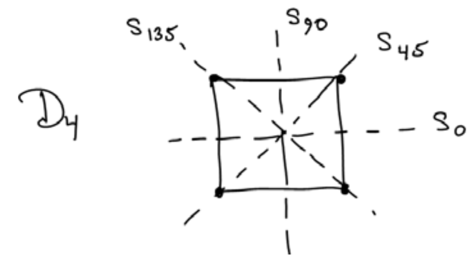

Fig. 9.2. The 4− reflection symmetries axis of a regular 4 – gon,. i.e. a square.

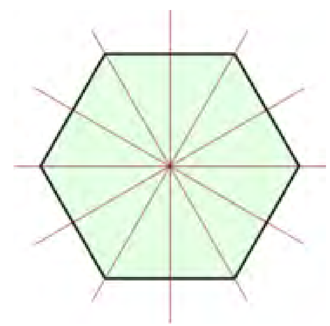

Fig. 9.3. The 6− reflection symmety axis of a regular 6 – gon,. i.e. a heagon. There are also 6 rotation symmetries.

Proof. We know that $r^k = R_{k\frac{2\pi}{n}}$ and that $r^k f = R_{k\frac{2\pi}{n}} S_0 = S_{k\frac{\pi}{n}}$ from which Eq. (9.1) follows. It is also clear that $r^n = 1 = f^2$. Moreover,

$$frf = S_0 R_{\frac{2\pi}{n}} S_0 = S_0 S_{\frac{\pi}{n}} = R_{2\left(0-\frac{\pi}{n}\right)} = r^{-1}$$

as desired. (Poetically, a rotation viewed through a mirror is a rotation in the opposite direction.) ■

For computational purposes, observe that

$$fr^3 f = frf\ frf\ frf = \left(r^{-1}\right)^3 = r^{-3}$$

and therefore $fr^{-3}f = f\left(fr^3 f\right)f = r^3$. In general we have $fr^k f = r^{-k}$ for all $k \in \mathbb{Z}$.

Example 9.16. If $f \in D_n$ is a reflection, then $f^2 = e$ and $|f| = 2$. If $r := R_{2\pi/n}$ then $r^k = R_{2\pi k/n} \neq e$ for $1 \le k \le n-1$ and $r^n = 1$, so $|r| = n$ and

$$\langle r \rangle = \left\{R_{2\pi k/n} : 0 \le k \le n-1\right\} \subset D_n.$$

Example 9.17. Suppose that $G = D_n$ and $f = S_0$. Recall that $D_n = \left\{r^k, r^k f\right\}_{k=0}^{n-1}$. We wish to compute $C(f)$. We have $r^k \in C(f)$ iff $r^k f = fr^k$ iff $r^k = fr^k f = r^{-k}$. There are only two rotations R_θ for which $R_\theta = R_\theta^{-1}$, namely $R_0 = e$ and $R_{180} = -I$. The latter is in D_n only if n is even.

Let us now check to see if $r^k f \in C(f)$. This is the case iff

$$r^k = \left(r^k f\right) f = f\left(r^k f\right) = r^{-k}$$

and so again this happens iff $r = R_0$ or R_{180}. Thus we have shown,

$$C(f) = \begin{cases} \langle f \rangle = \{e, f\} & \text{if } n \text{ is odd} \\ \left\{e, r^{n/2}, f, r^{n/2} f\right\} & \text{if } n \text{ is even.} \end{cases}$$

Let us now find $C\left(r^k\right)$. In this case we have $\langle r \rangle \subset C\left(r^k\right)$ (as this is a general fact). Moreover $r^l f \in C\left(r^k\right)$ iff $\left(r^l f\right) r^k = r^k \left(r^l f\right)$ which happens iff

$$r^{l-k} = r^l r^{-k} = \left(r^l f\right) r^k f = r^{k+l},$$

i.e. iff $r^{2k} = e$. Thus we may conclude that $C\left(r^k\right) = \langle r \rangle$ unless $k = 0$ or $k = \frac{n}{2}$ and when $k = 0$ or $k = n/2$ we have $C\left(r^k\right) = D_n$. Of course the case $k = n/2$ only applies if n is even. By the way this last result is not too hard to understand as $r^0 = I$ and $r^{n/2} = -I$ where I is the 2×2 identity matrix which commutes with all matrices.

Example 9.18. For $n \ge 3$,

$$Z(D_n) = \begin{cases} \{R_0 = I\} & \text{if } n \text{ is odd.} \\ \{R_0, R_{180}\} & \text{if } n \text{ is even} \end{cases} \tag{9.2}$$

To prove this recall that $S_\alpha R_\theta S_\alpha^{-1} = R_{-\theta}$ for all α and θ. So if $S_\alpha \in Z(D_n)$ we would have $R_\theta = S_\alpha R_\theta S_\alpha^{-1} = R_{-\theta}$ for $\theta = k2\pi/n$ which is impossible. Thus $Z(D_n)$ contains no reflections. Moreover this shows that R_θ can only be in the center if $R_\theta = R_{-\theta}$, i.e. R_θ can only be R_0 or R_{180}. This completes the proof since $R_{180} \in D_n$ iff n is even.

Alternatively, observe that $Z(D_n) = C(f) \cap C(r) = C(\{f, r\})$ since if $g \in D_n$ commutes with the generators of a group it must commute with all elements of the group. Now according to Example 9.17, we again easily see that Eq. (9.2) is correct. For example when n is even we have,

$$Z(D_n) = C(f) \cap C(r) = \left\{e, r^{n/2}, f, r^{n/2} f\right\} \cap \langle r \rangle = \left\{e, r^{n/2}\right\} = \{R_0, R_{180}\}.$$

10

Lecture 10 (1/28/2009) Midterm I.

Lecture 11 (1/30/2009)

11.1 Cyclic Groups

Definition 11.1. *We say a group, G, is a* ***cyclic group*** *if there exists $g \in G$ such that $G = \langle g \rangle$. We call such a g a* ***generator of the cyclic group*** *G.*

Example 11.2. Recall that $U(9) = \{1, 2, 4, 5, 7, 8\}$ and that

$$\langle 2 \rangle = \left\{2^0 = 1,\ 2^1 = 2,\ 2^2 = 4,\ 2^3 = 8,\ 2^4 = 7,\ 2^5 = 5,\ 2^6 = 1\right\}$$

so that $|2| = |\langle 2 \rangle| = 6$ and $U(9)$ and 2 is a generator.

Notice that $2^2 = 4$ is not a generator, since

$$\left\langle 2^2 \right\rangle = \{1, 4, 7\} \neq U(9).$$

Example 11.3. The group $U(8) = \{1, 3, 5, 7\}$ is not cyclic since,

$$\langle 3 \rangle = \{1, 3\},\ \langle 5 \rangle = \{1, 5\},\ \text{and}\ \langle 7 \rangle = \{1, 7\}.$$

This group may be understood by observing that $3 \cdot 5 = 15 \bmod 8 = 7$ so that

$$U(8) = \left\{3^a 5^b : a, b \in \mathbb{Z}_2\right\}.$$

Moreover, the multiplication on $U(8)$ becomes two copies of the group operation on $\mathbb{Z}_2$, i.e.

$$\left(3^a 5^b\right)\left(3^{a'} 5'\right) = 3^{a+a'} 5^{b+b'} = 3^{\left(a+a'\right) \bmod 2} 5^{\left(b+b'\right) \bmod 2}.$$

So in a sense to be made precise later, $U(8)$ is equivalent to "$\mathbb{Z}_2^2$."

Example 11.4. Here are some more examples of cyclic groups.

1. $\mathbb{Z}$ is cyclic with generators being either 1 or -1.
2. $\mathbb{Z}_n$ is cyclic with 1 being a generator since
$$\langle 1 \rangle = \{0, 1, 2 = 1 + 1, 3 = 1 + 1 + 1, \dots, n - 1\}.$$
3. Let
$$G := \left\{e^{i\frac{k}{n}2\pi} : k \in \mathbb{Z}\right\},$$
then G is cyclic and $g := e^{i2\pi/n}$ is a generator. Indeed, $g^k = e^{i\frac{k}{n}2\pi}$ is equal to 1 for the first time when $k = n$.

These last two examples are essentially the same and basically this is the list of all cyclic groups. Later today we will list all of the generators of a cyclic group.

Lemma 11.5. *If $H \subset \mathbb{Z}$ is a subgroup and $a := \min H \cap \mathbb{Z}_+$, then $H = \langle a \rangle = \{ka : k \in \mathbb{Z}\}$.*

Proof. It is clear that $\langle a \rangle \subset H$. If $b \in H$, we may write it as $b = ka + r$ where $0 \le r < a$. As $r = b - ka \in H$ and $0 \le r < a$, we must have $r = 0$. This shows that $b \in \langle a \rangle$ and thus $H \subset \langle a \rangle$. ∎

Example 11.6. If $f = \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix} \in GL_2(\mathbb{R})$, then f is reflection about the line $y = x$. In particular $f^2 = I$ and $\langle f \rangle = \{I, f\}$ and $|f| = 2$. So we can have elements of finite order inside an infinite group. In fact any element of a Dihedral subgroup of $GL_2(\mathbb{R})$ gives such an example.

Notation 11.7 *Let $n \in \mathbb{Z}_+ \cup \{\infty\}$. We will write $b \equiv a \pmod{n}$ iff $(b - a) \bmod n = 0$ or equivalently $n | (b - a)$. here we use the convention that if $n = \infty$ then $b \equiv a \pmod{n}$ iff $b = a$ and $\infty | m$ iff $m = 0$.*

Theorem 11.8 (More properties of cyclic groups). *Let $a \in G$ and $n = |a|$. Then;*

1. *$a^i = a^j$ iff $i \equiv j \pmod{n}$,*
2. *If $k | m$ then $\langle a^m \rangle \subset \left\langle a^k \right\rangle$.*
3. *$\left\langle a^k \right\rangle = \left\langle a^{\gcd(n,k)} \right\rangle$.*
4. *$\left|a^k\right| = |a| / \gcd(|a|, k)$.*
5. *$\left\langle a^i \right\rangle = \left\langle a^j \right\rangle$ iff $\gcd(i, n) = \gcd(j, n)$*
6. *$\left\langle a^k \right\rangle = \langle a \rangle$ iff $\gcd(k, n) = 1$.*

Proof. 1. We have $a^i = a^j$ iff

$$e = a^{i-j} = a^{(i-j) \bmod n}$$

which happens iff $(i - j) \bmod n = 0$ by Theorem 8.12.

2. If $m = lk$, then $(a^m)^q = \left(a^{lk}\right)^q = \left(a^k\right)^{lq}$, and therefore $\langle a^m \rangle \subset \left\langle a^k \right\rangle$.

3. Let $d := \gcd(n,k)$, then $d|k$ and therefore $\langle a^k \rangle \subset \langle a^d \rangle$. For the opposite inclusion we must show $a^d \in \langle a^k \rangle$. To this end, choose $s,t \in \mathbb{Z}$ such that $d = sk + tn$. It then follows that

$$a^d = a^{sk}a^{tn} = \left(a^k\right)^s \in \langle a^k \rangle$$

as desired.

4. Again let $d := \gcd(n,k)$ and set $m := n/d \in \mathbb{N}$. Then $\left(a^d\right)^k = a^{dk} \neq e$ for $1 \leq k < m$ and $a^{dm} = a^n = e$. Hence we may conclude that $\left|a^d\right| = m = n/d$. Combining this with item 3. show,

$$\left|a^k\right| = \left|\langle a^k \rangle\right| = \left|\langle a^d \rangle\right| = \left|a^d\right| = n/d = |a| / \gcd(k, |a|).$$

5. By item 4., if $\gcd(i,n) = \gcd(j,n)$ then

$$\langle a^i \rangle = \left\langle a^{\gcd(i,n)} \right\rangle = \left\langle a^{\gcd(j,n)} \right\rangle = \langle a^j \rangle.$$

Conversely if $\langle a^i \rangle = \langle a^j \rangle$ then by item 4.,

$$\frac{n}{\gcd(i,n)} = \left|\langle a^i \rangle\right| = \left|\langle a^j \rangle\right| = \frac{n}{\gcd(j,n)}$$

from which it follows that $\gcd(i,n) = \gcd(j,n)$.

6. This follows directly from item 3. or item 5. ■

Example 11.9. Let use Theorem 11.8 to find all generators of $Z_{10} = \{0,1,2,\ldots,9\}$. Since 1 is a generator it follow by item 6. of the previous theorem that the generators of Z_{10} are precisely those $k \geq 1$ such that $\gcd(k,10) = 1$. (Recall we use the additive notation here so that a^k becomes ka.) In other words the generators of Z_{10} is precisely

$$U(10) = \{1,3,7,9\}$$

of which their are $\varphi(10) = \varphi(5 \cdot 2) = (5-1)(2-1) = 4$.

More generally the generators of Z_n are the elements in $U(n)$. It is in fact easy to see that every $a \in U(n)$ is a generator. Indeed, let $b := a^{-1} \in U(n)$, then we have

$$\mathbb{Z}_n = \langle 1 \rangle = \langle (b \cdot a) \bmod n \rangle = \langle b \cdot a \rangle \subset \langle a \rangle \subset \mathbb{Z}_n.$$

Conversely if and $a \in [\mathbb{Z}_n \setminus U(n)]$, then $\gcd(a,n) = d > 1$ and therefore $\gcd(a/d, n) = 1$ and $a/d \in U(n)$. Thus a/d generates $\mathbb{Z}_n$ and therefore $|a| = n/d$ and hence $|\langle a \rangle| = n/d$ and $\langle a \rangle \neq \mathbb{Z}_n$.

Lecture 12 (2/2/2009)

Theorem 12.1 (Fundamental Theorem of Cyclic Groups). *Suppose that $G = \langle a \rangle$ is a cyclic group and H is a sub-group of G, and*

$$m := m(H) = \min\left\{k \geq 1 : a^k \in H\right\}. \tag{12.1}$$

Then:

1. *$H = \langle a^m \rangle$ – so all subgroups of G are of the form $\langle a^m \rangle$ for some $m \geq 1$.*
2. *If $n = |a| < \infty$, then $m|n$ and $|H| = n/m$.*
3. *To each divisor, $k \geq 1$, of n there is precisely one subgroup of G of order k, namely $H = \left\langle a^{n/k} \right\rangle$.*

In short, if $G = \langle a \rangle$ with $|a| = n$, then

$$\begin{array}{ccc} \{\text{Positive divisors of } n\} & \longleftrightarrow & \{\text{sub-groups of } G\} \\ m & \rightarrow & \langle a^m \rangle \\ m(H) & \leftarrow & H \end{array}$$

is a one to one correspondence. These subgroups may be indexed by their order, $k = |\langle a^m \rangle| = n/m$.

Proof. We prove each point in turn.

1. Suppose that $H \subset G$ is a sub-group and m is defined as in Eq. (12.1). Since $a^m \in H$ and H is closed under the group operations it follows that $\langle a^m \rangle \subset H$. So we must show $H \subset \langle a^m \rangle$. If $a^l \in H$ with $l \in \mathbb{Z}$, we write $l = jm + r$ with $r := l \bmod m$. Then $a^l = a^{mj} a^r$ and hence $a^r = a^l (a^m)^{-j} \in H$. As $0 \leq r < m$, it follows from the definition of m that $r = 0$ and therefore $a^l = a^{jm} = (a^m)^j \in \langle a^m \rangle$. Thus we have shown $H \subset \langle a^m \rangle$ and therefore that $H = \langle a^m \rangle$.
2. From Theorem 11.8 we know that $H = \langle a^m \rangle = \left\langle a^{\gcd(m,n)} \right\rangle$ and that $|H| = n/\gcd(m,n)$. Using the definition of m, we must have $m \leq \gcd(m,n)$ which can only happen if $m = \gcd(m,n)$. This shows that $m|n$ and $|H| = n/m$.
3. From what we have just shown, the subgroups, $H \subset G$, are precisely of the form $\langle a^m \rangle$ where m is a divisor of n. Moreover we have shown that $|\langle a^m \rangle| = n/m =: k$. Thus for each divisor k of n, there is exactly one subgroup of G of order k, namely $\langle a^m \rangle$ where $m = n/k$.

■

Example 12.2. Let $G = \mathbb{Z}_{20}$. Since $20 = 2^2 \cdot 5$ it has divisors, $k = 1, 2, 4, 5, 10, 20$. The subgroups having these orders are,

Order		
1	$\langle 0 \rangle = \left\langle \frac{20}{1} \cdot 1 \right\rangle$	$= \{0\}$
2	$\langle 10 \rangle = \left\langle \frac{20}{2} \cdot 1 \right\rangle$	$= \{0, 10\}$
4	$\langle 5 \rangle = \left\langle \frac{20}{4} \cdot 1 \right\rangle$	$= \{0, 5, 10, 15\}$
5	$\langle 4 \rangle = \left\langle \frac{20}{5} \cdot 1 \right\rangle$	$= \{0, 4, 8, 12, 16, 20\}$
10	$\langle 2 \rangle = \left\langle \frac{20}{10} \cdot 1 \right\rangle$	$= \{0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20\}$
20	$\langle 1 \rangle = \left\langle \frac{20}{20} \cdot 1 \right\rangle$	$= \mathbb{Z}_{20}$

Corollary 12.3. *Suppose G is a cyclic group of order n with generator g, d is a divisor of n, and $a = g^{n/d}$. Then*

$$\{\text{elements of order } d \text{ in } G\} = \left\{a^k : k \in U(d)\right\}$$

and in particular G contains exactly $\varphi(d)$ elements of order d. It should be noted that $\left\{a^k : k \in U(d)\right\}$ is also the list of all the elements of G which generate the unique cyclic subgroup of order d.

Proof. We know that $a := g^{n/d}$ is the generator of the unique (cyclic) subgroup, $H \leq G$, of order d. This subgroup must contain all of the elements of order d for if not there would be another distinct cyclic subgroup of order d in G. The elements of H which have order d are precisely of the form a^k with $1 \leq k < d$ and $\gcd(k, d) = 1$, i.e. with $k \in U(d)$. As there are $\varphi(d)$ such elements the proof is complete. ■

Example 12.4. Let us find all the elements of order 10 in $\mathbb{Z}_{20}$. Since $|2| = 10$, we know from Corollary 12.3 that

$$\{2k : k \in U(10)\} = \{2k : k = 1, 3, 7, 9\} = \{2, 6, 14, 18\}$$

are precisely the elements of order 10 in $\mathbb{Z}_{20}$.

Corollary 12.5. *The Euler Phi – function satisfies, $n = \sum_{1 \leq d : d|n} \varphi(d)$.*

Proof. Every element of $\mathbb{Z}_n$ has a unique order, d, which divides n and therefore,

$$n = \sum_{1 \le d : d|n} \# \{k \in \mathbb{Z}_n : |k| = d\} = \sum_{1 \le d : d|n} \varphi(d).$$

■

Example 12.6. Let us test this out for $n = 20$. In this case we should have,

$$\begin{aligned} 20 &\stackrel{?}{=} \varphi(1) + \varphi(2) + \varphi(4) + \varphi(5) + \varphi(10) + \varphi(20) \\ &= 1 + 1 + 2 + 4 + 4 + \left(2^2 - 2\right)(5 - 1) \\ &= 1 + 1 + 2 + 4 + 4 + 8 = 20. \end{aligned}$$

Remark 12.7. In principle it is possible to use Corollary 12.5 to compute φ. For example using this corollary and the fact that $\varphi(1) = 1$, we find for distinct primes p and q that,

$$\begin{aligned} p &= \varphi(1) + \varphi(p) = 1 + \varphi(p) \implies \varphi(p) = p - 1, \\ p^2 &= \varphi(1) + \varphi(p) + \varphi\left(p^2\right) = p + \varphi\left(p^2\right) \implies \varphi(p) = p^2 - p \\ pq &= \varphi(1) + \varphi(p) + \varphi(q) + \varphi(pq) = p + q - 1 + \varphi(pq) \end{aligned}$$

which then implies,

$$\varphi(pq) = pq - p - q + 1 = (p - 1)(q - 1).$$

Similarly,

$$\begin{aligned} p^2 q &= \varphi(1) + \varphi(p) + \varphi(q) + \varphi(pq) + \varphi\left(p^2\right) + \varphi\left(p^2 q\right) \\ &= pq + \left(p^2 - p\right) + \varphi\left(p^2 q\right) \end{aligned}$$

and hence,

$$\begin{aligned} \varphi\left(p^2 q\right) &= p^2 q - pq - \left(p^2 - 1\right) = p^2 q - p^2 - pq + p \\ &= p(pq - p - q + 1) = p(p - 1)(q - 1). \end{aligned}$$

Theorem 12.8. *Suppose that G is any finite group and $d \in \mathbb{Z}_+$, then the number elements of order d in G is divisible by $\varphi(d)$.*

Proof. Let

$$G_d := \{g \in G : |g| = d\}.$$

If $G_d = \emptyset$, the statement of the theorem is true since $\varphi(d)$ divides $0 = \#(G_d)$.

If $a \in G_d$, then $\langle a \rangle$ is a cyclic subgroup of order d with precisely $\varphi(d)$ element of order d. If $G_d \setminus \langle a \rangle = \emptyset$ we are done since there are precisely $\varphi(d)$ elements of order d in G. If not, choose $b \in G_d \setminus \langle a \rangle$. Then the elements of order d in $\langle b \rangle$ must be distinct from the elements of order d in $\langle a \rangle$ for otherwise $\langle a \rangle = \langle b \rangle$, but $b \notin \langle a \rangle$. If $G_d \setminus (\langle a \rangle \cup \langle b \rangle) = \emptyset$ we are again done since now $\#(G_d) = 2\varphi(d)$ will be the number of elements of order d in G. If $G_d \setminus (\langle a \rangle \cup \langle b \rangle) \neq \emptyset$ we choose a third element, $c \in G_d \setminus (\langle a \rangle \cup \langle b \rangle)$ and argue as above that $\#(G_d) = 3\varphi(d)$ if $G_d \setminus (\langle a \rangle \cup \langle b \rangle \cup \langle c \rangle) = \emptyset$. Continuing on this way, the process will eventually terminate since $\#(G_d) < \infty$ and we will have shown that $\#(G_d) = n\varphi(d)$ for some $n \in \mathbb{N}$. ■

Example 12.9 (Exercise 4.20). Suppose that G is an Abelian group, $|G| = 35$, and every element of G satisfies $x^{35} = e$. Prove that G is cyclic. Since $x^{35} = e$, we have seen in Corollary 9.1 that $|x|$ must divide $35 = 5 \cdot 7$. Thus every element in G has order either, 1, 5, 7, or 35. If there is an element of order 35, G is cyclic and we are done. Since the only element of order 1 is e, there are 34 elements of either order 5 or 7. As $\varphi(5) = 4$ and $\varphi(7) = 6$ do not divide 35, there must exists $a, b \in G$ such that $|a| = 5$ and $|b| = 7$. We now let $x := ab$ and claim that $|x| = 35$ which is a contradiction. To see that $|x| = 35$ observe that $|x| > 1$, $x^5 = a^5 b^5 = eb^5 \neq e$ so $|x| \neq 5$ and $x^7 = a^7 b^7 = a^2 \neq e$ so that $|x| \neq 7$. Therefore $|x| = 35$ and we are done.

Alternatively, for this last part. Notice that $x^n = a^n b^n = e$ iff $a^n = b^{-n}$. If $a^n = b^{-n} \neq e$, then $|a^n| = 5$ while $|b^{-n}| = 7$ which is impossible. Thus the only way that $a^n b^n = e$ is if $a^n = e = b^n$. Thus we must $5|n$ and $7|n$ and therefore $35|n$ and therefore $|x| = 35$.

Lecture 13 (2/4/2009)

The **least common multiple**, $\mathrm{lcm}(a_1,\dots,a_k)$, of k integers, $a_1,\dots,a_k \in \mathbb{Z}_+$, is the smallest integer $n \geq 1$ which is a multiple of each a_i for $i = 1,\dots,k$.
For example,

$$\mathrm{lcm}(10,14,15) = \mathrm{lcm}(2\cdot 5, 2\cdot 7, 3\cdot 5) = 2\cdot 3\cdot 5\cdot 7 = 210$$

Corollary 13.1. *Let $a_1,\dots,a_k \in \mathbb{Z}_+$, then*

$$\langle a_1\rangle \cap \dots \cap \langle a_k\rangle = \langle \mathrm{lcm}(a_1,\dots,a_k)\rangle \subset \mathbb{Z}.$$

Moreover, $m \in \mathbb{Z}$ is a common multiple of $a_1,\dots,a_k$ iff m is a multiple of $\mathrm{lcm}(a_1,\dots,a_k)$.

Proof. First observe that

$$\{\text{common multiples of } a_1,\dots,a_k\} = \langle a_1\rangle \cap \dots \cap \langle a_k\rangle$$

which is a sub-group of $\mathbb{Z}$ and therefore by Lemma 11.5,

$$\{\text{common multiples of } a_1,\dots,a_k\} = \langle n\rangle$$

where

$$n = \min\{\text{common multiples of } a_1,\dots,a_k\} \cap \mathbb{Z}_+ = \mathrm{lcm}(a_1,\dots,a_k).$$

■

Corollary 13.2. *Let $a_1,\dots,a_k \in \mathbb{Z}_+$, then*

$$\mathrm{lcm}(a_1,\dots,a_k) = \mathrm{lcm}(a_1, \mathrm{lcm}(a_1,\dots,a_k)).$$

Proof. This follows from the following sequence of identities,

$$\begin{aligned}\langle \mathrm{lcm}(a_1,\dots,a_k)\rangle &= \langle a_1\rangle \cap \dots \cap \langle a_k\rangle = \langle a_1\rangle \cap (\langle a_2\rangle \cap \dots \cap \langle a_k\rangle) \\ &= \langle a_1\rangle \cap \langle \mathrm{lcm}(a_1,\dots,a_k)\rangle = \langle \mathrm{lcm}(a_1, \mathrm{lcm}(a_1,\dots,a_k))\rangle.\end{aligned}$$

■

Proposition 13.3. *Suppose that G is a group and a and b are two finite order commuting elements of a group G such that*[1] $\langle a\rangle \cap \langle b\rangle = \{e\}$. *Then* $|ab| = \mathrm{lcm}(|a|, |b|)$.

Proof. If $e = (ab)^m = a^m b^m$ for some $m \in \mathbb{Z}$ then

$$\langle a\rangle \ni a^m = b^{-m} \in \langle b\rangle$$

from which it follows that $a^m = b^{-m} \in \langle a\rangle \cap \langle b\rangle = \{e\}$, i.e. $a^m = e = b^m$. This happens iff m is a common multiple of $|a|$ and $|b|$ and therefore the order of ab is the smallest such multiple, i.e. $|ab| = \mathrm{lcm}(|a|, |b|)$. ■

It is not possible to drop the assumption that $\langle a\rangle \cap \langle b\rangle = \{e\}$ in the previous proposition. For example consider $a = 2$ and $b = 6$ in $\mathbb{Z}_8$, so that $|a| = 4$, $|6| = 8/\gcd(6,8) = 4$, and $\mathrm{lcm}(4,4) = 4$, while $a + b = 0$ and $|0| = 1$. More generally if $b = a^{-1}$ then $|ab| = 1$ while $|a| = |b|$ can be anything. In this case, $\langle a\rangle \cap \langle b\rangle = \langle a\rangle$.

13.1 Cosets and Lagrange's Theorem (Chapter 7 of the book)

Let G be a group and H be a non-empty subset of G. Soon we will assume that H is a subgroup of G.

Definition 13.4. *Given $a \in G$, let*

1. $aH := \{ah : h \in H\}$ – *called the **left coset of** H **in** G **containing** a when $H \leq G$,*
2. $Ha := \{ha : h \in H\}$ – *called the **right coset of** H **in** G **containing** a when $H \leq G$, and*
3. $aHa^{-1} := \{aha^{-1} : h \in H\}$.

Definition 13.5. *If $H \leq G$, we let*

$$G/H := \{aH : a \in G\}$$

[1] You showed in Exercise 4.54 of homework 4, that if $|a|$ and $|b|$ are relatively prime, then $\langle a\rangle \cap \langle b\rangle = \{e\}$ holds automatically.

be the set of left cosets of H in G. The ***index*** *of H in G is* $|G:H| := \#(G/H)$, *that is*

$$|G:H| = \#(G/H) = (\text{the number of distinct cosets of } H \text{ in } G).$$

Example 13.6. Suppose that $G = GL(2,\mathbb{R})$ and $H := SL(2,\mathbb{R})$. In this case for $A \in G$ we have,

$$AH = \{AB : B \in H\} = \{C : \det C = \det A\}.$$

Each coset of H in G is determined by value of the determinant on that coset. As G/H may be indexed by $\mathbb{R}\setminus\{0\}$, it follows that

$$|GL(2,\mathbb{R}) : SL(2,\mathbb{R})| = \#(\mathbb{R}\setminus\{0\}) = \infty.$$

Example 13.7. Let $G = U(20) = U(2^2 \cdot 5) = \{1,3,7,9,11,13,17,19\}$ and take

$$H := \langle 3 \rangle = \{1,3,9,7\}$$

in which case,

$$\begin{aligned} 1H &= 3H = 9H = 7H = H, \\ 11H &= \{11,13,19,17\} = 13H = 17H = 19H. \end{aligned}$$

We have $|G:H| = 2$ and

$$|G:H| \times |H| = 2 \times 4 = 8 = |G|.$$

Example 13.8. Let $G = \mathbb{Z}_9$ and $H = \langle 3 \rangle = \{0,3,6\}$. In this case we use additive notation,

$$\begin{aligned} 0+H &= 3+H = 6+H = H \\ 1+H &= \{1,4,7\} = 4+H = 7+H \\ 2+H &= \{2,5,8\} = 2+H = 8+H \end{aligned}$$

We have $|G:H| = 3$ and

$$|G:H| \times |H| = 3 \times 3 = 9 = |G|.$$

Example 13.9. Suppose that $G = D_4 := \{r^k, r^k f\}_{k=0}^{3}$ with $r^4 = 1$, $f^2 = 1$, and $frf = r^{-1}$. If we take $H = \langle f \rangle = \{1, f\}$ then

$$r^k H = \{r^k, r^k f\} = \{r^k f, r^k f f\} = r^k f H \text{ for } k = 0,1,2,3.$$

In this case we have $|G:H| = 4$ and

$$|G:H| \times |H| = 4 \times 2 = 8 = |G|$$

Recall that we have seen if G is a finite cyclic group and $H \le G$, then $|H|$ divides G. This along with the last three examples suggests the following theorem of Lagrange. They also motivate Lemma 14.2 below.

Theorem 13.10 (Lagrange's Theorem). *Suppose that G is a finite group and $H \le G$, then $|H|$ divides $|G|$ and $|G|/|H|$ is the number of distinct cosets of H in G, i.e.*

$$|G:H| \times |H| = |G|.$$

Corollary 13.11. *If G is a group of prime order p, then G is cyclic and every element in $G \setminus \{e\}$ is a generator of G.*

Proof. Let $g \in G \setminus \{e\}$ and take $H := \langle g \rangle$. Then $|H| > 1$ and $|H| \,|\, |G| = p$ implies $|H| = p$. Thus it follows that $H = G$, i.e. $G = \langle g \rangle$. ∎

Before proving Theorem 13.10, we will pause for some basic facts about the cosets of H in G.

Lecture 14 (2/6/2009)

Suppose that $f : X \to Y$ is a bijection (f being one to one is actually enough here). Then if A, B are subsets of X, we have

$$A = B \iff f(A) = f(B),$$

where $f(A) = \{f(a) : a \in A\} \subset Y$. Indeed, it is clear that $A = B \implies f(A) = f(B)$. For the opposite implication, let $g : Y \to X$ be the inverse function to f, then $f(A) = f(B) \implies g(f(A)) = g(f(B))$. But $g(f(A)) = \{a = g(f(a)) : a \in A\} = A$ and $g(f(B)) = B$.

Let us also observe that if f is one to one and $A \subset X$ is a finite set with n elements, then $\#(f(A)) = n = \#(A)$. Indeed if $\{a_1, \ldots, a_n\}$ are the distinct elements of A then $\{f(a_1), \ldots, f(a_n)\}$ are the distinct elements of $f(A)$.

Lemma 14.1. *For any $a \in G$, the maps $L_a : G \to G$ and $R_a : G \to G$ defined by $L_a(x) = ax$ and $R_a(x) = xa$ are bijections.*

Proof. We only prove the assertions about L_a as the proofs for R_a are analogous. Suppose that $x, y \in G$ are such that $L_a(x) = L_a(y)$, i.e. $ax = ay$, it then follows by cancellation that $x = y$. Therefore L_a is one to one. It is onto since if $x \in G$, then $L_a(a^{-1}x) = x$.

Alternatively. Simply observe that $L_{a^{-1}} : G \to G$ is the inverse map to L_a. ■

Lemma 14.2. *Let G be a group, $H \le G$, and $a, b \in H$. Then*

1. *$a \in aH$,*
2. *$aH = H$ iff $a \in H$.*
3. *If $a \in G$ and $b \in aH$, then $aH = bH$.*
4. *If $aH \cap bH \ne \emptyset$ then $aH = bH$. So either $aH = bH$ or $aH \cap bH = \emptyset$.*
5. *$aH = bH$ iff $a^{-1}b \in H$.*
6. *G is the disjoint union of its **distinct** cosets.*
7. *$aH = Ha$ iff $aHa^{-1} = H$.*
8. *$|aH| = |H| = |bH|$ where $|aH|$ denotes the number of element in aH.*
9. *aH is a subgroup of G iff $a \in H$.*

Proof. For the most part we refer the reader to p. 138-139 of the book for the details of the proof. Let me just make a few comments.

1. Since $e \in H$ we have $a = ae \in aH$.
2. If $aH = H$, then $a = ae \in aH = H$. Conversely, if $a \in H$, then $aH \subset H$ since H is a group. For the opposite inclusion, if if $h \in H$, then $h = a\left(a^{-1}h\right) \in aH$, i.e. $H \subset aH$. **Alternatively:** as above it follows that $a^{-1}H \subset H$ and therefore, $H = a\left(a^{-1}H\right) \subset aH$.
3. If $b \in ah' \in aH$, then $bH = ah'H = aH$.
4. If $ah = bh' \in aH \cap bH$, then $b = ah\, h'^{-1} \in aH$ and therefore $bH = aH$.
5. If $a^{-1}b \in H$ then $a^{-1}b = h \in H$ and $b = ah$ and hence $aH = bH$. Conversely if $aH = bH$ then $b = be = ah$ for some for some $h \in H$. Therefore, $a^{-1}b = h \in H$.
6. See item 1 shows G is the union of its cosets and item 4. shows the distinct cosets are disjoint.
7. We have $aH = Ha \iff H = (Ha)a^{-1} = (aH)a^{-1} = aHa^{-1}$.
8. Since L_a and L_b are bijections, it follows that $|aH| = \#(L_a(H)) = \#(H)$. Similarly, $|bH| = |H|$.
9. $e \in aH$ iff $a \in H$.

■

Remark 14.3. Much of Lemma 14.2 may be understood with the aid of the following equivalence relation. Namely, write $a \sim b$ iff $a^{-1}b \in H$. Observe that $a \sim a$ since $a^{-1}a = e \in H$, $a \sim b \implies b \sim a$ since $a^{-1}b \in H \implies b^{-1}a = \left(a^{-1}b\right)^{-1} \in H$, and $a \sim b$ and $b \sim c$ implies $a \sim c$ since $a^{-1}b \in H$ and

$$b^{-1}c \in H \implies a^{-1}c = a^{-1}bb^{-1}c \in H.$$

The equivalence class, $[a]$, containing a is then

$$[a] = \{b : a \sim b\} = \left\{b : h := a^{-1}b \in H\right\} = \{ah : h \in H\} = aH.$$

Definition 14.4. *A subgroup, $H \le G$, is said to be **normal** if $aHa^{-1} = H$ for all $a \in G$ or equivalently put, $aH = Ha$ for all $a \in G$. We write $H \lhd G$ to mean that H is a normal subgroup of G.*

We will prove later the following theorem. (If you want you can go ahead and try to prove this theorem yourself.)

Theorem 14.5 (Quotient Groups). *If $H \lhd G$, the set of left cosets, G/H, becomes a group under the multiplication rule,*

$$aH \cdot bH := (ab)\,H \text{ for all } a, b \in H.$$

In this group, eH is the identity and $(aH)^{-1} = a^{-1}H$.

We are now ready to prove Lagrange's theorem which we restate here.

Theorem 14.6 (Lagrange's Theorem). *Suppose that G is a finite group and $H \le G$, then*

$$|G : H| \times |H| = |G|,$$

where $|G : H| := \#(G/H)$ is the number of ***distinct*** *cosets of H in G. In particular $|H|$ divides $|G|$ and $|G|/|H| = |G : H|$.*

Proof. Let $n := |G : H|$ and choose $a_i \in G$ for $i = 1, 2, \dots, n$ such that $\{a_i H\}_{i=1}^n$ is the collection of distinct cosets of H in G. Then by item 6. of Lemma 14.2 we know that

$$G = \cup_{i=1}^n [a_i H] \text{ with } a_i H \cap a_j H = \emptyset \text{ for all } i \ne j.$$

Thus we may conclude, using item 8. of Lemma 14.2 that

$$|G| = \sum_{i=1}^n |a_i H| = \sum_{i=1}^n |H| = n \cdot H = |G : H| \cdot |H|.$$

■

Remark 14.7 (Becareful!). Despite the next two results, it is **not** true that all groups satisfy the converse to Lagrange's theorem. That is there exists groups G for which there is a divisor, d, of $|G|$ for which there is no subgroup, $H \le G$ with $|H| = d$. We will eventually see that $G = A_4$ is a group of order 12 with no subgroups of order 6. Here, A_4, is the so called alternating group on four letters.

Lemma 14.8. *If H and K satisfy the converse to Lagrange's theorem, then so does $H \times K$. In particular, every finite abelian group satisfies the converse to Lagrange's theorem.*

Proof. Let $m := |H|$ and $n = |K|$. If $d|mn$, then we may write $d = d_1 d_2$ with $d_1|m$ and $d_2|n$. We may now choose subgroups, $H' \le H$ and $K' \le K$ such that $|H'| = d_1$ and $|K'| = d_2$. It then follows that $H' \times K' \le H \times K$ with $|H' \times K'| = d_1 d_2 = d$.

The second assertion follows from the fact that all finite abelian groups are isomorphic to a product of cyclic groups and we already know the converse to Lagrange's theorem holds for these groups. ■

Example 14.9. Consider $G = D_n = \left\langle r, f : r^n = e = f^2 \text{ and } frf = r^{-1} \right\rangle$. The divisors of $2n$ are the divisors, Λ of n and 2Λ. If $d \in \Lambda$, let $H := \left\langle r^{n/d} \right\rangle$ to construct a group of order d. To construct a group of order $2d$, take,

$$H = \left\langle r^{n/d} \right\rangle f \cup \left\langle r^{n/d} \right\rangle.$$

Notice that this is subgroup of G since,

$$\left(r^{kn/d} f\right)\left(r^{ln/d} f\right) = r^{kn/d} r^{ln/d} f f = r^{(k-l)n/d}$$
$$\left(r^{kn/d} f\right) r^{ln/d} = r^{(k-l)n/d} f$$
$$r^{ln/d} r^{kn/d} f = r^{(k+l)n/d} f.$$

This shows that D_n satisfies the converse to Lagrange's theorem.

Example 14.10. Let $G = U(30) = U(2 \cdot 3 \cdot 5) = \{1, 7, 11, 13, 17, 19, 23, 29\}$ and $H = \langle 11 \rangle = \{1, 11\}$. In this case we know $|G : H| = |G|/|H| = 8/2 = 4$, i.e. there are 4 distinct cosets which we now find.

$$1H = H = \{1, 11\}$$
$$7H = \{7, 17\}$$
$$13H = \{13, 13 \cdot 11 \bmod 30 = 23\}$$
$$19H = \{19, 19 \cdot 11 \bmod 30 = 29\}.$$

Notice that

$$19 \cdot 11 = -11^2 \bmod 30 = -121 \bmod 30 = -1 \bmod 30 = 29.$$

Corollary 14.11. *If G is a finite group and $g \in G$, then $|g|$ divides $|G|$, i.e.*

Proof. Let $H := \langle g \rangle$, then $|H| = |g|$ and $|G : H| \cdot |g| = |G|$. ■

Corollary 14.12. *If G is a finite group and $g \in G$, then $g^{|G|} = e$.*

Proof. By the previous corollary, we know that $|G| = |g|\, n$ where $n := |G : \langle g \rangle|$. Therefore $g^{|G|} = g^{|g|n} = \left(g^{|g|}\right)^n = e^n = e$. ■

Corollary 14.13 (Fermat's Little Theorem). *Let p be a prime number and $a \in \mathbb{Z}$. Then*

$$a^p \bmod p = a \bmod p. \tag{14.1}$$

Proof. Let $r := a \bmod p \in \{0, 1, 2, \dots, p-1\}$. Since

$$a^p \bmod p = (a \bmod p)^p \bmod p = r^p \bmod p$$

it suffices to show

$$r^p \bmod p = r \text{ for all } r \in \{0, 1, 2, \ldots, p-1\}.$$

As this latter equation is true when $r = 0$ we may now assume that $r \in U(p) = \{1, 2, \ldots, p-1\}$. The previous equation is then equivalent to $r^p = r$ in $U(p)$ which is equivalent to $r^{p-1} = 1$ in $U(p)$. However this last assertion is true by Corollary 14.12 and the fact that $|U(p)| = p - 1$. ■

Lecture 15 (2/9/2009)

Example 15.1. Consider

$$32 \bmod 5 = 2^5 \bmod 5 = 2 \bmod 5 = 2.$$

Example 15.2. Let us now show that 35 is not prime by showing

$$2^{35} \bmod 35 \neq 2 \bmod 35 = 2.$$

To do this we have

$$\begin{aligned} 2 \bmod 35 &= 2 \\ 2^2 \bmod 35 &= 4 \\ 2^4 \bmod 35 &= \left(2^2 \bmod 35\right)^2 \bmod 35 = 4^2 \bmod 35 = 16 \\ 2^8 \bmod 35 &= \left(2^4 \bmod 35\right)^2 \bmod 35 = (16)^2 \bmod 35 = 256 \bmod 35 = 11 \\ 2^{16} \bmod 35 &= (11)^2 \bmod 35 = 121 \bmod 35 = 16 \\ 2^{32} \bmod 35 &= (16)^2 \bmod 35 = 11 \end{aligned}$$

and therefore,

$$2^{35} \bmod 35 = \left(2^3 \bmod 35 \cdot 2^{32} \bmod 35\right) \bmod 35 = 88 \bmod 35 = 18 \neq 2.$$

Therefore 35 is not prime!

Example 15.3 (Primality Test). Suppose that $n \in \mathbb{Z}_+$ is a large number we wish to see if it is prime or not. Hard to do in general. Here are some tests to perform on n. Pick a few small primes, p, like $\{2,3,5,7\}$ less than n:

1. compute $\gcd(p,n)$. If $\gcd(p,n) = p$ we know that $p|n$ and hence n is not prime.
2. If $\gcd(p,n) = 1$, compute $p^n \bmod n$ (as above). If $p^n \bmod n \neq p$, then n is again not prime.
3. If we have $p^n \bmod n = p = \gcd(p,n)$ for p from our list, the test has failed to show n is not prime. We can test some more by adding some more primes to our list.

Remark: This is not a fool proof test. There are composite numbers n such that $a^n \bmod n = a \bmod n$ for a. These numbers are called pseudoprimes and $n = 561 = 3 \times 11 \times 17$ is one of them. See for example:

$$\begin{aligned} &http://en.wikipedia.org/wiki/Fermat\_primality\_test \\ &\quad and \\ &http://en.wikipedia.org/wiki/Pseudoprime \end{aligned}$$

Example 15.4 (Exercise 7.16.). The same proof shows that if $n \in \mathbb{Z}_+$ and $a \in \mathbb{Z}$ is relatively prime to n, then

$$a^{\varphi(n)} \bmod n = 1.$$

Indeed, we have $a^{\varphi(n)} \bmod n = r^{\varphi(n)} \bmod n$ where $r := a \bmod n$ and we have seen that $\gcd(r,n) = \gcd(a,n) = 1$ so that $r \in U(n)$. Since $\varphi(n) = |U(n)|$ we may conclude that $r^{\varphi(n)} = 1$ in $U(n)$, i.e.

$$a^{\varphi(n)} \bmod n = r^{\varphi(n)} \bmod n = 1.$$

Theorem 15.5. *Suppose G is a group of order $p \geq 3$ which is prime. Then G is isomorphic to $\mathbb{Z}_{2p}$ or D_p.*

Before giving the proof let us first prove a couple of lemmas.

Lemma 15.6. *If G is a group such that $a^2 = e$ for all $a \in G$, then G is abelian.*

Proof. Since $a^2 = e$ we know that $a = a^{-1}$ for all $a \in G$. So for any $a, b \in G$ it follows that

$$ab = (ab)^{-1} = b^{-1}a^{-1} = ba,$$

i.e. G must be abelian. ■

Lemma 15.7. *If G is a group having two distinct commuting elements, a and b, with $|a| = 2 = |b|$, then $H := \{e, a, b, ab\}$ is a sub-group of order 4.*

Proof. By cancellation ab is not equal to a or b. Moreover if $ab = e$, then $a = b^{-1} = b$ which again is not allowed by assumption. Therefore H has four elements. It is easy to see that $H \leq G$. ■

We are now ready for the proof of Theorem 15.5.

Proof. Proof of Theorem 15.5.

Case 1. There is an element, $g \in G$ of order $2p$. In this case $G = \langle g \rangle \cong \mathbb{Z}_{2p}$ and we are done.

Case 2. $|g| \leq p$ for all $g \in G$. In this case we must have at least one element, $a \in G$, such that $|a| = p$. Otherwise we would have (by Lagrange's theorem) $|g| \leq 2$ for all $g \in G$. However, by Lemmas 15.6 and 15.7 this would imply that G contains a subgroup, H, of order 4 which is impossible because of Lagrange's theorem.

Let $a \in G$ with $|a| = p$ and set

$$H := \langle a \rangle = \left\{e, a, a^2, \dots, a^{p-1}\right\}.$$

As $[G : H] = |G| / |H| = 2p/p = 2$, there are two distinct disjoint cosets of H in G. So if b is **any** element in $G \setminus H$ the two distinct cosets are H and

$$bH = b \langle a \rangle = \left\{b, ba, ba^2, \dots, ba^{p-1}\right\}.$$

We are now going to show that $b^2 = e$ for all $b \in G \setminus H$. What we know is that b^2H is either H or bH. If $b^2H = bH$ then $b = b^{-1}b^2 \in H$ which contradicts the assumption that $b \notin H$. Therefore we must have $b^2H = H$, i.e. $b^2 \in H$. If $b^2 \neq e$, then $b^2 = a^l$ for some $1 \leq l < p$ and therefore $\left|b^2\right| = \left|a^l\right| = p/\gcd(l, p) = p$ and therefore $|b| = 2p$. However, we are in case 2 where it is assumed that $|g| \leq p$ for all $g \in G$ so this can not happen. Therefore we may conclude that $b^2 = e$ for all $b \notin H$.

Let us now fix some $b \notin H = \langle a \rangle$. Then $ba \notin H$ and therefore we know $(ba)^2 = e$ which is to say $ba = (ba)^{-1} = a^{-1}b^{-1}$, i.e. $bab^{-1} = a^{-1}$. Therefore

$$G = H \cup bH = \left\{a^k, ba^k : 0 \leq k < n\right\} \text{ with } a^p = e,\ b^2 = e, \text{ and } bab = a^{-1}.$$

But his is precisely our description of D_p. Indeed, recall that for $n \geq 3$,

$$D_n = \left\{r^k, fr^k : 0 \leq k < n\right\} \text{ with } f^2 = e,\ r^n = e, \text{ and } frf = r^{-1}.$$

Thus we may map $G \to D_{2p}$ via, $a^k \to r^k$ and $ba^k \to br^k$. This map is an "**isomorphism**" of groups – a notion we discuss next. ∎

15.1 Homomorphisms and Isomorphisms

Definition 15.8. *Let G and $\bar{G}$ be two groups. A function, $\varphi : G \to \bar{G}$ is a **homomorphism** if $\varphi(ab) = \varphi(a)\varphi(b)$ for all $a, b \in G$. We say that φ is an **isomorphism** if φ is also a bijection, i.e. one to one and onto.*

Lemma 15.9. *If $\varphi : G \to \bar{G}$ is an isomorphism, the inverse map, φ^{-1}, is also a homomorphism and $\varphi^{-1} : \bar{G} \to G$ is also an isomorphism.*

Proof. Suppose that $\bar{a}, \bar{b} \in \bar{G}$ and $a := \varphi^{-1}(\bar{a})$ and $b := \varphi^{-1}\left(\bar{b}\right)$. Then $\varphi(ab) = \varphi(a)\varphi(b) = \bar{a}\bar{b}$ from which it follows that

$$\varphi^{-1}\left(\bar{a}\bar{b}\right) = ab = \varphi^{-1}(\bar{a})\varphi^{-1}\left(\bar{b}\right)$$

as desired. ∎

Notation 15.10 *If $\varphi : G \to \bar{G}$ is a homomorphism, then the **kernel of** φ is defined by,*

$$\ker(\varphi) := \varphi^{-1}(\{e_{\bar{G}}\}) := \{x \in G : \varphi(x) = e_{\bar{G}}\} \subset G$$

*and the **range of** φ by*

$$\mathrm{Ran}(\varphi) := \varphi(G) = \{\varphi(g) : g \in G\} \subset \bar{G}.$$

Example 15.11. Suppose that $G = \mathbb{R}^n$ and $H = \mathbb{R}^m$ both equipped with $+$ as their binary operation. Then any $m \times n$ matrix, A, gives rise to a homomorphism[1] from $G \to H$ via the map, $\varphi_A(x) := Ax$ for all $x \in \mathbb{R}^n$. In this case $\ker(\varphi_A) = \mathrm{Nul}(A)$ and $\mathrm{Ran}(\varphi_A) = \mathrm{Ran}(A)$. Moreover, φ_A is an isomorphism iff $m = n$ and A is invertible.

Example 15.12. Let $G = GL(n, \mathbb{R})$ denote the set of $n \times n$ - invertible matrices with the binary operation being matrix multiplication and let $H := \mathbb{R}\setminus\{0\}$ equipped with multiplication as the binary operation. Then $\det : G \to H$ is a homomorphism.

[1] **Fact:** any continuous homomorphism is of this form.

Lecture 16 (2/11/2009)

Theorem 16.1. *If $\varphi : G \to \bar{G}$ is a homomorphism, then*

1. $\varphi(e) = \bar{e} \in \bar{G}$,
2. $\varphi(a^{-1}) = \varphi(a)^{-1}$ *for all* $a \in G$,
3. $\varphi(a^n) = \varphi(a)^n$ *for all* $n \in \mathbb{Z}$,
4. *If* $|g| < \infty$ *then* $|\varphi(g)|$ *divides* $|g|$,
5. $\varphi(G) \le \bar{G}$,
6. $\ker(\varphi) \le G$,
7. $\varphi(a) = \varphi(b)$ *iff* $a^{-1}b \in \ker(\varphi)$ *iff* $a \ker(\varphi) = b \ker(\varphi)$, *and*
8. *If* $\varphi(a) = \bar{a} \in \bar{G}$, *then*

$$\varphi^{-1}(\bar{a}) := \{x \in G : \varphi(x) = \bar{a}\} = a \ker \varphi.$$

Proof. We prove each of these results in turn.

1. By the homomorphism property,
$$\varphi(e) = \varphi(e \cdot e) = \varphi(e) \cdot \varphi(e)$$
and so by cancellation, we learn that $\varphi(e) = \bar{e}$.
2. If $a \in G$ we have,
$$\bar{e} = \varphi(e) = \varphi(a \cdot a^{-1}) = \varphi(a) \cdot \varphi(a^{-1})$$
and therefore, $\varphi(a^{-1}) = \varphi(a)^{-1}$.
3. When $n = 0$ item 3 follows from item 1. For $n \ge 1$, we have
$$\varphi(a^n) = \varphi(a \cdot a^{n-1}) = \varphi(a) \cdot \varphi(a^{n-1})$$
from which the result then follows by induction. For $n \le 1$ we have,
$$\varphi(a^n) = \varphi\left(\left(a^{|n|}\right)^{-1}\right) = \varphi\left(a^{|n|}\right)^{-1} = \left(\varphi(a)^{|n|}\right)^{-1} = \varphi(a)^n.$$
4. Let $n = |g| < \infty$, then $\varphi(g)^n = \varphi(g^n) = \varphi(e) = e$. Therefore, $|\varphi(g)|$ divides $n = |g|$.
5. If $x, y \in G$, $\varphi(x)$ and $\varphi(y)$ are two generic elements of $\varphi(G)$. Since, $\varphi(x)^{-1}\varphi(y) = \varphi(x^{-1}y) \in \varphi(G)$, it follows that $\varphi(G) \le \bar{G}$.
6. If x, y are now in $\ker(\varphi)$, i.e. $\varphi(x) = e = \varphi(y)$, then
$$\varphi(x^{-1}y) = \varphi(x)^{-1}\varphi(y) = e^{-1}e = e.$$
This shows $x^{-1}y \in \ker(\varphi)$ and therefore that $\ker(\varphi) \le G$.
7. We have $\varphi(a) = \varphi(b)$ iff $e = \varphi(a)^{-1}\varphi(b) = \varphi(a^{-1}b)$ iff $a^{-1}b \in \ker(\varphi)$.
8. We will show $a \ker \varphi \subset \varphi^{-1}(\bar{a})$ and $\varphi^{-1}(\bar{a}) \subset a \ker \varphi$. For the first inclusion, if $x \in \ker \varphi$, we have $\varphi(ax) = \varphi(a)\varphi(x) = \bar{a}\bar{e} = \bar{a}$ which shows that $ax \in \varphi^{-1}(\bar{a})$, i.e. $a \ker \varphi \subset \varphi^{-1}(\bar{a})$. For the opposite inclusion, if $x \in \varphi^{-1}(\bar{a})$ then $\varphi(x) = \bar{a} = \varphi(a)$.Thus it follows by item 7. that $a^{-1}x \in \ker(\varphi)$, i.e. $x \in a \ker(\varphi)$ and therefore $\varphi^{-1}(\bar{a}) \subset a \ker \varphi$.

■