

Math493: Honors Algebra I

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Abstract

This course is **a basic introduction on finite group theory** and **representation theory**, containing my personal thoughts as well as lecture notes. My course instructor is **Mircea Mustață**.

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Chapter 1

Group Actions

1.1 Introduction

We now lay our focus to group actions, group actions are useful because we can endowed the **symmetric structure** of a group into other mathematical objects through group actions, specifically:

- often groups acts on various mathematical structure, such as sets, topological spaces, manifolds, etc.
- It will be of great significance for us to consider the actions of a group on itself via **conjugation**.

Definition 1.1.1. Let's fix a group G and a set X , an **action** (say also a left action of) G on X is a map:

$$\begin{aligned} G \times X &\rightarrow X \\ (g, x) &\mapsto gx \end{aligned}$$

such that the following holds:

$$\begin{aligned} ex &= x \quad \forall x \in X \\ g(hx) &= (gh)x \quad \forall g, h \in G, x \in X \end{aligned}$$

We now introduce an **equivalent formulation** for group action:

Recall that:

$$S_X = (\{\text{bijections } X \rightarrow X\}, \circ)$$

is a group.

Definition 1.1.2. Now suppose we have the action of G on X as above, we may define a map $\varphi : G \rightarrow S_X$ as follows: for every $g \in G$, $\varphi(g)$ which written as φ_g is the map:

$$\varphi_g : X \rightarrow X, \varphi_g(x) = gx$$

It is easy to see that by inheritance of the existence of inverses in G , φ_g is a bijection. In particular, one can see that it is actually a **group homomorphism**.

And the following conclusion is easy to deduce:

Conclusion 1.1.1.

$$\{\text{Actions of } G \text{ on } X\} \leftrightarrow \{\text{Group Homomorphism } G \rightarrow S_X\}$$

forms a **bijection**.

We then give some examples of group actions:

Example. Given any set X , we have the identity, **trivial** group action given by the group homomor-

phism:

$$S_X \xrightarrow{Id} S_X$$

which is equivalent to the action of S_X on X by:

$$S_X \times X \rightarrow X, (f, x) \mapsto f(x)$$

Example. If $n > 3$ and P_n be the regular n -gon, we then have a group homomorphism:

$$D_{2n} \rightarrow S_{P_n}$$

which leads to an action of D_{2n} on P_n

Note. See that in this case D_{2n} preserve the distance structure within the regular n -gon.

Example. The group $GL_n(\mathbb{C})$ acts on \mathbb{C}^n via:

$$(A, u = \begin{pmatrix} u_1 \\ \vdots \\ u_n \end{pmatrix}) \mapsto Au$$

which represent the matrix as **linear transformation**. Such corresponds to the group homomorphism:

$$GL_n(\mathbb{C}) \rightarrow S_{\mathbb{C}^n}$$

$A \mapsto \text{corresponds linear transformation on } \mathbb{C}^n$

Example. (Cayley's Theorem) Define an action of G on itself by:

$$G \times G \rightarrow G$$

$$(g, h) \mapsto g \cdot h$$

which acts by the natural left multiplication. Note such corresponds to a group homomorphism:

$$G \xrightarrow{\varphi} S_G$$

And we shall have:

Proposition 1.1.1. (Cayley) φ is always injective

In particular, if G is finite, G is then **isomorphic** to a subgroup of S_n .

$$G \cong \text{Im}(\varphi) \subseteq S_G$$

The proof is immediate by showing $\ker(\varphi) = \{e\}$ by cancellation.

Example. Suppose $H \leq G$, we have:

$$G \times (G/H)_I \rightarrow (G/H)_I$$

$$(g, ah) \mapsto gaH$$

easy to see such is a group action after checking well-definedness. Such action is induced by the action of group on itself, note H here is **not necessarily normal**.

Example. (Group action by **Conjugation**) The following will be the most interesting example for us. First recall we have an **automorphism** given by $g \in G$:

$$\alpha_g : G \rightarrow G, \alpha_g(x) = gxg^{-1}$$

Moreover, observe $\text{Aut}(G) \leq S_G$, so we have a group homomorphism:

$$\begin{aligned} G &\rightarrow \text{Aut}(G) \leq S_G \\ g &\mapsto \alpha_g \end{aligned}$$

We can understand $\text{Aut}(G)$ as those **permutation that preserve the group structure**. In particular, by our discussion, we get an action of G on itself:

$$(g, x) \mapsto gxg^{-1}$$

1.2 Orbits and Orbits-Stablizer Theorem

Definition 1.2.1. Write $x \sim y$ for $x, y \in X$, if $\exists g \in G$, s.t. $gx = y$.

Lemma 1.2.1. Such gives us a equivalent relation, directly check by **reflexive, symmetric, transitive**.

Conclusion 1.2.1. We get a partition of X into equivalence classes, called **orbits**. If $x \in X$, then the corresponding equivalence classes is given by:

$$\{gx \mid g \in G\}$$

which is denoted by **Gx** or **O(x)**.

Notation. X/G denotes the sets of the orbits of X .

Definition 1.2.2. The action of G on X is transitive if X has only one orbits, which is:

$$\forall x, y \in X, \exists g \in G \text{ s.t. } gx = y$$

Example. The action given by the left multiplication of G on itself is **transitive**.

Example. Induced by above example, the action of G on the **set of left cosets** of H is also transitive.

Definition 1.2.3. For every $x \in X$, the stablizer of $x \in G$ is given by:

$$\text{Stab}_G(x) = \{g \in G \mid gx = x\}$$

namely those elements in G that doesn't move the position of x .

Lemma 1.2.2. $\text{Stab}_G(x) \leq G$ being a subgroup.

Example. Consider the action of G on itself by conjugation, the orbits of $a \in G$ is called the

conjugate class of a . Two elements of G are conjugate of each other if they lie in the same conjugate class (**same orbit**).

What is the stablizer in this case?

$$\text{Stab}_G(x) = \{y \in G \mid yxy^{-1} = x\} =: C_G(x)$$

which is the centralizer of x in G .

Note. $C_G(x) = G$ iff $x \in Z(G)$

Remark. Consider the conjugacy classes of S_n , then $\sigma, \tau \in S_n$ are conjugate of each other if and only if when they written as **product of disjoint cycles**, then $\#$ of k -cycle for both of them is the **same** for all k (**they have same cycle type**).

We now introduce Orbit-Stablizer theorem.

Theorem 1.2.1. If G acts on X , then for every $x \in X$:

$$\#O(x) = (G : \text{Stab}_G(x))$$

In particular, if G is finite group, then

$$\#O(x) \mid |G|$$

Proof. Define a map:

$$f : (G/\text{Stab}_G(x))_l \longrightarrow O(x)$$

$$f(g\text{Stab}_G(x)) = gx$$

- Well-defineness + injectivity:

$$g_1\text{Stab}_G(x) = g_2\text{Stab}_G(x)$$

$$\Leftrightarrow g_2^{-1}g_1 \in \text{Stab}_G(x)$$

$$\Leftrightarrow (g_2^{-1}g_1)x = x$$

$$\Leftrightarrow g_2^{-1}(g_1x) = x$$

$$\Leftrightarrow g_1x = g_2x$$

- Surjectivity:

$$y \in O(x)$$

$$\Rightarrow y = gx$$

$$\Rightarrow y = f(g\text{Stab}_G(x))$$

So we see f is a bijection. The first isomorphism theorem direct yields the result. ■

Note. When the action is transitive, with X being finite, we have:

$$\#O(x) = (G : \text{Stab}_G(x)) = |X|$$

In particular, transitive means there is only one orbits.

Proposition 1.2.1. If G acts on X , then:

$$|X| = \sum_{i \in I} (G : \text{Stab}_G(x_i))$$

where x_i are a system of representative for the orbits of G in X .

Proof. We have a partition:

$$X = \bigsqcup_{i \in I} O(x_i) \Rightarrow \#X = \sum \#O(x_i)$$

with:

$$\#O(x_i) = (G : \text{Stab}_G(x_i))$$

■

Example. (Class Equation: A important special case) Consider the action of $G \times G \rightarrow G$ by **conjugation**, with G be finite group:

$$\begin{aligned} |G| &= \sum_{i \in I} (G : C_G(x_i)) \\ \Rightarrow |G| &= |Z(G)| + \sum_{i \in I'} (G : C_G(x_i)) \end{aligned}$$

where I' runs over indices such that $(G : C_G(x_i)) > 1$.

Such results direct yields from the fact that elements in $Z(G)$ attains its centralizer (stablizer) to be the whole group.

Note. Such only works for actions by **conjugation!**

We now give an application for orbits-stablizer theorem, which is important when we study the construction of groups.

Definition 1.2.4. If p be prime number, and G be group, if $|G| = p^n$ for some $n \geq 1$, then we say G is a p -group.

Proposition 1.2.2. If G is a p -group, then:

$$Z(G) \neq \{e\}$$

Proof. Since $p \mid |G|$ and $(G : \text{Stab}_G(x)) \mid |G| = p^n$, then:

$$p \mid (G : C_G(x_i))$$

whenever this is > 1 , then class equation yields that:

$$p \mid |Z(G)|$$

■

Corollary 1.2.1. If p prime, $|G| = p^2$, then G is an abelian group.

To proof this we need first a lemma:

Lemma 1.2.3. For all group G , if $G/Z(G)$ is cyclic, then G is abelian.

Proof. By cyclic property, first suppose that $xZ(G)$ is a generator of $G/Z(G)$, then there exists

$i, j \in \mathbb{Z}$, such that:

$$\begin{aligned} aZ(G) &= x^i Z(G) \\ bZ(G) &= x^j Z(G) \\ \Leftrightarrow a &= x^i a' \\ b &= x^j b' \quad \text{for some } a', b' \in Z(G) \\ \Rightarrow ab &= x^i a' x^j b' = x^{i+j} a' b' \\ ba &= x^j b' x^i a' = x^{i+j} b' a' \\ \Rightarrow ab &= ba \quad \text{since } a', b' \in Z(G) \end{aligned}$$

■

We now give proof to **Corollary 1.2.1**:

Proof. We know that:

$$Z(G) \neq \{e\}$$

Then by **Lagrange's theorem**, see that either $Z(G) = G$ or $|Z(G)| = p$.

If $Z(G) = G$, we already done! Now suppose that $|Z(G)| = p$, now observe that every subgroup of $Z(G)$ is a **normal subgroup** of G by definition.

In particular, we then consider the group $G/Z(G)$, this is of order p , so it is cyclic. Then by **Lemma 1.2.3**, see that G is abelian, contradict to the fact that $Z(G) \neq G$. ■

Chapter 2

Sylow's Theorem

Sylow's Theorem is important when we want to understand and classify the category of finite groups, simply by looking on the order of such finite group. Further, it lays foundation and gives tools for us when we want to understand the structure of the building blocks of finite group (simple group).

2.1 Cauchy's Theorem

Our motivation to study Cauchy's Theorem, as well as Sylow's Theorem, in the first place, is we want to give a partial inverse to **Lagrange's theorem**. Recall that Lagrange's theorem implies that:

Proposition 2.1.1. If G is a finite group, with order n , then $\forall x \in G$, it satisfies that:

$$|x| \mid n$$

In general, the converse of this statement is not true, in particular:

$$\exists q \mid |G|, \text{ but there exists no } g \in G, \text{ s.t. } |g| = q$$

for example we can take $q = |G|$, but G is **not a cyclic group**.

So we give partial converse of this statement by stating **Cauchy's Theorem** and later Sylow's theorem.

Theorem 2.1.1. (Cauchy) If G is a finite group and p is a prime integer, s.t. $p \mid |G|$, then $\exists g \in G$, $|g| = p$.

We first proof for the case when G is **abelian group**, then one can easily derive the general cases by invoking **Z(G)** of any group.

Proof. We reason by deviding cases for abelian and non-abelian group:

- When G is **abelian**: We argue by contradiction, suppose that $|x| \neq p, \forall x \in G$, in this case see that $p \nmid |x|, \forall x \in G$, otherwise if $|x| = m, p \mid m \Rightarrow |x^{\frac{m}{p}}| = p \nmid$.

Let $N = \text{lcm}\{|x| \mid x \in G\}$, use prime factorization of N see that $p \nmid N$. Now suppose g_1, \dots, g_n are the elements of G , we define:

$$f : \underbrace{\mathbb{Z}/N\mathbb{Z} \times \dots \times \mathbb{Z}/N\mathbb{Z}}_{n \text{ times}} \longrightarrow G$$
$$f(a_1 + N\mathbb{Z}, \dots, a_n + N\mathbb{Z}) = g_1^{a_1} \dots g_n^{a_n}$$

one can easily check the well-definedness of such map. The point is G be an abelian group makes

this map a group homomorphism:

$$\begin{aligned}
 f((a_1 + N\mathbb{Z}, \dots, a_n + N\mathbb{Z}) + (b_1 + N\mathbb{Z}, \dots, b_n + N\mathbb{Z})) &= f(a_1 + b_1 + N\mathbb{Z}, \dots, a_n + b_n + N\mathbb{Z}) \\
 &= g_1^{a_1+b_1} \dots g_n^{a_n+b_n} \\
 &= (g_1^{a_1} \dots g_n^{a_n})(g_1^{b_1} \dots g_n^{b_n}) \quad \text{By } G \text{ is abelian} \\
 &= f((a_1 + N\mathbb{Z}, \dots, a_n + N\mathbb{Z})) \\
 &\quad + f((b_1 + N\mathbb{Z}, \dots, b_n + N\mathbb{Z}))
 \end{aligned}$$

so f indeed be a group homomorphism. One should then see that f is clearly surjective by taking:

$$g_i = f(0, \dots, \overset{i}{1}, \dots, 0)$$

By fundamental isomorphism theorem:

$$G \cong (\mathbb{Z}/N\mathbb{Z})^n / \ker(f) \Rightarrow |G| = \frac{|\mathbb{Z}/N\mathbb{Z}|^n}{|\ker(f)|}$$

And by Lagrange theorem:

$$|G| \mid |(\mathbb{Z}/N\mathbb{Z})^n| = N^n$$

however, since $p \mid |G|$, but $p \nmid N$, hence $p \nmid N^n$, leading to contradiction \nmid .

- When G is **non-abelian**: We argue by induction on $|G|$.
 - Base case: If $|G| = p \Rightarrow G$ is cyclic, then we are done.
 - Inductive case: we assume we know the assertion for all G' , such that $p \mid |G'|$, with $|G'| < |G|$, and prove the assertion for G . Note that if there exists $H \leq G$, with $H \neq G$, but $p \mid |H|$, then by the induction hypothesis we are done. Hence, may assume: $\forall H \leq G, H \neq G, p \nmid |H|$. Then by Lagrange theorem: $|G| = |H| \cdot (G : H) \Rightarrow p \mid (G : H)$. By class equation:

$$|G| = |Z(G)| + \sum_{i=1}^d (G : C_G(x_i))$$

where x_i runs over a system of representatives of conjugacy classes with ≥ 2 elements. By our assumptions, we saw:

$$p \mid (G : C_G(x_i)), \quad p \mid |G| \Rightarrow p \mid |Z(G)|$$

Since among all subgroups of G , **only itself** can be divided by p , so this means that:

$$Z(G) = G$$

so we see G is abelian and yields back to the case we've proven before. ■

2.2 Sylow's First Theorem

With the help of Cauchy's theorem, we now give proof to Sylow's first theorem.

Definition 2.2.1. If G is finite group, p prime integer, s.t. $p \mid |G|$ and $p^m \mid |G|$, $p^{m+1} \nmid |G|$, then a subgroup of G with order p^m is called a p -Sylow subgroup of G .

Theorem 2.2.1. (Sylow's First Theorem) If G is a finite group and p is a prime integer, if $p \mid |G| \Rightarrow G$ contains a p -Sylow subgroup.

Note. Sylow's first theorem actually implies Cauchy's theorem.

If $H \leq G$ be a p -Sylow subgroup and $g \in H \setminus \{e\} \Rightarrow |g| = p^r \Rightarrow |g^{p^{r-1}}| = p$.

However, we will **use** Cauchy's theorem to prove Sylow's theorem.

Proof. We argue by induction on $|G|$.

- Base case: $|G| = p$, the assertion is clear, G is its own p -Sylow subgroup.
- Inductive case: Assume that we know the theorem for all groups G' , s.t. $p \mid |G'|$, and $|G'| < |G|$, we want to show the assertion for G .

Suppose that $p^m \mid |G|$, but $p^{m+1} \nmid |G|$, then there are two cases:

- If there is a **proper subgroup** H of G , s.t. $p^m \mid |H|$, then by induction hypothesis, H contains a p -Sylow subgroup, and this is also a p -Sylow subgroup of G .
- If **for all proper subgroup** H of G , $p^m \nmid |H|$, then p^m has to **divide the index of such subgroup**. Then by class equation:

$$|G| = |Z(G)| + \sum_{i=1}^d \underbrace{(G : C_G(x_i))}_{\geq 2 \text{ hence divided by } p}.$$

And see that:

$$p \mid |G| \Rightarrow p \mid |Z(G)|$$

By Cauchy's theorem for the abelian group $Z(G)$, there exists $x \in Z(G)$, s.t. $|x| = p$. Since $x \in Z(G) \Rightarrow \langle x \rangle$ is a normal subgroup of G . Now consider: $G' := G/\langle x \rangle$

- * If $m = 1$, then we are done! Since $\langle x \rangle$ is a p -Sylow subgroup of G .
- * If $m \geq 2$, see that $|G'| = \frac{|G|}{p} < |G|$ is divisible by p , so we apply induction on G' , see that G' contains a p -Sylow subgroup, which is of the form: $H/\langle x \rangle$ for some subgroup H of G . Notice that:

$$|H/\langle x \rangle| = p^{m-1} \Rightarrow |H| = p^{m-1} \cdot p = p^m$$

by prime factorization, $G = p^m \cdot (\dots)$, so see $|G'| = \frac{|G|}{p} = p^{m-1} \cdot (\dots)$

2.3 Sylow's Second and Third Theorem

Sylow's Second theorem basically tells us how the p -Sylow subgroup of G relate to each other, and Sylow's third theorem tells us the possible number of each p -Sylow subgroup can take. Before diving into the proof, we need to dig more intuition on what group actions can do, i.e. how it **permute the endian sets**.

2.3.1 More on Group Action

Example. Suppose G is a group acting on a set X :

$$\begin{aligned} G \times X &\longrightarrow X \\ (g, x) &\longmapsto gx \end{aligned}$$

If $\mathcal{P}(X)$ is the set of all subsets of X , we then get an **induced group action**:

$$\begin{aligned} G \times \mathcal{P}(X) &\longrightarrow \mathcal{P}(X) \\ (g, A) &\longmapsto gA = \{ga \mid a \in A\} \end{aligned}$$

and it's clear that such satisfy the group action properties, we get a group action of G acting on $\mathcal{P}(X)$.

Important example: If in this case we consider the action on G acting on itself by conjugation, we can get a corresponding action of G on $\mathcal{P}(G)$:

$$(g, A) \longmapsto gAg^{-1} = \{gag^{-1} \mid a \in A\}$$

Note. If A is a subgroup of G , then gAg^{-1} is also a subgroup of G .

the conjugation map is a group automorphism

Remark. If H is a p -Sylow subgroup of G and $\sigma : G \rightarrow G$ be an automorphism, then $\sigma(H)$ will also be a p -Sylow subgroup, in particular, **every conjugation** of H which is p -Sylow subgroup will also be a p -Sylow subgroup.

2.3.2 Sylow's Second and Third Theorem

Theorem 2.3.1. (Sylow's Second Theorem) If H is a p -Sylow subgroup of G , K is **any** p -subgroup of G , then there exists $a \in G$, s.t. $K \subseteq aHa^{-1}$.

In particular: if K is a p -Sylow subgroup, too. Then H, K are conjugate of each other: $K = aHa^{-1}$ for some $a \in G$.

Theorem 2.3.2. (Sylow's Third Theorem) If we denote:

$$n_p = \#p\text{-Sylow subgroups of } G$$

Then we have:

$$\begin{cases} n_p \equiv 1 \pmod{p} \\ n_p = (G : N_G(H)) \Rightarrow n_p \mid (G : H) \end{cases}$$

with:

$$N_G(H) := \{g \in G \mid gHg^{-1} = H\}$$

where H is a p -Sylow subgroup of G .

Note. $N_G(H)$ will be the largest subgroup of G in which H is a normal subgroup.

Note. The assertion:

$$n_p = (G : N_G(H)) \Rightarrow n_p \mid (G : H)$$

is derived from Lagrange's theorem:

$$\begin{aligned} H &\leq N_G(H) \leq G \\ \Rightarrow (G : H) &= \frac{|G|}{|H|} = \frac{|G|}{|N_G(H)|} \cdot (N_G(H) : H) \\ \text{And } (G : N_G(H)) &= \frac{|G|}{|N_G(H)|} \end{aligned}$$

We shall prove both of the theorem at the same time.

Proof. We've seen in **Example**, G has an action on $\mathcal{P}(G) = \{T \mid T \leq G\}$ by conjugation: $(g, T) \rightarrow gTg^{-1}$. We now define:

$$\mathcal{S} = \{H = H_1, H_2, \dots, H_r\}$$

which is the collection of the orbits of H with respect to such action. By **Orbit-Stabilizer Theorem 1.2.1**:

$$\begin{aligned} r &= (G : \text{Stab}_G(H)) \\ \text{Stab}_G(H) &= \{g \in G \mid gHg^{-1} = H\} = N_G(H) \\ \Rightarrow r &= (G : N_G(H)) \end{aligned}$$

Now suppose we have a p -subgroup K of G , the action of G on $\mathcal{P}(G)$ then induces an action of K on $\mathcal{P}(G)$, and we shall have the canonical injective homomorphism:

$$K \cap N_G(H)/K \cap H \hookrightarrow N_G(H)/H$$

For the right hand side, see that:

$$|N_G(H)/H| = \frac{|N_G(H)|}{|H|} \mid \frac{|G|}{|H|} = \frac{|G|}{p^m}$$

Note that $\frac{|G|}{p^m}$ is relatively primed to p .

For the left hand side, it attains a non-negative order (can be 0), since K is a p -group, it should attain its order to be **power of p** by **Lagrange's Theorem**.

Now since it is a injective homomorphism, it attains a trivial kernel, so by **Lagrange's theorem + first isomorphism theorem**:

$$|K \cap N_G(H)/K \cap H| \mid |N_G(H)/H|$$

But notice that the right hand side is coprime with p but left hand side divides p , this leads to:

$$|K \cap N_G(H)/K \cap H| = 1 \Rightarrow K \cap N_G(H) = K \cap H \quad (2.1)$$

Now suppose $I \subseteq \{1, \dots, r\}$ are those such that $\{H_i \mid i \in I\}$ which gives a system of representatives for the orbits of the K action on \mathcal{S} , then by class equation:

$$r = |\mathcal{S}| = \sum_{i \in I} (K : \underbrace{\text{Stab}_K(H_i)}_{=K \cap \text{Stab}_G(H_i) = K \cap H_i \text{ by 2.1}}) \quad (2.2)$$

Now we want to prove:

$$(K : K \cap H_i) \Leftrightarrow K \subseteq H_i \quad (2.3)$$

If it is not the case, then $(K : K \cap H_i)$ is divisible by p since K is a p -group. First take $K = H$, since $|H| = |H_i|$, $\forall i$, we have $H \leq H_i \Leftrightarrow i = 1$. Hence by **Equation 2.2**, $r \equiv 1 \pmod{p}$.

Suppose that K is an arbitrary p -group, if $K \not\subseteq H_i$, $\forall i \in I \Rightarrow p \mid r$ by **Equation 2.2**, which contradicts to $r \equiv 1 \pmod{p}$. Hence there exists i , s.t. $K \subseteq H_i = aHa^{-1}$ for some $a \in G$, such yields **Sylow's Second Theorem**.

In particular, we see $\mathcal{S} = \{p\text{-Sylow subgroups of } G\} \Rightarrow r = n_p$:

$$\begin{aligned} \Rightarrow n_p &\equiv 1 \pmod{p} \\ n_p &= r = (G : N_G(H)) \end{aligned}$$

which yields **Sylow's Third Theorem**. ■

Note. All p -Sylow subgroups are conjugate to each other.

Remark.

$$n_p = 1 \Leftrightarrow H \trianglelefteq G$$

We state a small proposition that is helpful when we analyze the group structure along with Sylow's Theorem, it is also the midterm problem of this course.

Proposition 2.3.1. Let $H, K \leq G$, and $H \cap K = \{e\}$, then:

$$\begin{aligned} H \times K &\longrightarrow HK \\ (h, k) &\longmapsto hk \end{aligned}$$

is a group isomorphism.

Appendix