Math 460 Fall 2025 - Class Notes

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1 Partitions and Equivalence Relations

Definition 1.1 (Partition)**.** *Given a set S, a* partition *of S is a collection $\mathcal{P}$ of subsets of S such that:*

1. *Every $P \in \mathcal{P}$ is nonempty.*

2. *Every $s \in S$ belongs to exactly one $P \in \mathcal{P}$.*

Remark 1.1. *Given a set S, a binary relation $\sim$ on S is a subset of $S \times S$. Usually, for $a, b \in S$, we write $a \sim b$ iff (a, b) lies in the subset.*

Definition 1.2 (Equivalence Relation)**.** *A binary relation $\sim$ on a set S is an* equivalence relation *if it is:*

1. *Reflexive: for every $x \in S$, $x \sim x$*

2. *Symmetric: for every x, $y \in S$, if $x \sim y$, $y \sim x$.*

3. *Transitive: for every $x, y, z \in S$, if $x \sim y$ and $y \sim z$, then $x \sim z$.*

Remark 1.2. *If $\sim$ is an equivalence relation on S, then for any $t \in S$, the* equivalence class *of t is defined as $C_t = \{s \in S : s \sim t\}$. The set of all equivalence classes forms a partition of S.*

Remark 1.3. *Giving a partition on S corresponds to giving an equivalence relation on S.*

2 Functions

Remark 2.1. *Suppose A and B are sets.*

1. *The identity function on A is the function $id_A : A \to A$ defined by $id_A(x) = x$*
2. *Given a function $f : A \to B$ and subsets $S \subseteq A$ and $T \subseteq B$, the image of S under f is defined as $f(S) = \{f(x) : x \in S\} \subseteq B$.*
3. *The inverse image (or preimage) of a subset $T \subseteq B$ under f is defined as $f^{-1}(T) = \{y \in A : f(y) \in T\} \subseteq A$.*

Definition 2.1 (Injective, Surjective, Bijective)**.** *Let $f : A \to B$ where A and B are sets.*

1. *f is* injective*(or 1-1) if, whenever $f(x) = f(y)$ for $x, y \in A$, then $x = y$.*
2. *f is* surjective*(or onto) if, for every $y \in B$, there exists $x \in A$ such that $f(x) = y$.*
3. *f is* bijective *if it is both injective and surjective.*

3 Groups

Definition 3.1 (Group)**.** *A* group *is a pair $(G, \cdot)$ where G is a set and $\cdot$ is a binary operation on G, satisfying:*

1. *(Associativity) for all $a, b, c \in G$, $(ab)c = a(bc)$*
2. *(Identity) There exists an identity element 1_G s.t. for all $a \in G$, $a1_G = 1_G a = a$.*
3. *(Inverses) For every $a \in G$, there exists $a^{-1} \in G$ such that $aa^{-1} = 1_G = a^{-1}a$.*

Remark 3.1. *A binary operation on a set G is a function from $G \times G$ to G defined as $(a, b) \mapsto a \cdot b = ab$.*

Remark 3.2 (Uniqueness of Identity and Inverses)**.**

1. *The identity element* 1_G *is unique.*
2. *The inverse* a^{-1} *of any element* $a \in G$ *is unique.*

Definition 3.2 (Abelian Group)**.** *A group* G *is called* abelian *(or commutative) if* $ab = ba$ *for all* $a, b \in G$*.*

Definition 3.3 (Subgroup)**.** *A subgroup of a group* $(G, \cdot)$ *is a subset* H *of* G *s.t.* $(H, \cdot)$ *is a group. We write* $H \leq G$ *to denote "*H *is a subgroup of* G*". Where* $\cdot$ *is the binary operation from* G *and* H *is closed under the group op in* G*, i.e. "*H *is closed under* $\cdot$*".*

Remark 3.3. *For any subgroup* H *of* G*,* $1_H = 1_G$

Definition 3.4 (Subgroup Criterion)**.** *Suppose* $(G, \cdot)$ *is a group and* H *is a nonempty subset of* G*. Then* $H \leq G$ *if and only if*

1. *for all* $a, b \in H$*,* $ab \in H$ *(closed under* $\cdot$*).*
2. *for all* $a \in H$*,* $a^{-1} \in H$ *(closed under taking inverses).*

Lemma 3.1 (Finite Subgroup Criterion)**.** *Suppose* $(G, \cdot)$ *is a group and* H *is a finite subset of* G*. Then* $H \leq G$ *if and only if* $H \neq \emptyset$ *and for all* $a, b \in H$*,* $ab \in H$ *(i.e.* H *is closed under* $\cdot$*).*

Remark 3.4. *Suppose* G *is a group, and* S, T *are subsets of* G *while* $g \in G$*. Then*

1. $gS = \{gs : s \in S\}$
2. $Sg = \{sg : s \in S\}$
3. $ST = \{st : s \in S, t \in T\}$

Definition 3.5 (Cosets)**.** *When* $H \leq G$*, a left coset (resp. right coset) of* H *in* G *is a set of the form* gH *(resp.* Hg*) for some* $g \in G$*.*

Lemma 3.2. *Any two left cosets of* H *in* G *have the same cardinality. (The same holds for right cosets.)*

Definition 3.6 (Left and Right Cosets)**.** *When* H *is a subgroup of a group* G

1. $G/H := \{gH : g \in G\}$ *the set of all left cosets of* H

2. $G\backslash H := \{Hg : g \in G\}$ *the set of all right cosets of* H

Proposition 3.1. *G/H is a partition of G. Similarly, $G\backslash H$ is a partition of G.*

Theorem 3.1 (Lagrange's Theorem)**.** *Suppose G is a finite group and $H \leq G$. Then $|H|$ divides $|G|$.*

Remark 3.5. *The converse of Lagrange's theorem is not true. The theorem does hold for cyclic groups.*

Remark 3.6. *For any set S we often write $|S|$ to denote the cardinality of S. If S is finite, then $|S|$ is a nonnegative integer. When S is a subgroup of a group, we also use $o(S)$ to denote its cardinality.*

Definition 3.7 (Index)**.** *We define the* index *of a subgroup H in G, denoted $[G : H] := |G/H| = |G\backslash H|$ equals the number of distinct (left or right) cosets.*

Definition 3.8 (Order of an Element)**.** *Let G be a group and $g \in G$. If $g^k = 1_G$ for some positive integer k, then the least such k is called the* order *of g denoted as $o(g)$ or $|g|$. If $g^k \neq 1_G$ for every positive k, then we say g has infinite order and write $o(g) = \infty$.*

Remark 3.7. *If $g \in G$ has infinite order, then all the integer powers of g are distinct.*

Proposition 3.2. *Suppose G is a group and $g \in G$.*

1. *if $o(g) = \infty$, then $g^i = g^j$ if and only if $i = j$.*

2. *if $o(g) = n < \infty$, then $g^i = g^j$ if and only if $n|(i - j)$.*

Proposition 3.3. *If G is a finite group, then for any $g \in G$, $o(g)$ divides $|G|$.*

Definition 3.9 (Normal Subgroup)**.** *Given a group G, a subgroup H of G. We say H is a* normal subgroup *of G if $gH = Hg$ for all $g \in G$ and write $H \trianglelefteq G$ if the following holds: $\forall h \in H, \forall g \in G, ghg^{-1} \in H$ the term ghg^{-1} is called a conjugate of h.*

Proposition 3.4 (Equivalent definitions of Normal Subgroups)**.** *In particular, if $H \leq G$, then $H \trianglelefteq G$ if and only if any of the following equivalent conditions hold:*

1. *$gH = Hg$ for all $g \in G$.*

2. *$aHbH = abH$ for all $a, b \in G$.*

(1) implies the coset spaces G/H and $G\backslash H$ coincide (equal as sets) (2) means we can define a binary operation on $G/H \times G/H \to G/H$ by $(aH, bH) \mapsto (ab)H = (aH)(bH)$ this map makes G/H into a group called the quotient group of G by H provided $H \trianglelefteq G$.

Remark 3.8. *Any subgroup of an abelian group is normal.*

4 Group Homomorphisms

Definition 4.1 (Group Homomorphism)**.** *Suppose G and H are groups. A group homomorphism from G to H is a function $\varphi : G \to H$ such that $\forall a, b \in G, \varphi(ab) = \varphi(a)\varphi(b)$.*

Remark 4.1 (Simple Facts)**.** *if $\varphi : G \to H$ is a group homomorphism, then for any $a \in G$,*

1. $\varphi(1_G) = 1_H$

2. $\varphi(a^{-1}) = (\varphi(a))^{-1}$