1 Inverse and Direct Limits

1.1 Inverse or Projective Limits

In this section we define the concept of inverse (or projective) limit and establish some of its elementary properties. Rather than developing the concept and establishing those properties under the most general conditions, we restrict ourselves to inverse limits of topological spaces or topological groups. We leave the reader the task of extending and translating the concepts and results obtained here to other objects such as sets, (topological) rings, modules, graphs..., or to more general categories.

Let $I = (I, \preceq)$ denote a directed partially ordered set or directed poset, that is, $I$ is a set with a binary relation $\preceq$ satisfying the following conditions:

(a) $i \preceq i$, for $i \in I$;
(b) $i \preceq j$ and $j \preceq k$ imply $i \preceq k$, for $i, j, k \in I$;
(c) $i \preceq j$ and $j \preceq i$ imply $i = j$, for $i, j \in I$; and
(d) if $i, j \in I$, there exists some $k \in I$ such that $i \preceq j \preceq k$.

An inverse or projective system of topological spaces (respectively, topological groups) over $I$, consists of a collection $\{X_i \mid i \in I\}$ of topological spaces (respectively, topological groups) indexed by $I$, and a collection of continuous mappings (respectively, continuous group homomorphisms) $\varphi_{ij} : X_i \to X_j$, defined whenever $i \succeq j$, such that the diagrams of the form

\[
\begin{array}{ccc}
X_i & \xrightarrow{\varphi_{ik}} & X_k \\
| & \searrow & | \\
| & \varphi_{ij} & | \\
X_j & \xleftarrow{\varphi_{jk}} & \\
\end{array}
\]

commute whenever they are defined, i.e., whenever $i, j, k \in I$ and $i \succeq j \succeq k$.

In addition we assume that $\varphi_{ii}$ is the identity mapping $\text{id}_{X_i}$ on $X_i$. We shall denote such a system by $\{X_i, \varphi_{ij}, I\}$, or by $\{X_i, \varphi_{ij}\}$ if the index set $I$ is clearly understood. If $X$ is a fixed topological space (respectively, topological group), we denote by $\{X, \text{id}\}$ the inverse system $\{X_i, \varphi_{ij}, I\}$, where $X_i = X$ for all $i \in I$, and $\varphi_{ij}$ is the identity mapping $\text{id} : X \to X$. We say that $\{X, \text{id}\}$ is the constant inverse system on $X$.
Let \( Y \) be a topological space (respectively, topological group), \( \{X_i, \varphi_{ij}, I\} \) an inverse system of topological spaces (respectively, topological groups) over a directed poset \( I \), and let \( \psi_i : Y \rightarrow X_i \) be a continuous mapping (respectively, continuous group homomorphism) for each \( i \in I \). These mappings \( \psi_i \) are said to be compatible if \( \varphi_{ij} \psi_i = \psi_j \) whenever \( j \preceq i \).

One says that a topological space (respectively, topological group) \( X \) together with compatible continuous mappings (respectively, continuous homomorphisms)

\[
\varphi_i : X \rightarrow X_i \quad (i \in I)
\]

is an inverse limit or a projective limit of the inverse system \( \{X_i, \varphi_{ij}, I\} \) if the following universal property is satisfied:

\[
\begin{array}{ccc}
Y & \xrightarrow{\psi} & X \\
\downarrow{\psi_i} & & \downarrow{\varphi_i} \\
X_i & & 
\end{array}
\]

whenever \( Y \) is a topological space (respectively, topological group) and \( \psi_i : Y \rightarrow X_i \) (\( i \in I \)) is a set of compatible continuous mappings (respectively, continuous homomorphisms), then there is a unique continuous mapping (respectively, continuous homomorphism) \( \psi : Y \rightarrow X \) such that \( \varphi_i \psi = \psi_i \) for all \( i \in I \). We say that \( \psi \) is “induced” or “determined” by the compatible homomorphisms \( \psi_i \).

The maps \( \varphi_i : X \rightarrow X_i \) are called projections. The projection maps \( \varphi_i \) are not necessarily surjections. We denote the inverse limit by \( (X, \varphi_i) \), or often simply by \( X \), by abuse of notation.

If \( \{X_i, I\} \) is a collection of topological spaces (respectively, topological groups) indexed by a set \( I \), its direct product or cartesian product is the topological space (respectively, topological group) \( \prod_{i \in I} X_i \), endowed with the product topology. In the case of topological groups the group operation is defined coordinatewise.

**Proposition 1.1.1** Let \( \{X_i, \varphi_{ij}, I\} \) be an inverse system of topological spaces (respectively, topological groups) over a directed poset \( I \). Then

(a) There exists an inverse limit of the inverse system \( \{X_i, \varphi_{ij}, I\} \);

(b) This limit is unique in the following sense. If \( (X, \varphi_i) \) and \( (Y, \psi_i) \) are two limits of the inverse system \( \{X_i, \varphi_{ij}, I\} \), then there is a unique homeomorphism (respectively, topological isomorphism) \( \varphi : X \rightarrow Y \) such that \( \psi_i \psi = \varphi_i \) for each \( i \in I \).

**Proof.** (a) Define \( X \) as the subspace (respectively, subgroup) of the direct product \( \prod_{i \in I} X_i \) of topological spaces (respectively, topological groups) consisting of those tuples \( (x_i) \) that satisfy the condition \( \varphi_{ij}(x_i) = x_j \) if \( i \geq j \).
Let 
\[ \varphi_i : X \rightarrow X_i \]
denote the restriction of the canonical projection \[ \prod_{i \in I} X_i \rightarrow X_i \]. Then one easily checks that each \( \varphi_i \) is continuous (respectively, a continuous homomorphism), and that \((X, \varphi_i)\) is an inverse limit.

(b) Suppose \((X, \varphi_i)\) and \((Y, \psi_i)\) are two inverse limits of the inverse system \(\{X_i, \varphi_{ij}, I\}\).

Since the maps \(\psi_i : Y \rightarrow X_i\) are compatible, the universal property of the inverse limit \((X, \varphi_i)\) shows that there exists a unique continuous mapping (respectively, continuous homomorphism) \(\psi : Y \rightarrow X\) such that \(\varphi_i \psi = \psi_i\) for all \(i \in I\). Similarly, since the maps \(\varphi_i : X \rightarrow X_i\) are compatible and \((Y, \psi_i)\) is an inverse limit, there exists a unique continuous mapping (respectively, continuous homomorphism) \(\varphi : X \rightarrow Y\) such that \(\psi_i \varphi = \varphi_i\) for all \(i \in I\). Next observe that

\[ \varphi \psi = \text{id}_X \]

commutes for each \(i \in I\). Since, by definition, there is only one map satisfying this property, one has that \(\psi \varphi = \text{id}_X\). Similarly, \(\varphi \psi = \text{id}_Y\). Thus \(\varphi\) is a homeomorphism (respectively, topological isomorphism). \(\square\)

If \(\{X_i, \varphi_{ij}, I\}\) is an inverse system, we shall denote its inverse limit by \(\varprojlim_{i \in I} X_i\), or \(\varprojlim_{i \in I} X_i\), or \(\lim_{i \in I} X_i\), depending on the context.

**Lemma 1.1.2** If \(\{X_i, \varphi_{ij}\}\) is an inverse system of Hausdorff topological spaces (respectively, topological groups), then \(\varprojlim X_i\) is a closed subspace (respectively, closed subgroup) of \(\prod_{i \in I} X_i\).

**Proof.** Let \((x_i) \in (\prod X_i) - (\varprojlim X_i)\). Then there exist \(r, s \in I\) with \(r \geq s\) and \(\varphi_{rs}(x_r) \neq x_s\). Choose open disjoint neighborhoods \(U\) and \(V\) of \(\varphi_{rs}(x_r)\) and \(x_s\) in \(X_s\), respectively. Let \(U'\) be an open neighborhood of \(x_r\) in \(X_r\), such that \(\varphi_{rs}(U') \subseteq U\). Consider the basic open subset \(W = \prod_{i \in I} V_i\) of \(\prod_{i \in I} X_i\) where \(V_r = U', V_s = V\) and \(U_i = X_i\) for \(i \neq r, s\). Then \(W\) is an open neighborhood of \((x_i)\) in \(\prod_{i \in I} X_i\), disjoint from \(\varprojlim X_i\). This shows that \(\varprojlim X_i\) is closed. \(\square\)
A topological space is *totally disconnected* if every point in the space is its own connected component. For example, a space with the discrete topology is totally disconnected, and so is the rational line. It is easily checked that the direct product of totally disconnected spaces is totally disconnected. The following result is an immediate consequence of Tychonoff’s theorem, that asserts that the direct product of compact spaces is compact (cf. Bourbaki [1989], Ch. 1, Theorem 3), and the fact that a closed subset of a compact space is compact.

**Proposition 1.1.3** Let \( \{X_i, \varphi_{ij}, I\} \) be an inverse system of compact Hausdorff totally disconnected topological spaces (respectively, topological groups) over the directed set \( I \). Then

\[
\lim_{i \in I} X_i
\]

is also a compact Hausdorff totally disconnected topological space (respectively, topological group).

**Proposition 1.1.4** Let \( \{X_i, \varphi_{ij}\} \) be an inverse system of compact Hausdorff nonempty topological spaces \( X_i \) over the directed set \( I \). Then

\[
\lim_{i \in I} X_i
\]

is nonempty. In particular, the inverse limit of an inverse system of nonempty finite sets is nonempty.

**Proof.** For each \( j \in I \), define a subset \( Y_j \) of \( \prod X_i \) to consist of those \((x_i)\) with the property \( \varphi_{jk}(x_j) = x_k \) whenever \( k \preceq j \). Using the axiom of choice and an argument similar to the one used in Lemma 1.1.2, one easily checks that each \( Y_j \) is a nonempty closed subset of \( \prod X_i \). Observe that if \( j \preceq j' \), then \( Y_j \supseteq Y_{j'} \); it follows that the collection of subsets \( \{Y_j \mid j \in I\} \) has the finite intersection property (i.e., any intersection of finitely many \( Y_j \) is nonempty), since the poset \( I \) is directed. Then, one deduces from the compactness of \( \prod X_i \) that \( \bigcap Y_j \) is nonempty. Since

\[
\lim_{i \in I} X_i = \bigcap_{j \in I} Y_j,
\]

the result follows. \( \Box \)

Let \( \{X_i, \varphi_{ij}, I\} \) and \( \{X'_i, \varphi'_{ij}, I\} \) be inverse systems of topological spaces (respectively, topological groups) over the same directed poset \( I \). A *map* or a *morphism* of inverse systems

\[
\Theta : \{X_i, \varphi_{ij}\} \rightarrow \{X'_i, \varphi'_{ij}\},
\]

consists of a collection of continuous mappings (respectively, continuous homomorphisms) \( \theta_i : X_i \rightarrow X'_i \) (\( i \in I \)) such that if \( i \preceq j \), then the following diagram commutes
We say that the mappings $\theta_i$ are the components of $\Theta$. A map

$$\Theta : \{X_i, \varphi_{ij}, I\} \rightarrow \{X_i, \varphi_{ij}, I\}$$

of an inverse system to itself, whose components $\theta_i : X_i \rightarrow X_i \ (i \in I)$ are identity mappings, is called the identity map of the system $\{X_i, \varphi_{ij}, I\}$, and it is usually denoted by $\text{id}$. Composition of maps of inverse systems is defined in a natural way. That is, if

$$\Theta : \{X_i, \varphi_{ij}\} \rightarrow \{X'_i, \varphi'_{ij}\},$$

with components $\theta_i$, and

$$\Psi : \{X'_i, \varphi'_{ij}\} \rightarrow \{X''_i, \varphi''_{ij}\},$$

with components $\psi_i$, are maps of inverse systems, then the components of the composition map

$$\Psi \Theta : \{X_i, \varphi_{ij}\} \rightarrow \{X''_i, \varphi''_{ij}\},$$

are $\psi_i \theta_i, \ i \in I$. Thus one obtains a category of inverse systems of topological spaces (respectively, topological groups), whose objects are inverse systems of topological spaces (respectively, topological groups), and whose morphisms are maps of inverse systems.

Let $\{X_i, \varphi_{ij}\}$ and $\{X'_i, \varphi'_{ij}\}$ be inverse systems of topological spaces (respectively, topological groups) over the same directed poset $I$, and let $(X = \lim X_i, \varphi_i)$ and $(X' = \lim X'_i, \varphi'_i)$ be their corresponding inverse limits. Assume that

$$\Theta : \{X_i, \varphi_{ij}, I\} \rightarrow \{X'_i, \varphi'_{ij}, I\}$$

is a map of inverse systems with components $\theta_i : X_i \rightarrow X'_i$. Then the collection of compatible mappings

$$\theta_i \varphi_i : X \rightarrow X'_i$$

induces a continuous mapping (respectively, continuous homomorphism)

$$\lim \Theta = \lim_{i \in I} \theta_i : \lim_{i \in I} X_i \rightarrow \lim_{i \in I} X'_i.$$

Observe that $\lim$ is a functor from the category of inverse systems of topological spaces (respectively, topological groups) over $I$ to the category of topological spaces (respectively, topological groups); that is, $\lim(\Psi \Theta) = \lim \Psi \lim \Theta$. 
and if id is the identity map on the inverse system \{X_i, \varphi_{ij}, I\}, then \(\lim\) id is the identity map on the topological space (respectively, topological group) \(\lim_{i\in I} X_i\).

If the components \(\theta_i : X_i \rightarrow X_i'\) of a map \(\Theta : \{X_i, \varphi_{ij}\} \rightarrow \{X_i', \varphi_{ij}'\}\) of inverse systems are embeddings, then obviously, so is

\[
\lim \theta_i : \lim X_i \hookrightarrow \lim X_i'.
\]

In contrast, if each of the components \(\theta_i\) is an onto mapping, \(\lim \theta_i\) is not necessarily onto. For example, consider the natural numbers \(I = \mathbb{N}\), with the usual partial ordering, as our indexing poset; define two inverse systems (of discrete spaces) over \(I\) as follows: the constant inverse system \(\{\mathbb{Z}, \text{id}\}\), and the inverse system \(\{\mathbb{Z}/p^n\mathbb{Z}, \varphi_{nm}\}\), where \(\varphi_{nm} : \mathbb{Z}/p^n\mathbb{Z} \rightarrow \mathbb{Z}/p^m\mathbb{Z}\) is the natural projection for \(m \leq n\). For each \(n \in \mathbb{N}\), define \(\theta_n : \mathbb{Z} \rightarrow \mathbb{Z}/p^n\mathbb{Z}\) to be the canonical epimorphism; then

\[
\Theta = \{\theta_n\} : \{\mathbb{Z}, \text{id}\} \rightarrow \{\mathbb{Z}/p^n\mathbb{Z}, \varphi_{nm}\}
\]

is a map of inverse systems. Observe that the inverse limit of the first system is \(\mathbb{Z}\), while the inverse limit of the second can be identified with

\[
\lim \mathbb{Z}/p^n\mathbb{Z} = \{(x_n) \mid x_n \in \mathbb{Z}, x_n \equiv x_m \pmod{p^m} \text{ if } m \leq n\}.
\]

The image of \(\mathbb{Z}\) in \(\lim \mathbb{Z}/p^n\mathbb{Z}\) under \(\lim \theta_n\) is the set of all constant tuples \(\{(a_n) \mid a_n = t, t \in \mathbb{Z}\}\). On the other hand, the tuple \((b_n)\), where \(b_n = 1 + p + \cdots + p^{n-1}\), is in \(\lim \mathbb{Z}/p^n\mathbb{Z}\), but it is not constant. Thus \(\lim \theta_n\) is not onto.

However, for inverse systems of compact Hausdorff spaces, one has the following result.

**Lemma 1.1.5** Let \(\Theta : \{X_i, \varphi_{ij}, I\} \rightarrow \{X_i', \varphi_{ij}', I\}\) be a map of inverse systems of compact Hausdorff topological spaces (respectively, topological groups), and assume that each component \(\theta_i : X_i \rightarrow X_i'\) \((i \in I)\) is onto. Then

\[
\lim \Theta = \lim_{i \in I} \theta_i : \lim_{i \in I} X_i \rightarrow \lim_{i \in I} X_i'
\]

is onto.

**Proof.** Let \((x'_i) \in \lim X_i'\). Put \(\tilde{X}_i = \theta_i^{-1}(x'_i)\) \((i \in I)\). Since \(\tilde{X}_i\) is closed in the compact space \(X_i\), it follows that \(\tilde{X}_i\) is compact \((i \in I)\). Observe that \(\varphi_{ij}(\tilde{X}_i) \subseteq \tilde{X}_j\) for \(i \geq j\). Therefore, \(\{\tilde{X}_i, \varphi_{ij}\}\) is an inverse system of nonempty compact topological spaces (respectively, compact topological groups). By Proposition 1.1.4, \(\lim \tilde{X}_i \neq \emptyset\). Let \((x_i) \in \lim \tilde{X}_i \subseteq \lim X_i\). Then one has \((\lim \Theta)(x_i) = (x'_i)\). \(\square\)
Corollary 1.1.6 Let \( \{X_i, \varphi_{ij}, I\} \) be an inverse system of compact Hausdorff spaces and \( X \) a compact Hausdorff space. Suppose that \( \{\varphi_i : X \to X_i\}_{i \in I} \) is a set of compatible continuous surjective mappings. Then the corresponding induced mapping \( \theta : X \to \lim_{\leftarrow} X_i \) is onto.

Proof. Consider the constant inverse system \( \{X, \text{id}\} \) over \( I \). The collection \( \{\theta_i\}_{i \in I} \) can be thought of as a map from \( \{X, \text{id}, I\} \) to \( \{X_i, \varphi_{ij}, I\} \). Then \( \theta = \lim_{\leftarrow} \theta_i \), and the result follows from the above proposition. \( \square \)

Lemma 1.1.7 Let \( \{X_i, \varphi_{ij}, I\} \) be an inverse system of topological spaces over a directed set \( I \), and let \( \rho_i : X \to X_i \) be compatible surjections from the space \( X \) onto the spaces \( X_i \) \((i \in I)\). Then either \( \lim_{\leftarrow} X_i = \emptyset \) or the corresponding induced mapping \( \rho : X \to \lim_{\leftarrow} X_i \) maps \( X \) onto a dense subset of \( \lim_{\leftarrow} X_i \).

Proof. Suppose \( \lim_{\leftarrow} X_i \neq \emptyset \). A general basic open subset \( V \) of \( \lim_{\leftarrow} X_i \) can be described as follows: let \( i_1, \ldots, i_n \) be a finite subset of \( I \) and let \( U_{i_j} \) be an open subset of \( X_{i_j} \) \((j = 1, \ldots, n)\); let

\[
V = (\lim_{\leftarrow} X_i) \cap \left( \prod_{i \in I} V_i \right)
\]

where \( V_{i_j} = U_{i_j} \) \((j = 1, \ldots, n)\) and \( V_i = X_i \) for \( i \neq i_1, \ldots, i_n \). Assume such \( V \) is not empty. We have to show that \( \rho(X) \cap V \neq \emptyset \). Let \( i_0 \succeq i_1, \ldots, i_n \), and let \( y = (y_i) \in V \). Choose \( x \in X \) so that \( \rho_{i_0}(x) = y_{i_0} \). Then \( \rho(x) \in V \). \( \square \)

Corollary 1.1.8 Let \( \{X_i, \varphi_{ij}\} \) be an inverse system of compact Hausdorff spaces, \( X = \lim_{\leftarrow} X_i \), and let \( \varphi_i : X \to X_i \) be the projections.

(a) If \( Y \) is a closed subspace of \( X \), then \( Y = \lim_{\leftarrow} \varphi_i(Y) \).
(b) If \( Y \) is a subspace of \( X \), then

\[
\bar{Y} = \lim_{\leftarrow} \varphi_i(Y),
\]

where \( \bar{Y} \) is the closure of \( Y \) in \( X \).
(c) If \( Y \) and \( Y' \) are subspaces of \( X \) and \( \varphi_i(Y) = \varphi_i(Y') \) for each \( i \), then their closures in \( X \) coincide: \( \bar{Y} = \bar{Y'} \).

Proof. (a) Observe that there are obvious embeddings

\[
Y \hookrightarrow \lim_{\leftarrow} \varphi_i(Y) \hookrightarrow \lim_{\leftarrow} X_i = X.
\]

Moreover, by Corollary 1.1.6, the first of these embeddings is onto. Hence, \( Y = \lim_{\leftarrow} \varphi_i(Y) \).

(b) According to Lemma 1.1.7, \( Y \) embeds as a dense subset of \( \lim_{\leftarrow} \varphi_i(Y) \). Arguing as in Lemma 1.1.2 one sees that \( \lim_{\leftarrow} \varphi_i(Y) \) is closed in \( X \). Hence the result follows.
(c) This follows from (a) and (b). \( \square \)
Let \((I, \preceq)\) be a directed poset. Assume that \(I'\) is a subset of \(I\) in such a way that \((I', \preceq)\) becomes a directed poset. We say that \(I'\) is cofinal in \(I\) if for every \(i \in I\) there is some \(i' \in I'\) such that \(i \preceq i'\). If \(\{X_i, \varphi_{ij}, I\}\) is an inverse system and \(I'\) is cofinal in \(I\), then \(\{X_i, \varphi_{ij}, I'\}\) becomes an inverse system in an obvious way, and we say that \(\{X_i, \varphi_{ij}, I'\}\) is a cofinal subsystem of \(\{X_i, \varphi_{ij}, I\}\).

Assume that \(\{X_i, \varphi_{ij}, I'\}\) is a cofinal subsystem of \(\{X_i, \varphi_{ij}, I\}\) and denote by \(\left(\bigcap_{i' \in I'} X_{i'}, \varphi'_{ij}\right)\) and \(\left(\bigcap_{i \in I} X_i, \varphi_i\right)\) their corresponding inverse limits. For \(j \in I\), let \(j' \in I'\) be such that \(j' \succeq j\). Define

\[
\varphi_j : \lim_{i' \in I'} X_{i'} \longrightarrow X_j
\]

as the composition of canonical mappings \(\varphi_{j'j} \varphi'_{ij}\). Observe that the maps \(\varphi_j\) are well-defined (independent of the choice of \(j'\)) and compatible. Hence they induce a map

\[
\varphi : \lim_{i' \in I'} X_{i'} \longrightarrow \lim_{i \in I} X_i
\]

such that \(\varphi \varphi_j = \varphi_j\) \((j \in I)\). We claim that the mapping \(\varphi\) is a bijection. Note that if \((x_{i'}) \in \bigcap_{i' \in I'} X_{i'}\) and \(\varphi(x_{i'}) = (y_i)\), then \(y_{i'} = x_{i'}\) for \(i' \in I'\). It follows that \(\varphi\) is an injection since \(I'\) is cofinal in \(I\). To see that \(\varphi\) is a surjection, let \((y_i) \in \bigcap_{i \in I} X_i\) and consider the element \((x_{i'})\), where \(x_{i'} = y_{i'}\) for every \(i' \in I'\). Then \((x_{i'}) \in \bigcap_{i' \in I'} X_{i'}\) and clearly, \(\varphi(x_{i'}) = (y_i)\). This proves the claim. We record these results in the following lemma.

**Lemma 1.1.9** Let \(\{X_i, \varphi_{ij}, I\}\) be a inverse system of compact topological spaces (respectively, compact topological groups) over a directed poset \(I\) and assume that \(I'\) is a cofinal subset of \(I\). Then

\[
\lim_{i \in I} X_i \cong \lim_{i' \in I'} X_{i'}.
\]

**Proof.** According to the above observations,

\[
\varphi : \lim_{i' \in I'} X_{i'} \longrightarrow \lim_{i \in I} X_i
\]

is a continuous bijection (respectively, group isomorphism). Since \(\lim_{i' \in I'} X_{i'}\) and \(\lim_{i \in I} X_i\) are compact spaces (respectively, compact topological groups), it follows that \(\varphi\) is a homeomorphism (respectively, topological isomorphism). We identify \(\lim_{i' \in I'} X_{i'}\) and \(\lim_{i \in I} X_i\) by means of this homeomorphism (respectively, topological isomorphism). \(\square\)

An inverse system \(\{X_i, \varphi_{ij}, I\}\) is called a surjective inverse system if each of the mappings \(\varphi_{ij}\) \((i \succeq j)\) is surjective. By Corollary 1.1.8(a), for any
inverse system \( \{X_i, \varphi_{ij}, I\} \), there is a corresponding surjective inverse system 
\( \{\varphi_i(X), \varphi'_{ij}, I\} \) (where \( \varphi'_{ij} \) is just the restriction of \( \varphi_{ij} \) to \( \varphi_i(X) \)) with the same inverse limit \( X \).

Let \( \{X_i, \varphi_{ij}, I\} \) be an inverse system of topological spaces \( X_i \) over a poset \( I \). Put \( X = \varprojlim X_i \), and let \( \varphi_j : X \to X_j \) be the projection map. Assume that \( X \neq \emptyset \). If \( \varphi_j \) is a surjection for each \( i \in I \), then evidently \( \varphi_{rs} : X_r \to X_s \) is a surjection for all \( r, s \in I \) with \( r \geq s \). The converse is not necessarily true. However, as the following proposition shows, the converse holds if one assumes in addition that each of the \( X_i \) is compact.

**Proposition 1.1.10** Let \( \{X_i, \varphi_{ij}, I\} \) be a surjective inverse system of compact Hausdorff nonempty topological spaces \( X_i \) over a poset \( I \). Then for each \( j \in I \), the projection map \( \varphi_j : \varprojlim X_i \to X_j \) is a surjection.

**Proof.** Fix \( j \in I \). The set \( I_j = \{i \in I \mid i \geq j\} \) is cofinal in \( I \); so, by Lemma 1.1.9, \( \varprojlim_{i \in I_j} X_i \cong \varprojlim_{i \in I} X_i \). Therefore, we may assume that \( i \geq j \) for every \( i \in I \). Let \( x_j \in X_j \) and set \( Y_r = \varphi_{rj}^{-1}(x_j) \) for \( r \in I \). Since \( \varphi_{rj} \) is onto and continuous, \( Y_r \) is a nonempty compact subset of \( X_r \) (\( r \in I \)). Furthermore, if \( r \geq s \) are indices in \( I \), then \( \varphi_{rs}(Y_r) \subseteq Y_s \). Hence \( \{Y_r, \varphi_{rs}, I\} \) is an inverse system. According to Proposition 1.1.4, \( \varprojlim Y_r \neq \emptyset \). Let \( (y_r) \in \varprojlim Y_r \subseteq \varprojlim X_i \). Then \( \varphi_j(y_r) = x_j \). \( \square \)

In what follows we shall be specially interested in topological spaces \( X \) that arise as inverse limits

\[
X = \varprojlim_{i \in I} X_i
\]

of finite spaces \( X_i \) endowed with the discrete topology. We call such a space a **profinite space** or a **Boolean space**. Before we give some characterizations of profinite spaces, we need the following lemma.

**Lemma 1.1.11** Let \( X \) be a compact Hausdorff topological space and let \( x \in X \). Then the connected component \( C \) of \( x \) is the intersection of all clopen (i.e., closed and open) neighborhoods of \( x \).

**Proof.** Let \( \{U_t \mid t \in T\} \) be the family of all clopen neighborhoods of \( x \), and put

\[
A = \bigcap_{t \in T} U_t.
\]

It is clear that every clopen neighborhood of \( x \) contains the connected component \( C \) of \( x \); and so \( C \subseteq A \). Therefore, it suffices to show that \( A \) is connected. Assume that \( A = U \cup V \), \( U \cap V = \emptyset \) with both \( U \) and \( V \) closed in \( A \) (and so, in \( X \)). We need to prove that either \( U \) or \( V \) is empty. Since \( X \) is Hausdorff and \( U \) and \( V \) are compact and disjoint, there exist open sets \( U' \) and \( V' \) in \( X \) such that \( U' \supseteq U \), \( V' \supseteq V \) and \( U' \cap V' = \emptyset \). So,
[X - (U' ∪ V')] ∩ A = ∅.

Now, X - (U' ∪ V') is closed; hence, by the compactness of X, there exists a finite subfamily T' of T such that

\[ [X - (U' ∪ V')] \cap \left( \bigcap_{t' \in T'} U_{t'} \right) = \emptyset. \]

Observe that \( B = \bigcap_{t' \in T'} U_{t'} \) is a clopen neighborhood of \( x \), since \( T' \) is finite. On the other hand,

\[ x \in (B \cap U') \cup (B \cap V') = B. \]

Say \( x \in B \cap U' \). Plainly \( B \cap U' \) is open, but it is also closed because \( B \cap V' \) is open and \( (X - B \cap V') \cap B = B \cap U' \). Therefore, \( A \subseteq B \cap U' \subseteq U' \). Hence \( A \cap V \subseteq A \cap V' = \emptyset \), and thus \( V = \emptyset \).

We say that an equivalence relation \( R \) on a topological space \( X \) is open (respectively, closed) if for every \( x \in X \), the equivalence class \( xR \) of \( x \) is open (respectively, closed) in \( X \). If \( R \) is open, then it is closed (\( xR \) is the complement of a union of open sets).

Observe that \( R \) is open in the above sense if and only if \( R \) considered as a subset of \( X \times X \) is open. Indeed, assume that \( R \) is open, and let \( (x, y) \in R \) \( x, y \in X \); then \( xR \times yR \) is an open neighborhood of \( (x, y) \) contained in \( R \), and hence \( R \) is an open subset of \( X \times X \). Conversely, assume that \( R \) is an open subset of \( X \times X \); since \( (x, x) \in R \), there exists an open neighborhood \( U \) of \( x \) in \( X \) such that \( U \times U \subseteq R \); hence \( U \subseteq xR \), proving that \( xR \) is open in \( X \), and thus that \( R \) is an open equivalence relation.

**Theorem 1.1.12** Let \( X \) be a topological space. Then the following conditions are equivalent.

(a) \( X \) is a profinite space;

(b) \( X \) is compact Hausdorff and totally disconnected;

(c) \( X \) is compact Hausdorff and admits a base of clopen sets for its topology.

**Proof.** (a) \( \Rightarrow \) (b): Let \( X \) be a profinite space. Say \( X = \lim_{\leftarrow i \in I} X_i \), where each \( X_i \) is a finite space. By Proposition 1.1.3, \( X \) is compact Hausdorff and totally disconnected.

(b) \( \Rightarrow \) (c): Let \( X \) be a compact Hausdorff and totally disconnected space. Let \( W \) be an open neighborhood of a point \( x \) in \( X \). We must show that \( W \) contains a clopen neighborhood of \( x \). Let \( \{ U_t \mid t \in T \} \) be the family of all clopen neighborhoods of \( x \). According to Lemma 1.1.11,

\[ \{ x \} = \bigcap_{t \in T} U_t. \]
Since $X - W$ is closed and disjoint from $\bigcap_{t \in T'} U_t$, we deduce from the compactness of $X$ that there is a finite subset $T''$ of $T$ such that
\[(X - W) \cap \left( \bigcap_{t \in T'} U_t \right) = \emptyset.\]
Thus $\bigcap_{t \in T'} U_t$ is a clopen neighborhood of $x$ contained in $W$, as desired.

(c) $\Rightarrow$ (a): Suppose that $X$ is compact Hausdorff and admits a base of clopen sets for its topology. Denote by $R$ the collection of all open equivalence relations $R$ on $X$; for such $R$, the space $X/R$ is finite and discrete since $X$ is compact. The set $R$ is naturally ordered as follows: if $R, R' \in R$, then $R \succeq R'$ if and only if $xR \subseteq xR'$ for all $x \in X$. Then $R$ is a poset. To see that this poset is directed, let $R_1$ and $R_2$ be two equivalence relations on $X$. Define its intersection $R_1 \cap R_2$ to be the equivalence relation corresponding to the partition of $X$ obtained by intersecting each equivalence class of $R_1$ with each equivalence class of $R_2$. Clearly $R_1 \cap R_2 \succeq R_1, R_2$. Now, if $R, R' \in R$ and $R \succeq R'$, define $\varphi_{RR'} : X/R \to X/R'$ by $\varphi_{RR'}(xR) = xR'$. Then \(\{X/R, \varphi_{RR'}\}\) is an inverse system over $R$. We shall show that $X \cong \lim_{\leftarrow R \in R} X/R$.

Let
\[\psi : X \to \lim_{\leftarrow R \in R} X/R\]
be the continuous mapping induced by the canonical continuous surjections
\[\psi_R : X \to X/R.\]
By Corollary 1.1.6, $\psi$ is a continuous surjection. To prove that $\psi$ is a homeomorphism, it suffices then to prove that it is an injection, since $X$ is compact. Let $x, y \in X$. By hypothesis, there exists a clopen neighborhood $U$ of $x$ that excludes $y$. Consider the equivalence relation $R'$ on $X$ with two equivalence classes: $U$ and $X - U$. Clearly, $R' \in R$ and $\psi_{R'}(x) \neq \psi_{R'}(y)$. So, $\psi(x) \neq \psi(y)$. Thus, $\psi$ is an injection. $\square$

A topological space $X$ is said to satisfy the second axiom of countability if it has a countable base of open sets; such space is also called second countable or countably based. A topological space $X$ is said to satisfy the first axiom of countability if each point of $X$ has a countable fundamental system of neighborhoods; such space is also called first countable.

**Corollary 1.1.13** A profinite space $X$ is second countable if and only if
\[X \cong \lim_{\leftarrow i \in I} X_i,\]
where $(I, \preceq)$ is a countable totally ordered set and each $X_i$ is a finite discrete space.
**Proof.** Suppose $X$ is profinite and second countable. Consider the set $R$ of all open equivalence relations on $X$. For $R \in R$, $xR$ is a finite union of basic open set. Hence $R$ is countable. Say $R = \{R_1, R_2, \ldots\}$. For each natural number $i$, define $R'_i = R_1 \cap \cdots \cap R_i$. Then $R'_1 \preceq R'_2 \preceq \cdots$ and $\{R'_i \mid i \in \mathbb{N}\}$ is cofinal in $R$. As seen in the proof of the implication (c) $\Rightarrow$ (a) in the theorem, $X = \lim_{\leftarrow} R \in R X/R$. Thus $X = \lim_{\leftarrow\ i \in \mathbb{N}} X/R'_i$.

Conversely assume that $X = \lim_{\leftarrow\ i \in I} X_i$, where the poset $(I, \preceq)$ is countable and each $X_i$ is a finite discrete space. Then obviously $\prod_{i \in I} X_i$ is second countable and profinite; thus so is $X$. $\square$

**Exercise 1.1.14** Let $\{X_i \mid i \in I\}$ be a collection of spaces. Prove that

$$\prod_{i \in I} X_i$$

can be expressed as an inverse limit of direct products $\prod_{i \in F} X_i$, where $F$ runs through the finite subsets of $I$.

**Exercise 1.1.15** Let $\{X_i, \varphi_{ij}\}$ be an inverse system of topological spaces indexed by a poset $I$, $X = \lim_{\leftarrow} X_i$, and denote by $\varphi_i : X \rightarrow X_i$ the projection map. Assume that for each $i \in I$, $U_i$ is a base of open sets of $X_i$. Prove that $\{\varphi_i^{-1}(U) \mid U \in U_i, i \in I\}$ is a base of open sets of $X$.

**Lemma 1.1.16**

(a) Let $\{X_i, \varphi_{ij}, I\}$ be an inverse system of profinite spaces. Let

$$X = \lim_{i \in I} X_i$$

and denote by $\varphi_i : X \rightarrow X_i$ the projection map $(i \in I)$. Let $\rho : X \rightarrow Y$ be a continuous mapping onto a discrete finite space $Y$. Then $\rho$ factors through some $\varphi_k$, that is, there exists some $k \in I$ and some continuous mapping $\rho' : X_k \rightarrow Y$ such that $\rho = \rho' \varphi_k$.

(b) Let $\{G_i, \varphi_{ij}, I\}$ be an inverse system of topological groups with underlying profinite spaces. Let

$$G = \lim_{i \in I} G_i$$

and denote by $\varphi_i : G \rightarrow G_i$ the projection continuous homomorphism $(i \in I)$. Let $\beta : G \rightarrow H$ be a continuous homomorphism into a discrete finite group $H$. Then $\beta$ factors through some $\varphi_k$, that is, there exists some $k \in I$ and some continuous homomorphism $\beta' : G_k \rightarrow H$ such that $\beta = \beta' \varphi_k$.

**Proof.** (a) Assume first that each $\varphi_i$ is a surjection. Let $Y = \{y_1, \ldots, y_r\}$, and consider the clopen subsets $U_i = \rho^{-1}(y_i)$ ($i = 1, \ldots, r$) of $X$. Clearly $X = \bigcup_{i=1}^r U_i$, and $U_i \cap U_j = \emptyset$ if $i \neq j$. Fix $i$. For each $x \in U_i$ choose
an index \( k_x \in I \) and a clopen neighborhood \( V_x = V_x^i \) of \( \varphi_{k_x}(x) \) in \( X_{k_x} \) such that \( \varphi_{k_x}^{-1}(V_x) \subseteq U_i \) (see Exercise 1.1.15). Put \( W_x = \varphi_{k_x}^{-1}(V_x) \). By the compactness of \( U_i \), there are finitely many points \( x_1, \ldots, x_{t_i} \) in \( U_i \) such that \( U_i = W_{x_1} \cup \cdots \cup W_{x_{t_i}} \). Choose an index \( k \in I \) such that \( k \geq k_{x_1}, \ldots, k_{x_{t_i}} \).

Replacing \( V_x \) by \( \varphi_{k_{kx}}^{-1}(V_x) \) \((s = 1, \ldots, t_i)\), we may assume that \( k_{x_1} = \cdots = k_{x_{t_i}} = k \). Note that this \( k \) depends on \( i \); however, since \( I \) is directed, we may assume that in fact \( k \) is valid for all \( i = 1, \ldots, r \). Hence we have constructed clopen subsets \( V_1, \ldots, V_i \) of \( X_k \) such that \( U_i = \bigcup_{s=1}^{t_i} \varphi_{k}^{-1}(V_s) \) \((i = 1, \ldots, r)\).

Put \( V = \bigcup_{s=1}^{t} V_s^{i} \). Then \( V \cap V^j = \emptyset \) if \( i \neq j \) \((1 \leq i, j \leq r)\); furthermore, \( X_k = \bigcup_{i=1}^{r} V^i \) since \( \varphi_k \) is a surjection. Define \( \rho' : X_k \rightarrow Y \) by \( \rho'(x) = y_i \) if \( x \in V^i \). Then \( \rho' \) is a continuous mapping since the \( V^i \) are clopen and form a disjoint covering of \( X \). Clearly \( \rho' = \rho' \varphi_k \).

To finish part (a), consider now the case when the projection maps \( \varphi_i \) are not necessarily surjective. By the construction above, there exists some \( k \in I \) and a continuous surjection \( \mu : \varphi_k(X) \rightarrow Y \) such that \( \rho = \mu \varphi_k \). Hence, it suffices to extend \( \mu \) to a continuous map \( \rho' : X_k \rightarrow Y \). Put \( Z = \varphi_k(X) \). For each \( i = 1, \ldots, r \), let \( W_i = \mu^{-1}(y_i) \). Then \( Z = W_1 \cup \cdots \cup W_r \) and each \( W_i \) is clopen in \( Z \). Since \( X_k \) is a profinite space and \( Z \) is closed in \( X_k \), there exist clopen subsets \( W_1', \ldots, W_r' \) of \( X_k \) such that \( X_k = W_1' \cup \cdots \cup W_r' \) and \( W_i = W_i' \cap Z \) \((i = 1, \ldots, r)\). Define \( \rho'(x) = y_i \) for \( x \in W_i' \) \((i = 1, \ldots, r)\). Then \( \rho' \) is clearly continuous and extends \( \mu \). This ends the proof of part (a).

(b) Thinking of \( G, H \) and each \( G_i \) as topological spaces, we infer from part (a) that \( \beta \) factors through a continuous function \( \beta_{i_0} : G_{i_0} \rightarrow H \), for some \( i_0 \in I \). However \( \beta_{i_0} \) need not be a homomorphism. Put \( I_0 = \{ i \in I \mid i \geq i_0 \} \).

For each \( i \in I_0 \), define \( \beta_i : G_i \rightarrow H \), by \( \beta_i = \beta_{i_0} \varphi_{i_0} \); then clearly \( \beta = \beta_i \varphi_i \).

We claim that for some \( k \in I_0 \), the map \( \beta_k \) is a homomorphism. To see this consider the continuous map

\[
\eta : G \times G \rightarrow H \times H, \quad (g_1, g_2) \mapsto (\beta(g_1) \beta(g_2), \beta(g_1 g_2)),
\]

and the analogous continuous maps \( \eta_i : G_i \times G_i \rightarrow H \times H \), for each \( i \in I_0 \), replacing \( \beta \) by \( \beta_i \). It is easy to check that

\[
G \times G = \lim_{i \geq i_0} G_i \times G_i, \quad \eta = \lim_{i \in I_0} \eta_i,
\]

and

\[
\eta(G \times G) = \lim_{i \in I_0} \eta_i(G_i \times G_i) = \bigcap_{i \geq i_0} \eta_i(G_i \times G_i).
\]

Since \( \eta(G_i \times G_i) \) is contained in the finite set \( H \times H \) and since \( I_0 \) is a directed poset, it follows that

\[
\eta(G \times G) = \eta_k(G_k \times G_k),
\]

for some \( k \in I_0 \). Next observe that since \( \beta \) is a homomorphism, \( \eta(G \times G) \subseteq \Delta = \{ (h, h) \mid h \in H \} \). Therefore \( \eta_k(G_k \times G_k) \subseteq \Delta \); thus \( \eta_k \) is a homomorphism. Put \( \beta' = \eta_k \). \( \square \)
1.2 Direct or Inductive Limits

In this section we study direct (or inductive) systems and their limits. The definitions and some of the properties obtained here are found by dualizing the corresponding ones in the case of inverse (or projective) limits developed in Section 1.1; however there some specific results for direct limits that we want to emphasize. Again, we shall not try to develop the theory under the most general conditions; we are mainly interested in direct limits of abelian groups (or modules). So, to avoid unnecessary repetitions, we shall work within the category of abelian groups and leave the reader the task of translating the results for other categories (sets, rings, modules, graphs, etc.).

Let \( I = (I, \preceq) \) be a partially ordered set (see Section 1.1) A direct or inductive system of abelian groups over \( I \) consists of a collection \( \{A_i\} \) of abelian groups indexed by \( I \) and a collection of homomorphisms \( \varphi_{ij} : A_i \to A_j \), defined whenever \( i \preceq j \), such that the diagrams of the form

\[
\begin{array}{c}
A_i \\
\downarrow \varphi_{ik} \\
A_k \\
\downarrow \varphi_{jk} \\
A_j
\end{array}
\]

commute whenever \( i \preceq j \preceq k \).

In addition, we assume that \( \varphi_{ii} \) is the identity mapping \( \text{id}_{A_i} \) on \( A_i \). We shall denote such a system by \( \{A_i, \varphi_{ij}, I\} \), or by \( \{A_i, \varphi_{ij}\} \) if the index set \( I \) is clearly understood. If \( A \) is a fixed abelian group, we denote by \( \{A, \text{id}\} \) the direct system \( \{A_i, \varphi_{ij}\} \), where \( A_i = A \) for all \( i \in I \), and \( \varphi_{ij} \) is the identity mapping \( \text{id} : A \to A \). We say that \( \{A, \text{id}\} \) is the constant direct system on \( A \).

Let \( A \) be an abelian group, \( \{A_i, \varphi_{ij}, I\} \) a direct system of abelian groups over a directed poset \( I \) and assume that \( \psi_i : A_i \to A \) is a homomorphism for each \( i \in I \). These mappings \( \psi_i \) are said to be compatible if \( \psi_j \varphi_{ij} = \psi_i \) whenever \( i \preceq j \). One says that an abelian group \( A \) together with compatible homomorphisms

\[
\varphi_i : A_i \to A
\]

\((i \in I)\) is a direct limit or an inductive limit of the direct system \( \{A_i, \varphi_{ij}, I\} \), if the following universal property is satisfied:

\[
\begin{array}{c}
A \\
\downarrow \varphi_i \\
A_i \\
\downarrow \psi_i \\
B
\end{array}
\]

whenever \( B \) is an abelian group and \( \psi_i : A_i \to B \) \((i \in I)\) is a set of compatible homomorphisms, then there exists a unique homomorphism

\[
\psi : A \to B
\]
such that $\psi \varphi_i = \psi_i$ for all $i \in I$. We say that $\psi$ is “induced” or “determined” by the compatible homomorphisms $\psi_i$.

**Proposition 1.2.1** Let $\{A_i, \varphi_{ij}, I\}$ be a direct system of abelian groups over a directed poset $I$. Then there exists a direct limit of the system. Moreover, this limit is unique in the following sense: if $(A, \varphi_i)$ and $(A', \varphi'_i)$ are two limits, then there is a unique isomorphism $\eta : A \to A'$ such that $\varphi'_i = \eta \varphi_i$ for each $i \in I$.

*Proof.* The uniqueness is immediate. To show the existence of the direct limit of the system $\{A_i, \varphi_{ij}, I\}$, let $U$ be the disjoint union of the groups $A_i$. Define a relation $\sim$ on $U$ as follows: we say that $x \in A_i$ is equivalent to $y \in A_j$ if there exists $k \in I$ with $k \geq i, j$ such that $\varphi_{ik}(x) = \varphi_{jk}(y)$. This is an equivalence relation. Denote by $\bar{x}$ the equivalence class of $x \in A_i$ under this relation. Denote by $A$ the set of all equivalence classes of $U$. Given $x \in A_i$ and $y \in A_j$ consider an index $k \in I$ with $k \geq i, j$, and define $\bar{x} + \bar{y}$ to be the class of $\varphi_{ik}(x) + \varphi_{jk}(y)$; this is easily seen to be well-defined. Then $A$ becomes an abelian group under this operation (its zero element is the class represented by the zero of $A_i$ for any $i \in I$). For each $i \in I$, let $\varphi_i : A_i \to A$ be given by $\varphi_i(x) = \bar{x}$; then $\varphi_i$ is a homomorphism. To check that $(A, \varphi_i)$ is a direct limit of the direct system $\{A_i, \varphi_{ij}, I\}$, let $\psi : A_i \to B$ ($i \in I$) be a collection of compatible homomorphisms into an abelian group $B$. Define the induced homomorphism $\psi : A \to B$ as follows. Let $a \in A$; say $a = \varphi_i(x)$ for some $x \in A_i$ and $i \in I$. Then define $\psi(a) = \psi_i(x)$. Observe that $\psi$ is a well-defined homomorphism and $\psi \varphi_i = \psi_i$ for all $i \in I$. Furthermore, $\psi$ is the only possible homomorphism satisfying these conditions. $\Box$

If $\{A_i, \varphi_{ij}, I\}$ is a direct system, we denote its direct limit by $\varinjlim_{i \in I} A_i$, or $\varinjlim_i A_i$, or $\varinjlim I A_i$, or $\varinjlim A_i$, depending on the context.

**Exercise 1.2.2** Let $\{A_i, \varphi_{ij}, I\}$ be a direct system of abelian groups over a directed poset $I$, and let $I'$ be a cofinal subset of $I$. Show that the groups $\{A_i \mid i \in I'\}$ form in a natural way a direct system of abelian groups over $I'$, and

$$\varinjlim_{i \in I} A_i = \varinjlim_{i \in I'} A_i.$$  

The following exercise provides an alternative way of constructing direct limits; this procedure is the dual of the construction for inverse limits used in the proof of Proposition 1.1.1.

**Exercise 1.2.3** Let $\{A_i, \varphi_{ij}, I\}$ be a direct system of abelian groups over a directed poset $I$. Define $A$ to be the quotient group of the direct sum $\bigoplus_{i \in I} A_i$, modulo the subgroup $R$ generated by the elements of the form $\varphi_{ij}(x) - x$ for all $x \in A_i$, $i \in I$ and $i \preceq j$. There are natural homomorphisms $\varphi_i : A_i \to A$. Prove that $A$ together with these homomorphisms is a direct limit of the system $\{A_i, \varphi_{ij}, I\}$. 


Proposition 1.2.4 Let \( \{A_i, \varphi_{ij}\} \) be a direct system of abelian groups over a directed poset \( I \), \( A = \varinjlim A_i \) its direct limit and \( \varphi_i : A_i \rightarrow A \) the canonical homomorphisms. Then

(a) \( A = \bigcup_{i \in I} \varphi_i(A_i) \);
(b) Let \( x \in A_i \) and assume \( \varphi_i(x) = 0 \); then there exists some \( k \succeq i \) such that \( \varphi_{ik}(x) = 0 \);
(c) If \( \varphi_{ik} \) is an injection for each \( k \succeq i \), then \( \varphi_i \) is an injection;
(d) If \( \varphi_{ik} \) is onto for each \( k \succeq i \), then \( \varphi_i \) is a surjection.

Proof. Part (a) is obvious from our construction. To prove (b), note that \( \varphi_i(x) = 0 \) means that \( \tilde{x} = \tilde{0} \), where \( 0 \in A_j \) for some \( j \in I \) (we use the notation of the proof of Proposition 1.2.1). Therefore, there exists \( k \succeq i, j \) such that \( \varphi_{ik}(x) = \varphi_{jk}(0) = 0 \). Part (c) follows from (b). To show (d), let \( a \in A \); then, by construction, \( a = \tilde{y} \), where \( y \in A_j \) for some \( j \in I \). Choose \( k \succeq i, j \). Since \( \varphi_{ik} \) is onto, there exists \( x \in A_i \) such that \( \varphi_{ik}(x) = \varphi_{jk}(y) \); therefore \( \varphi_i(x) = \tilde{x} = \tilde{y} = a \). \( \square \)

Example 1.2.5

(1) The prototype of a direct limit is a union. If an abelian group \( A \) is a union \( A = \bigcup_{i \in I} A_i \) of subgroups \( A_i \), then \( A \) is the direct limit of the subgroup generated by the finite unions \( \bigcup_{j \in J} A_j \), where \( J \) ranges over the finite subsets of \( I \). Conversely, if

\[
A = \varinjlim_{i \in I} A_i
\]

is a direct limit of a direct system \( \{A_i, \varphi_{ij}, I\} \), and if \( \varphi_i : A_i \rightarrow A \) are the canonical maps, then

\[
A = \bigcup_{i \in I} \varphi_i(A_i).
\]

(2) Every abelian group \( A \) is a direct limit of its finitely generated subgroups. In particular, if \( A \) is torsion, it is the direct limit of its finite subgroups.

(3) Let \( p \) be a prime number. We use the notation \( C_{p^{\infty}} \) for the \( p \)-quasicyclic or Prüfer group, i.e., the group of \( p^n \)th complex roots of unity, with \( n \) running over all non-negative integers. Equivalently, \( C_{p^{\infty}} \) can be defined as the direct limit

\[
C_{p^{\infty}} = \varinjlim_{n} C_{p^n},
\]

of the direct system of cyclic groups \( \{C_{p^n}, \varphi_{nm}\} \), where the homomorphism \( \varphi_{nm} : C_{p^n} \rightarrow C_{p^m} \), defined for \( n \leq m \), is the natural injection. A map

\[
\Psi : \{A_i, \varphi_{ij}, I\} \rightarrow \{A'_i, \varphi'_{ij}, I\}
\]
of direct systems \( \{A_i, \varphi_{ij}, I\} \) and \( \{A'_i, \varphi'_{ij}, I\} \) over the same directed poset \( I \) consists of a collection of homomorphisms

\[
\psi_i : A_i \longrightarrow A'_i \quad (i \in I)
\]

that commute with the canonical maps \( \varphi_{ij} \) and \( \varphi'_{ij} \). That is, whenever \( i \preceq j \), we have a commuting square

\[
\begin{array}{ccc}
A_i & \xrightarrow{\varphi_{ij}} & A_j \\
\psi_i \downarrow & & \downarrow \psi_j \\
A'_i & \xrightarrow{\varphi'_{ij}} & A'_j \\
\end{array}
\]

We refer to the homomorphisms \( \psi_{ij} \) as the \textit{components} of the map \( \Psi \).

Direct systems of abelian groups over a fixed poset \( I \) together with their maps, as defined above, form in a natural way a category. (This category is in fact an abelian category; although the analogous category of direct systems of sets, say, is not abelian.)

Let

\[
\{A_i, \varphi_{ij}, I\} \quad \text{and} \quad \{A'_i, \varphi'_{ij}, I\}
\]

be direct systems over the same poset \( (I, \preceq) \), and let

\[
A = \lim_{\rightarrow} A_i \quad \text{and} \quad A' = \lim_{\rightarrow} A'_i
\]

be their corresponding direct limits, with canonical maps \( \varphi_i : A_i \longrightarrow A \) and \( \varphi'_i : A'_i \longrightarrow A' \), respectively. Associated with each map

\[
\Psi = \{\psi_i\} : \{A_i, \varphi_{ij}, I\} \longrightarrow \{A'_i, \varphi'_{ij}, I\}
\]

of direct systems, there is a homomorphism

\[
\lim \Psi = A \longrightarrow A'
\]

defined by the universal property of direct limits:

\[
\lim \Psi = \lim_{i \in I} \psi_i.
\]

This is the unique homomorphism induced by the compatible maps

\[
\varphi'_i \psi_i : A_i \longrightarrow A' \quad (i \in I).
\]

With these definitions, it is straightforward to verify that \( \lim (\Psi \Psi') = \lim (\Psi) \lim (\Psi') \) and \( \lim (\id_{\{A_i, \varphi_{ij}, I\}}) = \id \lim A_i \); in other words, \( \lim \) is a functor from the category of direct systems of abelian groups over the same poset, to the category of abelian groups.

We restate all this as part of the following proposition.
Proposition 1.2.6 Let $I$ be a fixed poset. Then the collection $\mathcal{D}$ of all direct systems of abelian groups over $I$ and their maps form an abelian category. Furthermore, $\lim_{\to}$ is an exact (covariant) functor from $\mathcal{D}$ to the category of abelian groups.

The proof of this proposition follows easily from repeated applications of Proposition 1.2.4; we leave the details to the reader.

1.3 Notes, Comments and Further Reading

The material in this chapter is standard. For more details on inverse and direct limits the reader may consult, e.g., Eilenberg and Steenrod [1952], Bourbaki [1989] or Fuchs [1970].
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