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Abstract. Lattice structures are fundamental and useful in mathematics and theoretical computer science. It is well-known that lattice structures with meet and join operations satisfying associative, commutative and absorption laws are equivalent to lattice structures defined by ordering relations having joins and meets. This note defines a notion of lattices in Dedekind categories and studies on some basic properties on lattice structures with element-free discussion using relational calculi.

Keywords: lattice, Dedekind category, allegory, relational calculus.

1 Introduction

A lattice is a triple \((X, \vee, \wedge)\) of a set \(X\) and two functions \(\vee: X \times X \to X\) and \(\wedge: X \times X \to X\) satisfying:

- Associative Law: \((L1)\) \((x \vee y) \vee z = x \vee (y \vee z)\) and \((L1\wedge)\) \((x \wedge y) \wedge z = x \wedge (y \wedge z)\)
- Commutative Law: \((L2)\) \(x \vee y = y \vee x\) and \((L2\wedge)\) \(x \wedge y = y \wedge x\)
- Absorption Law: \((L3)\) \(x \wedge (x \vee y) = x\) and \((L3\wedge)\) \(x \vee (x \wedge y) = x\)

for all elements \(x, y\) and \(z\) of \(X\). It is well-known that a lattice \((X, \vee, \wedge)\) has a natural ordering \(\leq\) defined by \(x \leq y\) for \(x, y \in X\) iff \(x \vee y = y\). Demonstrating this fact is good exercise for undergraduate students. In detail it mainly consists of checking that the ordering \(\leq\) is in fact reflexive, transitive and antisymmetric, and that it has a few alternative definitions such as \(x \leq y\) iff \(x \wedge y = x\). Conversely, it is also well-known that the concept of lattices is obtained from ordered sets with joins and meets.

The motivation of this note is just to demonstrate these facts in categories [4]. To discuss binary operations such as \(\vee: X \times X \to X\) and \(\wedge: X \times X \to X\) the involved category needs to have (finite) cartesian products. Furthermore the category has to be equipped a kind of relational structures, as we treat with an ordering within it. This is a reason why categorical lattice theory is formalized in Dedekind categories [5]. The modern algebraic theory of binary relations was founded by Tarski [7], and the categorical study for relations was initiated by Mac Lane [3]. Thought Dedekind categories in this note are synonymous as allegories due to Freyd and Scedrov [1] and heterogeneous relation algebras by Schmidt and Ströhlein [6], the author adopt Dedekind categories after the historical emergence in literatures. The note is organized as follows:

In section 2 we define Dedekind categories and relational products, and review
some fundamentals on Dedekind categories. In section 3 a notion of lattices in Dedekind categories is defined, and some basic facts on a natural partial ordering on a lattice in a Dedekind category are investigated. In section 4 we try to construct a lattice from a partial ordering with joins and meets in a Dedekind category.

2 Dedekind Categories

In this section we recall the fundamentals on relation categories, which we will call elementary Dedekind categories.

Throughout this note, a morphism $\alpha$ from an object $X$ into an object $Y$ in a Dedekind category (which will be defined below) will be denoted by a half arrow $\alpha : X \rightarrow Y$, and the composite of a morphism $\alpha : X \rightarrow Y$ followed by a morphism $\beta : Y \rightarrow Z$ will be written as $\alpha \beta : X \rightarrow Z$. Also we will denote the identity morphism on $X$ as $\text{id}_X$.

**Definition 2.1.** A Dedekind category $\mathcal{D}$ is a category satisfying the following:

D1. [Distributive Lattice] For all pairs of objects $X$ and $Y$ the hom-set $\mathcal{D}(X,Y)$ consisting of all morphisms of $X$ into $Y$ is a distributive lattice with the least morphism $0_{XY}$ and the greatest morphism $\nabla_{XY}$. Its lattice structure will be denoted by

$$ \mathcal{D}(X,Y) = (\mathcal{D}(X,Y), \sqcap, \sqcup, \sqcap_{XY}, \nabla_{XY}). $$

D2. [Converse] There is given a converse operation $\check{} : \mathcal{D}(X,Y) \rightarrow \mathcal{D}(Y,X)$. That is, for all morphisms $\alpha, \alpha' : X \rightarrow Y$, $\beta : Y \rightarrow Z$, the following converse laws hold:

(a) $(\alpha \beta)^\check{} = \beta^\check{} \alpha^\check{}$, (b) $(\alpha^\check{})^\check{} = \alpha$, (c) If $\alpha \subseteq \alpha'$, then $\alpha^\check{} \subseteq \alpha'^\check{}$

for all morphisms $\alpha, \alpha' : X \rightarrow Y$ and $\beta : Y \rightarrow Z$.

D3. [Dedekind Formula] For all morphisms $\alpha : X \rightarrow Y$, $\beta : Y \rightarrow Z$ and $\gamma : Z \rightarrow Y$ the Dedekind formula $\alpha \beta \cap \gamma \subseteq \alpha (\beta \cap \alpha \check{} \gamma)$ holds.

D4. [Residues] For all morphisms $\beta : Y \rightarrow Z$ and $\gamma : X \rightarrow Z$ the residue (or division) $\gamma = \beta : X \rightarrow Y$ is a morphism such that $\alpha \beta \subseteq \gamma$ if and only if $\alpha \subseteq \gamma \check{}$ for all morphisms $\alpha : X \rightarrow Y$.

The following is a basic property of Dedekind categories, which will be repeatedly used in this paper.

**Proposition 2.1.** Let $\alpha, \alpha' : X \rightarrow Y$ and $\beta, \beta' : Y \rightarrow Z$ be morphisms in a Dedekind category. If $\alpha \subseteq \alpha'$ and $\beta \subseteq \beta'$, then $\alpha \beta \subseteq \alpha' \beta'$.

Proof. Assume $\alpha \subseteq \alpha'$ and $\beta \subseteq \beta'$. First we will see $\alpha \beta \subseteq \alpha' \beta'$. The characteristic property of residues leads $\alpha' \subseteq \alpha' \beta \check{} \beta$ from the reflexivity $\alpha' \beta \subseteq \alpha' \beta$. 


Hence we have \( \alpha \subseteq a' \beta \perp \beta \) by the assumption \( \alpha \subseteq a' \), and so \( \alpha \beta \subseteq \alpha' \beta \) again by the characteristic property of residues. Finally we will see \( \alpha \beta \subseteq \alpha \beta' \).

As \( \beta \perp \beta' \) by D2(c), the former result shows \( \beta' \alpha \perp \beta' \alpha \perp \beta \) and so we have 

\[
\alpha \beta = (\beta' \alpha')^2 \subseteq \beta' \alpha ^2 = \alpha \beta'
\]

by D2(a)-(c).

\[\square\]

More details on fundamental properties of relational categories is referred to [2]. The following is a basic lemma [1] in Dedekind categories.

**Lemma 2.1.** For two relations \( \alpha : X \rightarrow Y \) and \( \beta : Y \rightarrow X \) an equality

\[
\text{id}_X \cap (\alpha \cap \beta ^2)(\alpha \cap \beta ) = \text{id}_X \cap \alpha \beta
\]

holds.

**Proof.**

\[
\begin{align*}
\text{id}_X \cap \alpha \beta &= \text{id}_X \cap \text{id}_X \cap \alpha \beta \\
&\subseteq \text{id}_X \cap (\text{id}_X \cap \alpha \beta) (\alpha \cap \beta \cap \beta) \quad \{ \text{Dedekind Formula} \} \\
&= \text{id}_X \cap (\alpha \cap \beta ^2 \cap \beta \cap \beta) \\
&\subseteq \text{id}_X \cap \alpha \beta.
\end{align*}
\]

\[\square\]

A morphism \( f : X \rightarrow Y \) such that \( f^2 \cap \text{id}_Y \) (univalent) and \( \text{id}_X \subseteq f^2 \cap \text{id}_Y \) (total) is called a function and may be introduced as \( f : X \rightarrow Y \).

**Corollary 2.1.** Let \( \alpha : X \rightarrow Y \) and \( \beta : Y \rightarrow X \) be relations in a Dedekind category \( \mathcal{D} \). If \( \alpha \beta = \text{id}_X \) and \( \beta \alpha = \text{id}_Y \), then \( \alpha = \beta \).

**Proof.** As \( \alpha \beta = \text{id}_X \) we have \( \text{id}_X = \text{id}_X \cap \alpha \beta = \text{id}_X \cap (\alpha \cap \beta ^2) \cap \beta \) by Lemma 2.1. Hence \( \text{id}_X \subseteq \alpha \beta \) and \( \text{id}_X \subseteq \beta ^2 \). Also it follows from \( \text{id}_X \subseteq \alpha \beta \) and \( \beta \alpha = \text{id}_Y \) that \( \beta \beta ^2 \subseteq \beta ^2 \alpha \beta ^2 = \beta ^2 \alpha = \alpha \beta = \text{id}_X \).

Therefore \( \beta ^2 \beta = \text{id}_X \) and so \( \beta ^2 \beta \alpha = \alpha \) from \( \beta \alpha = \text{id}_Y \).

\[\square\]

**Definition 2.2.** A Dedekind category \( \mathcal{D} \) has relational products if for each pair of objects \( A \) and \( B \) there is a pair of functions \( p : A \times B \rightarrow A \) and \( q : A \times B \rightarrow B \) such that \( p^2 q = \nabla_{AB} \) and \( pp^2 \cap qq^2 = \text{id}_{A \times B} \). The functions \( p \) and \( q \) will be called a pair of projections of relational products.

Throughout the rest of the note we assume that \( \mathcal{D} \) is a fixed Dedekind category with relational products.

**Proposition 2.2.** Let \( p : A \times B \rightarrow A \) and \( q : A \times B \rightarrow B \) be a pair of projections of \( A \times B \). For each pair of functions \( f : X \rightarrow A \) and \( g : X \rightarrow B \), a relation \( f \upharpoonright g = \{ p \} \cap \{ q \} : X \rightarrow A \times B \) is a unique function such that \( (f \upharpoonright g) p = f \) and \( (f \upharpoonright g) q = g \).
Proof. Set \( h = f \uplus g \). The univalency (or, single-valuedness) of \( h \) simply follows from
\[
h^2h = (pf^2 \sqcap gg^2)(fp^2 \sqcap gg^2)
\]
\[
= (pf^2 \sqcap gg^2)(fp^2 \sqcap g^2)
\]
\[
\sqsubseteq pf^2 fp^2 \sqcap g^2 gg^2
\]
\[
\sqsubseteq pf^2 \sqcap gg^2 \quad \text{(by } f^2 f \sqsubseteq \text{id}_A \text{ and } g^2 g \sqsubseteq \text{id}_B\}
\]
\[
= \text{id}_{A \times B}.
\]
Also the totality of \( h \) comes from
\[
\text{id}_X \sqcap hh^2 = \text{id}_X \sqcap (pf^2 \sqcap gg^2)(fp^2 \sqcap g^2)^2
\]
\[
= \text{id}_X \sqcap (pf^2)(g^2)^2 \quad \{ \text{Lemma 2.1 } \}
\]
\[
= \text{id}_X \sqcap ff^2 gg^4
\]
\[
\sqsubseteq \text{id}_X \sqcap ff^2 \quad \{ f^2 g \sqsubseteq \nabla AB = p^2 q \}
\]
\[
= \text{id}_X \quad \{ \text{id}_X \sqsubseteq ff^2 \text{ and } \text{id}_X \sqsubseteq gg^4 \}
\]
The uniqueness of \( h \) follows from \( h = h \text{id}_{A \times B} = h(pf^2 \sqcap qq^2) = hpp^2 \sqcap hq^2 \).
\( \square \)

Remark. It is trivial that \( p \uplus q = \text{id}_{A \times B} \).

Corollary 2.2. For a function \( k : X \to A \) an equality \( k(f \uplus g) = kf \uplus kg \) holds.
\( \square \)

Proposition 2.3. Let \( p_{AB} : A \times B \to A \) and \( q_{AB} : A \times B \to B \) be a pair of projections of \( A \times B \), and \( p_{BA} : B \times A \to B \) and \( q_{BA} : B \times B \to B \) a pair of projections of \( B \times A \). The twist function \( t_{AB} : A \times B \to B \times A \) is defined as the unique function such that \( t_{AB}p_{BA} = q_{AB} \) and \( t_{AB}q_{BA} = p_{AB} \). (That is, \( t_{AB} = q_{AB}p_{BA} \sqcap p_{AB}q_{BA}^\uplus = q_{AB} \uplus p_{AB} \).) Then \( t_{AB}t_{BA} = \text{id}_{A \times B} \) and \( t_{BA}t_{AB} = \text{id}_{B \times A} \).

Proof. By Proposition 2.2 we have
\[
t_{AB}t_{BA} = t_{AB}(q_{BA} \sqcap p_{BA}) = t_{AB}q_{BA} \sqcap t_{AB}p_{BA} = p_{AB} \sqcap q_{AB} = \text{id}_{A \times B}.
\]
\( \square \)

In general the pair of projections will be denoted by \( p_{AB} : A \times B \to A \) and \( q_{AB} : A \times B \to B \). The diagonal function \( d_A : A \to A \times A \) is defined as a unique function such that \( d_A p_{AA} = \text{id}_A \) and \( d_A q_{AA} = \text{id}_A \). That is, \( d_A = \text{id}_A \uplus \text{id}_A = p_{AA} \sqcap q_{AA} \). The associative function \( a_{ABC} : (A \times B) \times C \to A \times (B \times C) \) is defined by
\[
a_{ABC} = p_{A \times BC} \sqcap (p_{A \times BC}q_{AB} \uplus q_{A \times BC})
\]
Another associative function \( b_{ABC} : A \times (B \times C) \to (A \times B) \times C \) is defined by
\[
b_{ABC} = (p_{AB} \times C \sqcup q_{ABC} \times C) \sqcap q_{ABC} \times C.
\]
It is trivial that $a_{ABC}$ and $b_{ABC}$ are mutually inverses, that is, $a_{ABC}b_{ABC} = id_{(A \times B) \times C}$ and $b_{ABC}a_{ABC} = id_{A \times (B \times C)}$.

For a pair of functions $f : A \to X$ and $g : B \to Y$ we define a function $f \times g : A \times B \to X \times Y$ by $f \times g = p_{AB}f \triangleleft q_{AB}g (= p_{AB}f \sqcup q_{AB}g q_{XY}^2)$. That is, $f \times g$ is a unique function such that $(f \times g)p_{XY} = p_{AB}f$ and $(f \times g)q_{XY} = q_{AB}g$.

$$\begin{align*}
A &\xrightarrow{f} X \\
\times &\xrightarrow{g} Y
\end{align*}$$

The following lemma indicates a well-known example of pullbacks.

**Lemma 2.2.** An equality $p_{AB}^2(f \times id_B) = fp_{XB}^1$ holds for every function $f : A \to B$.

**Proof.** Note that $p_{AB}^2 q_{AB}q_{XB}^1 = \nabla_{AB} q_{XB}^2 = \nabla_{AX \times B}$ by $p_{AB}^2 q_{AB} = q_{AB}$ and the totality of $q_{XB}$. ($\nabla_{AX \times B} \subseteq \nabla_{AX \times B} q_{XB}^1 \subseteq \nabla_{AX \times B} q_{XB}^2 = p_{AB}^2 q_{AB} q_{XB}^2$).

$$\begin{align*}
p_{AB}^2(f \times id_B) &= p_{AB}^2(p_{AB} f p_{XB}^1 q_{AB} q_{XB}^2) \\
&\subseteq p_{AB}^2 p_{AB} f p_{XB}^1 \\
&= f p_{XB}^1 \sqcup p_{AB}^2 q_{AB} q_{XB}^2 \\
&\subseteq p_{AB}^2(p_{AB} f p_{XB}^1 q_{AB} q_{XB}^2) \\
&= p_{AB}^2 f \times id_B
\end{align*}$$

$\square$

**Lemma 2.3.** Let $p : A \times B \to A$, $q : A \times B \to B$ and $p_0 : A \times B' \to A$, $q_0 : A \times B' \to B'$ be projections of products $A \times B$ and $A \times B'$, respectively. Then

(a) $\alpha = p^2(\alpha \cap q)$ for every relation $\alpha : A \to B$.
(b) If relations $\delta_0, \delta_1 : A \times B \to B$ satisfy $\delta_0 \subseteq q$ and $\delta_1 \subseteq q$, then $p^2 \delta_0 \cap p^2 \delta_1 = p^2(\delta_0 \cap \delta_1)$.
(c) If relations $\gamma_0, \gamma_1 : A \times B' \to A \times B$ satisfy $\gamma_0 \subseteq p_0 p^2$ and $\gamma_1 \subseteq p_0 p^2$, then $p_0^2 \gamma_0 \cap p_0^2 \gamma_1 = p_0^2(\gamma_0 \cap \gamma_1)$ and $\gamma_0 q \cap \gamma_1 q = (\gamma_0 \cap \gamma_1)q$.

**Proof.** (a) $\alpha = \alpha \cap p^2q \subseteq p^2(\alpha \cap q) \subseteq p^2 \alpha \subseteq \alpha$.
(b)
\[ p^i \delta_0 \sqcap p^i \delta_1 \sqsubseteq p^i (\delta_0 \sqcap p p^i \delta_1) \quad \text{[Dedekind Formula]}
= p^i (\delta_0 \sqcap p p^i \delta_1 \sqcap q) \quad \{ \delta_0 \sqsubseteq q \} 
\sqsubseteq p^i [\delta_0 \sqcap (p p^i \sqcap q \delta^i_1)] \quad \{ \delta_1 \sqsubseteq q \} 
\sqsubseteq p^i [\delta_0 \sqcap (p p^i \sqcap q q^i_1) \delta_1] \quad \{ \delta_1 \sqsubseteq q \} 
= p^i (\delta_0 \sqcap \delta_1). \quad \{ p p^i \sqcap q q^i = \text{id}_{A \times B} \} 
\]

(c)

\[ \gamma_0 q \sqcap \gamma_1 q \sqsubseteq (\gamma_0 \sqcap \gamma_1 q q^2)q \quad \text{[Dedekind Formula]}
= (\gamma_0 \sqcap p p^2 \sqcap \gamma_1 q q^2)q \quad \{ \gamma_0 \sqsubseteq p p^2 \} 
\sqsubseteq [\gamma_0 \sqcap \gamma_1 (\gamma_1 p p^2 \sqcap q q^2)]q \quad \text{[Dedekind Formula]}
\sqsubseteq [\gamma_0 \sqcap \gamma_1 (p p^2 \sqcap q q^2)]q \quad \{ \gamma_1 \sqsubseteq p p^2 \} 
\sqsubseteq [\gamma_0 \sqcap \gamma_1 (p p^2 \sqcap q q^2)]q \quad \{ p p^2 \sqcap q q^2 = \text{id}_{A \times B} \} 
= (\gamma_0 \sqcap \gamma_1)q. \quad \{ p p^2 \sqcap q q^2 = \text{id}_{A \times B} \} 
\]

\[ \Box \]

3 Lattices

In this section we will see that lattice structures with meet and join operations satisfying associative, commutative and absorption laws induce reflexive, transitive and antisymmetric relations. We will write \( p = p_{XX}, q = q_{XX}, \ t = t_{XX}, \ d = d_{XX}, \ a = a_{XXX} \) and \( b = b_{XXX} \).

**Definition 3.1.** A lattice in a Dedekind category \( D \) is a triple \((X, \lor, \land) \) of an object \( X \), and two functions (binary operations) \( \lor : X \times X \to X \) and \( \land : X \times X \to X \) satisfying

Associative Law:
\begin{align*}
(\text{L1} \lor) \quad & \lor \times \text{id}_X \lor = a(\text{id}_X \times \lor) \lor \\
& \{ (x \lor y) \lor z = x \lor (y \lor z) \}
\end{align*}
\begin{align*}
(\text{L1} \land) \quad & \land \times \text{id}_X \land = a(\text{id}_X \times \land) \land \\
& \{ (x \land y) \land z = x \land (y \land z) \}
\end{align*}

Commutative Law:
\begin{align*}
(\text{L2} \lor) \quad & t \lor = \lor \\
& \{ x \lor y = y \lor x \}
\end{align*}
\begin{align*}
(\text{L2} \land) \quad & t \land = \land \\
& \{ x \land y = y \land x \}
\end{align*}

Absorption Law:
\begin{align*}
(\text{L3} \lor) \quad & (p \lor \lor) \land = p \\
& \{ x \land (x \lor y) = x \}
\end{align*}
\begin{align*}
(\text{L3} \land) \quad & (p \lor \land) \lor = p \\
& \{ x \lor (x \land y) = x \}
\end{align*}

The above laws for lattices are illustrated by the following commutative diagrams:

\[ (\text{L1} \lor) \]
3 Lattices

$$(X \times X) \times X \xrightarrow{\vee \times \text{id}_X} X \times X$$

$$X \times (X \times X) \xrightarrow{\text{id}_X \times \vee} X \times X \xrightarrow{\vee} X$$

(L2\vee)

$$(X \times X) \times (X \times X) \xrightarrow{t} X \times X \xrightarrow{\vee} X$$

(L3\vee)

Recall $(p \top \vee)t = \top \vee p$ by the property of the twist function $t$ and so $(\top \vee p)\land = (p \top \vee)t\land = (p \top \vee)\land = p$ by (L2\land) and (L3\vee). Hence \((L3')\) $(\top \vee p)\land = p$ and $(L3' \land)$ $(\land \land)\vee = p$ are equivalent to (L3\vee) and (L3\land), respectively.

**Proposition 3.1.** An identity $d \vee = \text{id}_X$ holds in every lattice $(X, \vee, \land)$ in a Dedekind category.

Proof. First note that $d(p \top p) = dp \top dp = \text{id}_X \top \text{id}_X = d$ by Corollary 2.2. Hence

$$d \vee = d(p \top p) \vee$$

$= d\{ (p \top p) \top (p \top p) \}\vee$

$\quad = \{ (p \top p)p = p \text{ and (L3\vee)} \}$

$= \{ \text{Corollary 2.2} \}$

$= \{ (L3' \land) \}$

$= dp$

$\quad = \{ (p \top p)p = p \}$

$= \text{id}_X$

\[ \square \]

Define relations $\xi = p^i(q \cap \vee) : X \to X$ and $\eta = (p \cap \land)^2 q : X \to X$.

(For concrete relations: $\forall x, y \in X$, $x \xi y$ $\iff$ $y = x \lor y$ $\iff$ $x \leq y$, and $x \eta y$ $\iff$ $x = x \land y$ $\iff$ $x \leq y$.)

**Note.** It is easy to see the following basic fact on concrete lattices:

\[ (x, y) \in \xi = p^i(q \cap \vee) \]

$\iff \exists (x', y') : (x, (x', y')) \in p^i$ and $(x', y'), y) \in q \cap \vee$

$\iff \exists (x', y') : x = x'$ and $y' = y$ and $x' \lor y' = y$

$\iff x \lor y = y$. 

\[ \square \]
\[(x, y) \in p^q \quad \iff \quad \exists (x', y') :: (x, (x', y')) \in p^q \text{ and } ((x', y'), y) \in \forall \]
\[\iff \quad \exists y' :: y = x \forall y'.\]

\[(x, y) \in \eta = (p \cap \forall)^q \quad \iff \quad \exists (x', y') :: (x, (x', y')) \in (p \cap \forall)^q \text{ and } ((x', y'), y) \in q \]
\[\iff \quad \exists (x, y') :: x = x' \text{ and } x' \cap y' = x \text{ and } y' = y \quad \iff \quad x \cap y = x.\]

**Proposition 3.2.** Let \((X, \forall, \land)\) be a lattice in a Dedekind category and set \(
\xi = p^q \cap \forall : X \to X.\) Then an identity \(\text{id}_X \cap \forall \xi = \text{id}_X \cap \xi\) holds.

**Proof.**
\[
\text{id}_X \cap \xi = \text{id}_X \cap p^q \cap \forall \\
= \text{id}_X \cap (p \cap q \cap \forall)^t \quad \{ \text{Lemma 2.1} \} \\
= \text{id}_X \cap (p \cap q)^t \quad \{ \text{Lemma 2.1} \} \\
= \text{id}_X \cap \forall \xi. \\
\]

Combining with Propositions 3.1 and 3.1 we have the following

**Corollary 3.1.** Let \((X, \forall, \land)\) be a lattice in a Dedekind category. Then \(\xi = p^q \cap \forall : X \to X\) satisfies \(\text{id}_X \subseteq \xi \) (reflexive).

**Proposition 3.3.** Let \((X, \forall, \land)\) be a lattice in a Dedekind category. Then \(\xi = p^q \cap \forall : X \to X\) satisfies \(\xi \cap \xi^t \subseteq \text{id}_X\) (antisymmetric).

**Proof.**
\[
\xi \cap \xi^t = p^q \cap (q \cap \forall)^2 p \\
\subseteq (q \cap \forall)^t [(q \cap \forall)^2 p \cap p(q \cap \forall)^2] (q \cap \forall) \
\quad \{ \text{Dedekind Formula} \} \\
\subseteq \land^t [q \cap (q \cap \forall)^2 \land] (q \cap \forall) \\
\quad \{ \text{L2\forall} \} \\
\subseteq \land^t \land \quad \{ \text{t = pq} \land \} \\
\subseteq \text{id}_X. \\
\]

**Proposition 3.4.** Let \((X, \forall, \land)\) be a lattice in a Dedekind category, and set \(\xi = p^q \cap \forall : X \to X\) and \(\eta = (p \cap \land)^t q : X \to X.\) Then an identity \(\xi = p^q \land = \land^t q = \eta\) holds.
Proof. First note \( p = p \cap p = (p \lor \neg) p \cap (p \lor \neg) \lor = (p \lor \neg)(p \cap \lor) \) by (L3\lor) and Corollary 2.2. Hence

\[
\xi = p^2(q \cap \lor) \\
\subseteq p^2q \\
= [(p \lor \neg)(p \cap \lor)]^2(p \lor \neg)q \\
= (p \cap \lor)^2(p \lor \neg)q \\
\subseteq (p \cap \lor)^2 = \eta. \\
\]

Similarly it follows from \( p = p \cap p = (\lor \neg)p \cap (\lor \neg) \lor = (\lor \neg)(p \cap \lor) \lor \) by (L3\lor\lor), Proposition 2.2 and Corollary 2.2 and so \( q = tp = t(\lor \neg)(p \cap \lor) = (t \lor \neg tp)(p \cap \lor) = (\lor \neg q)(p \cap \lor) \lor \) by (L2\lor). Hence

\[
\eta = (p \cap \lor)^2q \\
\subseteq (\lor \neg)^2q \\
= [(\lor \neg q)p]^2(\lor \neg q)(p \cap \lor) \\
= q^2(\lor \neg q)(q \cap \lor) \\
\subseteq q^2(q \cap \lor) \\
= \xi. \\
\]

\[
\square
\]

**Proposition 3.5.** Let \((X, \lor, \land)\) be a lattice in a Dedekind category. Then \( \xi = p^2(q \cap \lor) : X \to X \) satisfies \( \xi \subseteq \xi \) (transitive).

Proof.

\[
\xi \xi = p^2 \lor p^2 \lor \\
= p^2p_0^{-1}(v \times \id_X) \lor \\
= p^2p_0^{-1}a(id_X \times v) \lor \\
= p^2p_0^{-1}b^2(id_X \times v) \lor \\
= (bp_0)^2(id_X \times v) \lor \\
= [id_X \times v]p^2(id_X \times v) \lor \\
= p^2(id_X \times v)(id_X \times v) \lor \\
\subseteq p^2v \\
= \xi. \\
\]

\[
\square
\]

**Note.** The following three diagrams may help to understand the proof of the last proposition.
Theorem 3.1. Let \((X, \vee, \wedge)\) be a lattice in a Dedekind category. Then \(\xi = p^2(q \cap \vee) : X \to X\) is reflexive, transitive and antisymmetric. Moreover, \(\xi = p^2(q \cap \vee) = p^2 \vee = \wedge^t q = (p \cap \wedge)^2 q\) holds.

4 Orderings

In this section we will see that orderings having joins and meets induce lattice structures also in Dedekind categories. First we show a technical lemma needed later.

Lemma 4.1. Let \(\xi : X \to X\) and \(\gamma : Y \to X\) be relations, and let \(h : Z \to Y\) and \(k : Y \to X\) be functions. Then

(a) \(h\{(\xi \div \gamma)^2 \cap \gamma\} = (\xi \div h\gamma)^2 \cap h\gamma\),
(b) If \(\text{id}_X \sqsubseteq \xi\) and \(\gamma \xi = \gamma\), then \(k \sqsubseteq (\xi \div \gamma)^2 \cap \gamma\) if and only if \(k\xi = \gamma\).

Proof.
(a) \[
h\{(\xi \div \gamma)^2 \cap \gamma\} = h(\xi \div h\gamma)^2 \cap h\gamma
= \{(\xi \div h\gamma)^2\} \cap h\gamma
= \{(\xi \div h\gamma)^2\} \cap h\gamma
= (\xi \div h\gamma)^2 \cap h\gamma.
\]
(b)
\[ k \subseteq (\xi \div \gamma)^2 \cap \gamma \iff k \subseteq (\xi \div \gamma)^2 \text{ and } k \subseteq \gamma \]
\[ k^2 \gamma \subseteq \xi \text{ and } k \subseteq \gamma \]
\[ \gamma \subseteq k\xi \wedge k \subseteq \gamma \{ \text{ } k \text{ } \text{ is } \text{ a function } \} \]
\[ \gamma = k\xi \{ \text{ } id_X \subseteq \xi \text{ and } \gamma \xi = \gamma \} \]

\textbf{Definition 4.1.} A relation \( \xi : X \rightarrow X \) is an \textit{ordering} on \( X \) if \( id_X \subseteq \xi \) (reflexive), \( \xi \xi \subseteq \xi \) (transitive) and \( \xi \cap \xi^2 \subseteq id_X \) (antisymmetric).  

For two relations \( \xi, \xi' : X \rightarrow X \) we define relations \( \xi \mid \xi' : X \times X \rightarrow X \) and \( \forall_0 : X \times X \rightarrow X \) by \( \xi \mid \xi' = p\xi \cap q\xi' = (\xi^2 \cap \xi'^2)^2 \) and \( \forall_0 = (\xi \div \xi\xi)^2 \cap \xi\xi \).

Note that this definition was suggested by Dr. Wolfram Kahl, Universität der Bundeswehr München, when he visited to Kyushu University in August, 1997.

\textbf{Note.} The following may give concrete meanings of relations \( \xi \mid \xi \) and \( \forall_0 \).

\[ x \leq z \text{ and } y \leq z \]
\[ \iff (x, z) \in \xi \text{ and } (y, z) \in \xi \]
\[ \iff ((x, y), z) \in p\xi \text{ and } ((x, y), z) \in q\xi \]
\[ \iff ((x, y), z) \in p\xi \cap q\xi = \xi \mid \xi. \]
\[ \forall z' : x \leq z' \text{ and } y \leq z' \Rightarrow z \leq z' \]
\[ \iff \forall z' : ((x, y), z') \in \xi \mid \xi \Rightarrow (z, z') \in \xi \]
\[ \iff (z, (x, y)) \in \xi \div \xi \mid \xi \]
\[ \iff ((x, y), z) \in (\xi \div \xi \mid \xi)^2. \]

\[ \forall_0 \forall_0 \subseteq (\xi \div \xi\xi)(\xi \mid \xi) \cap (\xi \mid \xi)^2(\xi \div \xi\xi)^2 \]
\[ \subseteq \xi \cap \xi^2 \cap id_X \]

As usual we say \( \xi \) has joins (least upper bounds) if \( \forall_0 = (\xi \div \xi\xi)^2 \cap \xi\xi \) is total, and \( \xi \) has meets (greatest lower bounds) if \( \forall_0 = (\xi^2 \div \xi\xi)^2 \cap \xi\xi^2 \) is total.

\textbf{Theorem 4.1.} Let \( \xi : X \rightarrow X \) be an ordering on \( X \), \( \forall_0 = (\xi \div \xi\xi)^2 \cap \xi\xi \)

and \( \forall_0 = (\xi^2 \div \xi\xi)^2 \cap \xi\xi^2 \).

If \( \xi \) has least upper bounds and greatest lower bounds, then

(a) \( \forall_0 \xi = \xi \mid \xi \),
(b) \( p^2 \forall_0 = \xi \) and \( q^1 \forall_0 = \xi \\
\text{(c) } t_0 = \forall_0 \text{ and } t_\emptyset = \wedge_0 \\
\text{(d) } (p \forall_0) \wedge_0 = p \text{ and } (p \forall_\emptyset) \forall_0 = p \\
\text{(e) } (\forall_0 \times \text{id}_X) /\forall_0 = \alpha (\text{id}_X \times \forall_0) /\forall_0 \\

\text{Proof. (a) By the transitivity } \xi \xi \subseteq \xi \text{ of } \xi \text{ we have } (\xi /\xi) /\xi \subseteq \xi /\xi \text{. Hence an equality } \forall_0 /\xi = \xi /\xi \text{ follows from the definition of } \forall_0 \text{ and Lemma 4.1(b).} \\
\text{(b) It is trivial that } p^2 \forall_0 \subseteq p^2 (\xi /\xi) \subseteq p^2 /\xi \subseteq \xi \text{. Recall that } \xi = p^2 (\rho /\xi \cap q) \text{ by Lemma 2.3(a). So it suffices to show that } p /\xi \cap q \subseteq \forall_0 \text{. First } p /\xi \cap q \subseteq \xi /\xi \text{ follows from } p /\xi \cap q = p /\xi \cap q (\xi /\xi \cap \xi /\xi) \subseteq p /\xi \cap q /\xi \text{. Now note that } p /\xi \cap q \subseteq (\xi /\xi \cap \xi /\xi)^2 \text{ if and only if } (p /\xi \cap q)^2 /\xi \subseteq \xi \text{. However, the latter condition follows from } (p /\xi \cap q)^2 /\xi = (p /\xi \cap q)^2 /\xi \cap q /\xi \subseteq q /\xi \subseteq \xi \text{.} \\
\text{(c) First note that } t /\xi = t /\xi \cap t /\xi = q /\xi \cap p /\xi = \xi /\xi \text{. By Lemma 4.1(a) we have} \\
t /\xi = \{ \xi \cap t (\xi /\xi) \} /\xi \cap t (\xi /\xi) = (\xi /\xi \cap \xi /\xi) /\xi \subseteq \forall_0 \\
\text{(d) An inequality } p /\xi \subseteq \forall_0 /\xi \text{ follows from } p /\xi \subseteq \forall_0 /\xi \subseteq \forall_0 /\xi \subseteq \forall_0 /\xi (\text{since } \xi \text{ is transitive). Then we have } (p \forall_0 /\xi) /\xi^2 = (p \forall_0 /\xi) /\xi^2 = \forall_0 /\xi^2 \text{, and so} \\
(p \forall_0) /\xi_0 = (p \forall_0) /\xi \{ (\xi /\xi \cap \xi /\xi) /\xi \cap \xi /\xi /\xi \} \\
\quad = \{ (\xi /\xi \cap (p \forall_0 /\xi) /\xi^2) /\xi \cap (p \forall_0 /\xi) /\xi^2 \} /\xi \text{ \{ Lemma 4.1(a) \}} \\
\quad = (\xi /\xi \cap p /\xi) /\xi \subseteq p /\xi^2 \text{.} \\

\text{Therefore Lemma 4.1(b) proves } p \subseteq (p \forall_0) /\xi_0 \text{, and so } p = (p \forall_0) /\xi_0 \\
\text{(e) Define two relations } \forall_1 : (X \times X) \times X \rightarrow X \text{ and } \forall_2 : X \times (X \times X) \rightarrow X \text{ by} \\
\forall_1 = \{ \xi \cap (\xi /\xi) /\xi \cap (\xi /\xi) /\xi \cap (\xi /\xi) /\xi \} \text{ and } \forall_2 = \{ \xi \cap (\xi /\xi) /\xi \cap (\xi /\xi) /\xi \} \\
\text{First we will prove that } (\forall_0 \times \text{id}_X) /\forall_0 = \forall_1 \text{ and } (\text{id}_X \times \forall_0) /\forall_0 = \forall_2 \text{, which follows from } (\forall_0 \times \text{id}_X) /\forall_0 \subseteq \forall_1 \text{ and } (\text{id}_X \times \forall_0) /\forall_0 \subseteq \forall_2 \text{, respectively, since } (\forall_0 \times \text{id}_X) /\forall_0 \text{ and } (\text{id}_X \times \forall_0) /\forall_0 \text{ are total functions, and } \forall_1 \text{ and } \forall_2 \text{ are partial functions. Hence, by Lemma 4.1(b) we have to see that } (\forall_0 \times \text{id}_X) /\forall_0 \xi = (\xi /\xi) /\xi \text{ and } (\text{id}_X \times \forall_0) /\forall_0 \xi = (\xi /\xi) /\xi \text{.} \\
\text{But we have} \\
(\forall_0 \times \text{id}_X) /\forall_0 \xi = (\forall_0 \times \text{id}_X) /\xi /\xi \\
\quad = (\forall_0 \times \text{id}_X) /\xi \cap \rho /\xi \\
\quad = (\forall_0 \times \text{id}_X) /\xi \cap (\forall_0 \times \text{id}_X) /\rho /\xi \\
\quad = \rho /\xi \cap (\forall_0 \times \text{id}_X) /\rho /\xi \\
\quad = \rho /\xi \cap (\forall_0 \times \text{id}_X) /\rho /\xi \\
\quad = (\xi /\xi) /\xi \\
\text{and} \\
(\text{id}_X \times \forall_0) /\forall_0 \xi = (\text{id}_X \times \forall_0) /\xi /\xi \\
\quad = (\text{id}_X \times \forall_0) /\xi \cap \rho /\xi \\
\quad = (\text{id}_X \times \forall_0) /\xi \cap (\text{id}_X \times \forall_0) /\rho /\xi \\
\quad = \rho /\xi \cap (\text{id}_X \times \forall_0) /\rho /\xi \\
\quad = (\xi /\xi) /\xi \text{.}
This proves that \((\nu_0 \times \text{id}_X)\nu_0 = \nu_1\) and \((\text{id}_X \times \nu_0)\nu_0 = \nu_2\). Finally we have
\[(\nu_0 \times \text{id}_X)\nu_0 = a(\text{id}_X \times \nu_0)\nu_0\]
from \(a_{\xi(\xi)}\xi = (\xi,\xi)\xi\) and
\[
a(\text{id}_X \times \nu_0)\nu_0 = a_{\nu_2}
= a_{\xi \times \xi(\xi)}\xi \cap a_{\xi(\xi)}\xi
= \left[\xi \cap a_{\xi(\xi)}\xi\right] \cap a_{\xi(\xi)}\xi
= \left(\xi \cap (\xi,\xi)\xi\right) \cap (\xi,\xi)\xi
= \nu_1
= (\nu_0 \times \text{id}_X)\nu_0,$
which completes the proof. \(\square\)

**Theorem 4.2.** Let \((X, \lor, \land)\) be a lattice in a Dedekind category \(D\). If \(\xi = p^2(\lor \cap q)\) and \(\nu_0 = (\xi \cap \xi)\xi \cap \xi\), then \(\lor = \nu_0\).

Proof. Since \(\lor\) is a function and \(\nu_0\) is univalent, it suffices to show that \(\lor \subseteq \nu_0\). To see this we have to show that \(\lor \subseteq \xi\xi\) and \(\xi\xi \subseteq \lor\) by Lemma 4.1(b). (Note that \(\xi\) is an ordering on \(X\) by the result in Section 2.) First \(\lor = \lor \cap \lor \cap \qcap \lor \lor = p^q \lor q^2 = \xi\xi\). Noticing that \((p \times \text{id}_X)q = q_0\) and \((q \times \text{id}_X)q = q_0\) and \(\text{id}_X \times f = p_0 p^2 \lor q_0 f^2 \lor p_0 p^2\), it follows that
\[
\begin{align*}
\xi\xi & = p^2(\lor \cap q) \cap q^2(\lor \cap q) \\
& = p^2_0(p \times \text{id}_X)(\lor \cap q) \cap q^2_0(q \times \text{id}_X)(\lor \cap q) \\
& = p^2_0[(p \times \text{id}_X)(\lor \cap q) \cap (q \times \text{id}_X)(\lor \cap q)] \\
& = p^2_0[(p \times \text{id}_X)(\lor \cap (q \times \text{id}_X)) \cap q_0] \\
& = p^2_0[(a(\text{id}_X \times q) \lor q \cap a(\text{id}_X \times \lor)q) \cap a(\text{id}_X \times q)] \\
& = p^2_0[(\text{id}_X \times q) \lor q \cap (\text{id}_X \times \lor)q] \\
& = p^2_0[(\text{id}_X \times q) \lor ((\text{id}_X \times \lor) \cap (\text{id}_X \times q))q] \\
& \subseteq p^2_0[(\text{id}_X \times \lor) \cap (\text{id}_X \times q)]((\text{id}_X \times \lor) \cap (\text{id}_X \times q))^2(\text{id}_X \times q) \lor q \\
& \subseteq p^2_0[(\text{id}_X \times \lor) \cap (\text{id}_X \times q)] \\
& = p^2_0[(\text{id}_X \times \lor) \lor q] \\
& = \lor \lor \lor \\
& = \lor \lor \lor \\
& = \lor \lor \lor \\
& = \lor \lor \lor \\
& = \lor \lor \lor .
\end{align*}
\(\square\)

**Note.** The following four diagrams may help to understand the proof of the last theorem.
(X \times X) \times X \xrightarrow{f \times id_X} X \times X \quad (X \times X) \times X \xrightarrow{p \times id_X} X \times X

\quad \xrightarrow{(PB)} \quad \xrightarrow{p} \quad \xrightarrow{id_{X \times X}}

X \times X \xrightarrow{f} X \quad X \times (X \times X) \xrightarrow{id_{X \times X}} X \times X

\quad \xrightarrow{a} \quad \xrightarrow{id_{X \times X}}

X \times (X \times X) \xrightarrow{id_X \times g} X \times X \quad (X \times X) \times X \xrightarrow{q \times id_X} X \times X

\quad \xrightarrow{(PB)} \quad \xrightarrow{q} \quad \xrightarrow{a} \quad \xrightarrow{id_{X \times X}}

\quad \xrightarrow{id_{X \times X}}

X \times X \xrightarrow{g} X \quad X \times (X \times X) \xrightarrow{q_1} X \times X

\quad \xrightarrow{a} \quad \xrightarrow{q_1}

\square

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