

An introduction to condensed mathematics
(after Dustin Clausen and Peter Scholze)
– Teaser –
(Rennes – 2024)

Bernard Le Stum

Université de Rennes 1

January 10, 2024

Abelian groups

Abelian groups

Let M and N be two abelian groups.

Abelian groups

Let M and N be two abelian groups. If we are given a homomorphism $f : M \rightarrow N$, we can then consider its **kernel**

Abelian groups

Let M and N be two abelian groups. If we are given a homomorphism $f : M \rightarrow N$, we can then consider its **kernel**

$$\ker f := \{s \in M \mid f(s) = 0\} \subset M$$

Abelian groups

Let M and N be two abelian groups. If we are given a homomorphism $f : M \rightarrow N$, we can then consider its **kernel**

$$\ker f := \{s \in M / f(s) = 0\} \subset M$$

and **image**

Abelian groups

Let M and N be two abelian groups. If we are given a homomorphism $f : M \rightarrow N$, we can then consider its **kernel**

$$\ker f := \{s \in M / f(s) = 0\} \subset M$$

and **image**

$$\operatorname{im} f := \{f(s) : s \in M\} \subset N.$$

Abelian groups

Let M and N be two abelian groups. If we are given a homomorphism $f : M \rightarrow N$, we can then consider its **kernel**

$$\ker f := \{s \in M / f(s) = 0\} \subset M$$

and **image**

$$\operatorname{im} f := \{f(s) : s \in M\} \subset N.$$

This is because abelian groups satisfy AB1 (pre-abelian category).

Abelian groups

Let M and N be two abelian groups. If we are given a homomorphism $f : M \rightarrow N$, we can then consider its **kernel**

$$\ker f := \{s \in M / f(s) = 0\} \subset M$$

and **image**

$$\operatorname{im} f := \{f(s) : s \in M\} \subset N.$$

This is because abelian groups satisfy AB1 (pre-abelian category). A celebrated theorem of Emmy Noether states that f induces an isomorphism

$$\bar{f} : M/\ker(f) \simeq \operatorname{im}(f).$$

Abelian groups

Let M and N be two abelian groups. If we are given a homomorphism $f : M \rightarrow N$, we can then consider its **kernel**

$$\ker f := \{s \in M \mid f(s) = 0\} \subset M$$

and **image**

$$\operatorname{im} f := \{f(s) \mid s \in M\} \subset N.$$

This is because abelian groups satisfy AB1 (pre-abelian category). A celebrated theorem of Emmy Noether states that f induces an isomorphism

$$\bar{f} : M/\ker(f) \simeq \operatorname{im}(f).$$

This is because abelian groups satisfy AB2 (abelian category).

Abelian groups

Let M and N be two abelian groups. If we are given a homomorphism $f : M \rightarrow N$, we can then consider its **kernel**

$$\ker f := \{s \in M / f(s) = 0\} \subset M$$

and **image**

$$\operatorname{im} f := \{f(s) : s \in M\} \subset N.$$

This is because abelian groups satisfy AB1 (pre-abelian category). A celebrated theorem of Emmy Noether states that f induces an isomorphism

$$\bar{f} : M/\ker(f) \simeq \operatorname{im}(f).$$

This is because abelian groups satisfy AB2 (abelian category). Actually, they even satisfy up to AB6 (and dually AB4*).

Topological abelian groups

Topological abelian groups

Let X be a topological space.

Topological abelian groups

Let X be a topological space. Then, any subset Y of X inherits a topology (the **induced** topology).

Topological abelian groups

Let X be a topological space. Then, any subset Y of X inherits a topology (the **induced** topology). Also, if we are given an equivalence relation R on X , then X/R inherits a topology (the **quotient** topology).

Topological abelian groups

Let X be a topological space. Then, any subset Y of X inherits a topology (the **induced** topology). Also, if we are given an equivalence relation R on X , then X/R inherits a topology (the **quotient** topology).

A **topological abelian group** is a topological space M endowed with a commutative group law which is continuous as well as the inverse mapping.

Topological abelian groups

Let X be a topological space. Then, any subset Y of X inherits a topology (the **induced** topology). Also, if we are given an equivalence relation R on X , then X/R inherits a topology (the **quotient** topology).

A **topological abelian group** is a topological space M endowed with a commutative group law which is continuous as well as the inverse mapping. A **morphism of topological abelian groups** is a continuous homomorphism $f : M \rightarrow N$.

Topological abelian groups

Let X be a topological space. Then, any subset Y of X inherits a topology (the **induced** topology). Also, if we are given an equivalence relation R on X , then X/R inherits a topology (the **quotient** topology).

A **topological abelian group** is a topological space M endowed with a commutative group law which is continuous as well as the inverse mapping. A **morphism of topological abelian groups** is a continuous homomorphism $f : M \rightarrow N$. Both $\ker f$ and $\operatorname{im} f$ inherit the structure of a topological abelian group.

Topological abelian groups

Let X be a topological space. Then, any subset Y of X inherits a topology (the **induced** topology). Also, if we are given an equivalence relation R on X , then X/R inherits a topology (the **quotient** topology).

A **topological abelian group** is a topological space M endowed with a commutative group law which is continuous as well as the inverse mapping. A **morphism of topological abelian groups** is a continuous homomorphism $f : M \rightarrow N$. Both $\ker f$ and $\operatorname{im} f$ inherit the structure of a topological abelian group. In other words, topological abelian groups satisfy AB1 (pre-abelian).

Topological abelian groups

Let X be a topological space. Then, any subset Y of X inherits a topology (the **induced** topology). Also, if we are given an equivalence relation R on X , then X/R inherits a topology (the **quotient** topology).

A **topological abelian group** is a topological space M endowed with a commutative group law which is continuous as well as the inverse mapping. A **morphism of topological abelian groups** is a continuous homomorphism $f : M \rightarrow N$. Both $\ker f$ and $\operatorname{im} f$ inherit the structure of a topological abelian group. In other words, topological abelian groups satisfy AB1 (pre-abelian). However, the morphism

Topological abelian groups

Let X be a topological space. Then, any subset Y of X inherits a topology (the **induced** topology). Also, if we are given an equivalence relation R on X , then X/R inherits a topology (the **quotient** topology).

A **topological abelian group** is a topological space M endowed with a commutative group law which is continuous as well as the inverse mapping. A **morphism of topological abelian groups** is a continuous homomorphism $f : M \rightarrow N$. Both $\ker f$ and $\operatorname{im} f$ inherit the structure of a topological abelian group. In other words, topological abelian groups satisfy AB1 (pre-abelian). However, the morphism

$$\bar{f} : M/\ker(f) \simeq \operatorname{im}(f)$$

Topological abelian groups

Let X be a topological space. Then, any subset Y of X inherits a topology (the **induced** topology). Also, if we are given an equivalence relation R on X , then X/R inherits a topology (the **quotient** topology).

A **topological abelian group** is a topological space M endowed with a commutative group law which is continuous as well as the inverse mapping. A **morphism of topological abelian groups** is a continuous homomorphism $f : M \rightarrow N$. Both $\ker f$ and $\operatorname{im} f$ inherit the structure of a topological abelian group. In other words, topological abelian groups satisfy AB1 (pre-abelian). However, the morphism

$$\bar{f} : M/\ker(f) \simeq \operatorname{im}(f)$$

is **not** a homeomorphism in general.

Topological abelian groups

Let X be a topological space. Then, any subset Y of X inherits a topology (the **induced** topology). Also, if we are given an equivalence relation R on X , then X/R inherits a topology (the **quotient** topology).

A **topological abelian group** is a topological space M endowed with a commutative group law which is continuous as well as the inverse mapping. A **morphism of topological abelian groups** is a continuous homomorphism $f : M \rightarrow N$. Both $\ker f$ and $\operatorname{im} f$ inherit the structure of a topological abelian group. In other words, topological abelian groups satisfy AB1 (pre-abelian). However, the morphism

$$\bar{f} : M/\ker(f) \simeq \operatorname{im}(f)$$

is **not** a homeomorphism in general. In other words, topological abelian groups do **not** satisfy AB2 (not abelian).

Condensed abelian groups

Condensed abelian groups

This is however the case for **compact Hausdorff** abelian groups.

Condensed abelian groups

This is however the case for **compact Hausdorff** abelian groups. Unfortunately, an infinite discrete abelian group like \mathbb{Z} or a non-trivial Banach space like \mathbb{R} are not compact.

Condensed abelian groups

This is however the case for **compact Hausdorff** abelian groups. Unfortunately, an infinite discrete abelian group like \mathbb{Z} or a non-trivial Banach space like \mathbb{R} are not compact.

The **trick** consists in considering the category of all compact Hausdorff spaces.

Condensed abelian groups

This is however the case for **compact Hausdorff** abelian groups. Unfortunately, an infinite discrete abelian group like \mathbb{Z} or a non-trivial Banach space like \mathbb{R} are not compact.

The **trick** consists in considering the category of all compact Hausdorff spaces. They form what is called a **pretopos** (a very stable category).

Condensed abelian groups

This is however the case for **compact Hausdorff** abelian groups. Unfortunately, an infinite discrete abelian group like \mathbb{Z} or a non-trivial Banach space like \mathbb{R} are not compact.

The **trick** consists in considering the category of all compact Hausdorff spaces. They form what is called a **pretopos** (a very stable category). Then, a **condensed abelian group** is a sheaf \mathcal{M} on this pretopos (for the subcanonical topology).

Condensed abelian groups

This is however the case for **compact Hausdorff** abelian groups. Unfortunately, an infinite discrete abelian group like \mathbb{Z} or a non-trivial Banach space like \mathbb{R} are not compact.

The **trick** consists in considering the category of all compact Hausdorff spaces. They form what is called a **pretopos** (a very stable category). Then, a **condensed abelian group** is a sheaf \mathcal{M} on this pretopos (for the subcanonical topology).

In down to earth terms, a **condensed abelian group** is the data of an abelian group $\mathcal{M}(S)$ for any compact Hausdorff space S and a compatible family of homomorphisms $\mathcal{M}(S) \rightarrow \mathcal{M}(S')$ for any continuous map $S' \rightarrow S$.

Condensed abelian groups

This is however the case for **compact Hausdorff** abelian groups. Unfortunately, an infinite discrete abelian group like \mathbb{Z} or a non-trivial Banach space like \mathbb{R} are not compact.

The **trick** consists in considering the category of all compact Hausdorff spaces. They form what is called a **pretopos** (a very stable category). Then, a **condensed abelian group** is a sheaf \mathcal{M} on this pretopos (for the subcanonical topology).

In down to earth terms, a **condensed abelian group** is the data of an abelian group $\mathcal{M}(S)$ for any compact Hausdorff space S and a compatible family of homomorphisms $\mathcal{M}(S) \rightarrow \mathcal{M}(S')$ for any continuous map $S' \rightarrow S$.

It is subject to the following conditions:

1. $\mathcal{M}(\emptyset) = 0,$

1. $\mathcal{M}(\emptyset) = 0$,
2. If $S \cap S' = \emptyset$, then $\mathcal{M}(S \cup S') = \mathcal{M}(S) \oplus \mathcal{M}(S')$,

1. $\mathcal{M}(\emptyset) = 0$,
2. If $S \cap S' = \emptyset$, then $\mathcal{M}(S \cup S') = \mathcal{M}(S) \oplus \mathcal{M}(S')$,
3. If R is a closed equivalence relation on S , then

1. $\mathcal{M}(\emptyset) = 0$,
2. If $S \cap S' = \emptyset$, then $\mathcal{M}(S \cup S') = \mathcal{M}(S) \oplus \mathcal{M}(S')$,
3. If R is a closed equivalence relation on S , then

$$\mathcal{M}(S/R) \simeq \ker(\mathcal{M}(S) \rightarrow \mathcal{M}(R)).$$

1. $\mathcal{M}(\emptyset) = 0$,
2. If $S \cap S' = \emptyset$, then $\mathcal{M}(S \cup S') = \mathcal{M}(S) \oplus \mathcal{M}(S')$,
3. If R is a closed equivalence relation on S , then

$$\mathcal{M}(S/R) \simeq \ker(\mathcal{M}(S) \rightarrow \mathcal{M}(R)).$$

As an example, if M is topological abelian group, then setting $\mathcal{M}(S) := \mathcal{C}(S, M)$ defines a condensed abelian group.

1. $\mathcal{M}(\emptyset) = 0$,
2. If $S \cap S' = \emptyset$, then $\mathcal{M}(S \cup S') = \mathcal{M}(S) \oplus \mathcal{M}(S')$,
3. If R is a closed equivalence relation on S , then

$$\mathcal{M}(S/R) \simeq \ker(\mathcal{M}(S) \rightarrow \mathcal{M}(R)).$$

As an example, if M is topological abelian group, then setting $\mathcal{M}(S) := \mathcal{C}(S, M)$ defines a condensed abelian group. Actually it is equivalent to give M or \mathcal{M} as long as M is compactly (Hausdorff) generated.

1. $\mathcal{M}(\emptyset) = 0$,
2. If $S \cap S' = \emptyset$, then $\mathcal{M}(S \cup S') = \mathcal{M}(S) \oplus \mathcal{M}(S')$,
3. If R is a closed equivalence relation on S , then

$$\mathcal{M}(S/R) \simeq \ker(\mathcal{M}(S) \rightarrow \mathcal{M}(R)).$$

As an example, if M is topological abelian group, then setting $\mathcal{M}(S) := \mathcal{C}(S, M)$ defines a condensed abelian group. Actually it is equivalent to give M or \mathcal{M} as long as M is compactly (Hausdorff) generated. This is the case for example if M locally compact Hausdorff or if it is a metric space (and in particular if M is a normed vector space).

1. $\mathcal{M}(\emptyset) = 0$,
2. If $S \cap S' = \emptyset$, then $\mathcal{M}(S \cup S') = \mathcal{M}(S) \oplus \mathcal{M}(S')$,
3. If R is a closed equivalence relation on S , then

$$\mathcal{M}(S/R) \simeq \ker(\mathcal{M}(S) \rightarrow \mathcal{M}(R)).$$

As an example, if M is topological abelian group, then setting $\mathcal{M}(S) := \mathcal{C}(S, M)$ defines a condensed abelian group. Actually it is equivalent to give M or \mathcal{M} as long as M is compactly (Hausdorff) generated. This is the case for example if M locally compact Hausdorff or if it is a metric space (and in particular if M is a normed vector space).

Condensed abelian groups satisfy AB2 (abelian).

1. $\mathcal{M}(\emptyset) = 0$,
2. If $S \cap S' = \emptyset$, then $\mathcal{M}(S \cup S') = \mathcal{M}(S) \oplus \mathcal{M}(S')$,
3. If R is a closed equivalence relation on S , then

$$\mathcal{M}(S/R) \simeq \ker(\mathcal{M}(S) \rightarrow \mathcal{M}(R)).$$

As an example, if M is topological abelian group, then setting $\mathcal{M}(S) := \mathcal{C}(S, M)$ defines a condensed abelian group. Actually it is equivalent to give M or \mathcal{M} as long as M is compactly (Hausdorff) generated. This is the case for example if M locally compact Hausdorff or if it is a metric space (and in particular if M is a normed vector space).

Condensed abelian groups satisfy AB2 (abelian). Actually, they even satisfy up to AB6 and AB4* exactly like usual abelian groups do (Clausen/Scholze).

Program

Program

1. Some category theory (quick review),

Program

1. Some category theory (quick review),
2. Some topology related to compact Hausdorff spaces,

Program

1. Some category theory (quick review),
2. Some topology related to compact Hausdorff spaces,
3. The notions of sheaf and topos,

Program

1. Some category theory (quick review),
2. Some topology related to compact Hausdorff spaces,
3. The notions of sheaf and topos,
4. Condensed sets,

Program

1. Some category theory (quick review),
2. Some topology related to compact Hausdorff spaces,
3. The notions of sheaf and topos,
4. Condensed sets,
5. Abelian categories (quick review),

Program

1. Some category theory (quick review),
2. Some topology related to compact Hausdorff spaces,
3. The notions of sheaf and topos,
4. Condensed sets,
5. Abelian categories (quick review),
6. Condensed abelian groups,

Program

1. Some category theory (quick review),
2. Some topology related to compact Hausdorff spaces,
3. The notions of sheaf and topos,
4. Condensed sets,
5. Abelian categories (quick review),
6. Condensed abelian groups,
7. Homological algebra (hopefully),

Program

1. Some category theory (quick review),
2. Some topology related to compact Hausdorff spaces,
3. The notions of sheaf and topos,
4. Condensed sets,
5. Abelian categories (quick review),
6. Condensed abelian groups,
7. Homological algebra (hopefully),
8. Cohomology of condensed abelian groups (hopefully).

Program

1. Some category theory (quick review),
2. Some topology related to compact Hausdorff spaces,
3. The notions of sheaf and topos,
4. Condensed sets,
5. Abelian categories (quick review),
6. Condensed abelian groups,
7. Homological algebra (hopefully),
8. Cohomology of condensed abelian groups (hopefully).

The students should be comfortable with the basics of category theory from the first semester course of Matthieu.

Program

1. Some category theory (quick review),
2. Some topology related to compact Hausdorff spaces,
3. The notions of sheaf and topos,
4. Condensed sets,
5. Abelian categories (quick review),
6. Condensed abelian groups,
7. Homological algebra (hopefully),
8. Cohomology of condensed abelian groups (hopefully).

The students should be comfortable with the basics of category theory from the first semester course of Matthieu.

– Thank you –