A Survey on Intersections of Maximal Partial Clones of Boolean Partial Functions
Miguel Couceiro, Lucien Haddad

To cite this version:
Miguel Couceiro, Lucien Haddad. A Survey on Intersections of Maximal Partial Clones of Boolean Partial Functions. ISMVL 2012 - 42nd IEEE International Symposium on Multiple-Valued Logic, May 2012, Victoria, BC, Canada. hal-01093663

HAL Id: hal-01093663
https://hal.archives-ouvertes.fr/hal-01093663
Submitted on 18 Feb 2017

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L’archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d’enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.
A survey on intersections of maximal partial clones of Boolean partial functions

Miguel Couceiro* and Lucien Haddad†

*Mathematics Research Unit, FSTC, University of Luxembourg
6, rue Richard Coudenhove-Kalergi, L-1359 Luxembourg, Luxembourg
Email: miguel.couceiro@uni.lu

†Math & Info, Collège militaire royal du Canada
B.P 17000, STN Forces, Kingston ON, K7K 7B4 Canada.
Email: haddad-l@rmc.ca

Abstract—We survey known results and present some new ones about intersections of maximal partial clones on a 2-element set.

I. Preliminaries

Let $A$ be a finite non-singleton set. Without loss of generality we assume that $A = k := \{0, \ldots, k-1\}$. For a positive integer $n$, an $n$-ary partial function on $k$ is a map $f : \text{dom} \ (f) \to k$ where $\text{dom} \ (f)$ is a subset of $k^n$ called the domain of $f$. Let $\text{Par}^{(n)}(k)$ denote the set of all $n$-ary partial functions on $k$ and let $\text{Par}(k) := \bigcup_{n \geq 1} \text{Par}^{(n)}(k)$. An $n$-ary partial function $g$ is said to be a total function if $\text{dom} \ (g) = k^n$. Let $\text{Op}(k)$ be the set of all total functions on $k$.

For $n, m \geq 1$, $f \in \text{Par}^{(n)}(k)$ and $g_1, \ldots, g_n \in \text{Par}^{(m)}(k)$, the composition of $f$ and $g_1, \ldots, g_n$, denoted by $f[g_1, \ldots, g_n] \in \text{Par}^{(m)}(k)$, is defined by

$$\text{dom} \ (f|[g_1, \ldots, g_n]) := \{\bar{a} \in k^m \mid \bar{a} \in \bigcap_{i=1}^m \text{dom} \ (g_i), \ (g_i(\bar{a}), \ldots, g_m(\bar{a})) \in \text{dom} \ (f)\},$$

and $f[g_1, \ldots, g_n](\bar{a}) := f(g_1(\bar{a}), \ldots, g_n(\bar{a}))$, for all $\bar{a} \in \text{dom} \ (f|[g_1, \ldots, g_n])$.

For every positive integer $n$ and each $1 \leq i \leq n$, let $e^n_i$ denote the $n$-ary $i$-th projection function defined by $e^n_i(a_1, \ldots, a_n) = a_i$ for all $(a_1, \ldots, a_n) \in k^n$. Furthermore, let $J_k := \{e^n_i : 1 \leq i \leq n\}$ be the set of all (total) projections.

Definition 1. A partial clone on $k$ is a composition closed subset of $\text{Par}(k)$ containing $J_k$. If a partial clone is contained in the set of all total functions $\text{Op}(k)$, then it is called a clone on $k$.

Remark 1. There are two other equivalent definitions for partial clones. One definition uses Mal'tsev’s formalism and the other uses the concept of one point extension. These definitions can be found in chapter 20 of [12].

The partial clones on $k$ (clones on $k$), ordered by inclusion, form a lattice $L_{\text{Par}}$ ($L_{\text{Op}}$, respectively) in which the infimum is the set-theoretical intersection. That means that the intersection of an arbitrary family of partial clones (clones) on $k$ is also a partial clone on $k$ (clone on $k$, respectively). A maximal partial clone on $k$ is a clone on $k$, respectively). A maximal partial clone on $k$ is a coatom of the lattice $L_{\text{Par}}$. Therefore, a partial clone $M$ is maximal if there is no partial clone $C$ over $k$ such that $M \subset C \subset \text{Par}(k)$.

Example 2. Let

$$\Omega_k := \bigcup_{n \geq 1} \{f \in \text{Par}^{(n)}(k) \mid \text{dom} \ (f) \neq \emptyset \implies \text{dom} \ (f) = k^n\} = \bigcup_{n \geq 1} \{f \in \text{Par}^{(n)}(k) \mid \text{dom} \ (f) \neq \emptyset \implies f \in \text{Op}(k)\}.$$

Then $\Omega_k$ is a maximal partial clone on $k$.

An interesting and somehow difficult problem in clone theory is to study intersections of maximal clones and maximal partial clones. The lattice $L_{\text{Par}}$ is known and was completely described by E. Post in [14]. In chapter 14 of [12] are listed all submaximal elements of $L_{\text{Par}}$, i.e., all clones on 3 covered by the maximal elements of $L_{\text{Par}}$. Several results dealing with intersection of maximal clones can be found in the literature, we refer the reader to the list of reference in [12] for details.

In this paper we focus on $L_{\text{Par}}$, the lattice of partial clones of Boolean functions. We survey the known results and present some new results concerning the intersections of the maximal elements of $L_{\text{Par}}$.

With one exception, every maximal partial clone is the polymorphism of a relation. We have:

Definition 3. For $h \geq 1$, let $\rho$ be an $h$-ary relation on $k$ and $f$ be an $n$-ary partial function on $k$. We say that $f$ preserves $\rho$ if for every $h \times n$ matrix $M = [M_{ij}]$ whose columns $M_{ij} \in \rho$, $(j = 1, \ldots, n)$ and whose rows $M_{is} \in \text{dom} \ (f)$ $(i = 1, \ldots, h)$, the $h$-tuple $(f(M_{i1}), \ldots, f(M_{ih})) \in \rho$. Define $p\text{Pol}\rho := \{f \in \text{Par}(k) \mid f \text{ preserves } \rho\}$. 
It is well known that $pPol\rho$ is a partial clone called the \emph{partial clone determined by the relation $\rho$}.

Note that if there is no $n \times n$ matrix $M = [M_{ij}]$ whose columns $M_{ij} \in \rho$ and whose rows $M_{i*} \in \text{dom}(f)$, then $f \in pPol\rho$.

**Example 4.** Let $2 := \{0, 1\}$, let $\{(0, 0), (0, 1), (1, 1)\}$ be the natural order on $2$ and consider the binary relation $\{(0, 1), (1, 0)\}$ on $2$.

Then $pPol\{(0, 0), (0, 1), (1, 1)\}$ is the set of all \emph{monotone} partial functions and $pPol\{(0, 1), (1, 0)\}$ is the set of all \emph{self-dual} partial functions on $2$. For simplicity we will write $pPol\{(\leq)\}$ and $pPol\{(\neq)\}$ for $pPol\{(0, 0), (0, 1), (1, 1)\}$ and $pPol\{(0, 1), (1, 0)\}$, respectively.

It is easy to see that if $\rho$ is an $h$-ary relation on $k$, then $pPol\rho = pPol(\rho \otimes 2)$. This fact motivates the concept of irredundant relation.

Let $h \geq 1$ and let $\rho$ be an $h$-ary relation on $k$. We say that $\rho$ is \emph{repetition-free} if for all $1 \leq i < j \leq h$, there exists $(a_1, \ldots, a_h) \in \rho$ with $a_i \neq a_j$. Moreover, $\rho$ is said to be \emph{irredundant} if it is repetition-free and has no fictitious components, i.e., there is no $i \in \{1, \ldots, h\}$ such that $(a_1, \ldots, a_h) \in \rho$ implies $(a_1, \ldots, a_i-1, x, a_{i+1}, \ldots, a_h) \in \rho$ for all $x \in k$.

It can be shown that if $\mu$ is a nonempty relation, then we can find an irredundant relation $\rho$ such that $pPol\mu = pPol\rho$ (see, e.g., [4] for details).

The following result, known as the Definability Lemma, was first established by B. Romov in [15] (see Lemma 20.3.4 in [12]) and has been widely used to handle maximal partial clones via the relational approach.

**Lemma 5. (The Definability Lemma)** Let $h_1, \ldots, h_n$, $t \geq 1$ be integers, $\rho_i$ be an $h_i$-ary relation on $k$, $i = 1, \ldots, n$, and $\beta$ be a $t$-ary irredundant relation on $k$. Then

$$
\bigcap_{1 \leq i \leq n} pPol\rho_i \subseteq pPol\beta
$$

if and only if there exists a family of $h_i$-ary auxiliary relations $\{q_1, \ldots, q_n\}$ whose vertex sets is $\{1, \ldots, t\}$, and such that

$$
\beta = \{(x_1, \ldots, x_t) \in k^t \mid (i_{1j}, \ldots, i_{nj}) \in q_j \Rightarrow (x_{i_{1j}}, \ldots, x_{i_{nj}}) \in \rho_j, \quad \text{for } j = 1, \ldots, n\}.
$$

**Example 6.** Let $\rho_1$ be a binary and $\rho_2$ be a ternary relation on $k$. Let $\beta$ be the 4-ary relation defined by

$$
\beta := \{(x_1, \ldots, x_4) \in k^4 \mid (x_1, x_2) \in \rho_1, \quad (x_3, x_2) \in \rho_1, \quad \text{and } (x_1, x_4, x_3) \in \rho_2\}.
$$

Then $pPol\rho_1 \cap pPol\rho_2 \subseteq pPol\beta$. (Here $n = 2$, $\omega_1 = \{(1, 2), (3, 2)\}$ and $\omega_2 = \{(1, 4, 3)\}$.)

As mentioned earlier, Freivald showed that there are exactly eight maximal partial clones on $2$. The following two relations determine maximal partial clones. Set

$$
R_1 := \{(x, y, y, y) \mid x, y \in 2\} \cup \{(x, y, y, x) \mid x, y \in 2\}
$$

and

$$
R_2 := R_1 \cup \{(x, y, x, y) \mid x, y \in 2\}.
$$

**Theorem 7.** \([3]\) There are exactly 8 maximal partial clones on $2$, namely: $pPol\{0\}$, $pPol\{1\}$, $pPol\{(0, 1)\}$, $pPol\{(\leq)\}$, $pPol(\neq)$, $pPol(R_1)$, $pPol(R_2)$ and $\Omega_2$.

The three maximal partial clones $pPolR_1$, $pPolR_2$ and $\Omega_2$ contain the unary functions $Op^{(1)}(2)$ (i.e., maps) on $2$. Such partial clones are called \emph{Shupecki type} partial clones in [8], [16]. They are the only three maximal partial clones of Shupecki type on $2$.

It is known that $pPolR_2 \cap Op(2)$ is the maximal clone of all (total) linear functions over $2$ (see, e.g., section 5.2.4 of [12]). Alekseev and Voronenko studied the classes of partial clones of Boolean functions that contain $pPolR_2 \cap Op(2)$ on $2$. From the main result of [1] we have:

**Theorem 8.** The interval of partial clones $[pPolR_2 \cap Op(2), Par(2)]$ is of continuum cardinality on $2$.

The proof of this result is quite complicated and is given in ([11]) (see also Theorem 20.8.1 of [12]). We refer the reader to Theorem 19 of [8] and Theorem 20.7.13 of [12] for the generalization of Theorem 8 to partial clones on $k$ with $k \geq 3$. A consequence of Theorem 8 is that the interval of partial clones $[pPolR_2 \cap \Omega_2, Par(2)]$ is of continuum cardinality on $2$.

On the other hand it is shown in [5] that $pPolR_1 \cap Op(k)$ is the clone over $k$ generated by $Op^{(1)}(k)$ for every $k \geq 2$. We present a result similar to Theorem 8 that is established for $pPolR_3$ in [5].

For $n \geq 3$ define the 2$n$-ary relation $\tau_{2n}$ on $2$ by setting:

$$
(x_1, \ldots, x_{2n}) \in \tau_n \quad \text{if and only if either } x_1 = \cdots = x_{2n}, \quad \text{or each of 0 and 1 appears exactly } n \text{ times in } (x_1, \ldots, x_{2n}).
$$

It is shown in [5] that $Op^{(1)}(2) \subseteq pPol\tau_{2n}$ for all $n \geq 3$. Since

$$
R_1 = \{ (x_1, x_2, x_3, x_4) \in 2^4 \mid (x_1, \ldots, x_1, x_2, x_3, \ldots, x_3, x_4) \in \tau_{2n}\}
$$

holds for all $n \geq 3$, it follows from Lemma 5 that $pPol\tau_{2n} \subseteq pPolR_1$ for all $n \geq 3$.

Let $P := \{3, 5, 7, \ldots\}$ be the set of all odd prime numbers and $\mathcal{P}(P)$ be its power set. It is shown in [5] that the map

$$
\chi: \mathcal{P}(P) \rightarrow [pPolR_1 \cap \Omega_2, pPolR_1]
$$

defined by $X \mapsto \chi(X) := \bigcap_{n \in P \setminus X} pPol\tau_{2n}$ is one-to-one. Hence we have the following result:

**Theorem 9.** The interval of partial clones $[pPol(R_1) \cap \Omega_2, Par(2)]$ is of continuum cardinality on $2$.

Together with D. Lau, the second author studied several intersections of Shupecki type partial clones on a non-singleton finite set. The following result comes from [8]:

**Theorem 10.** The partial clone $pPolR_1 \cap pPolR_2$ is covered by the maximal partial clone $pPolR_2$.

The dual of the above result does not hold for $pPolR_1$. It is shown in [8] that there is at least one partial clone that strictly
lies between \( pPol R_1 \cap pPol R_2 \) and \( pPol R_1 \). Indeed, let
\[
\lambda := \{(x_1, \ldots, x_7) \in 2^7 \mid (x_1, x_2, x_5, x_6) \in R_1, \\
(x_2, x_4, x_6, x_7) \in R_1, \text{ and } (x_1, x_2, x_3, x_4) \in R_2\}.
\]

Then it is shown in [8] that \( pPol R_1 \cap pPol R_2 \not\subseteq pPol \lambda \subseteq pPol R_1 \). Therefore the partial clone \( pPol R_1 \cap pPol R_2 \) is not covered by the maximal partial clone \( pPol R_1 \). To our knowledge, little seems to be known about the interval of partial clones \([pPol R_1 \cap pPol R_2, pPol R_1]\).

Intersections of maximal partial clones that are not of Slupecki type have been studied as well. Intersections of the form \( pPol \rho \cap pPol \theta \) where \( \rho, \theta \in \{\{0\}, \{1\}, \{(0,1)\}, \neq, \leq\) with the exception of \( \{\rho, \theta\} = \{\leq, \neq\} \), have been studied in [6], [7]. Almost all proofs given in [6], [7] are based on the composition of partial functions. In the same direction, deeper results were established in [10] and [9] where partial clones are handled via relations, and all proofs are based on the Lemma 5. Let
\[
C_M := pPol \{0\} \cap pPol \{1\} \cap pPol \{0,1\} \cap pPol (\leq) \quad \text{and} \quad C_D := pPol \{0\} \cap pPol \{1\} \cap pPol \{0,1\} \cap pPol (\neq).
\]

Then \( C_M \) (respectively \( C_D \)) is the set of all idempotent monotonic partial functions on \( 2 \) (idempotent self-dual partial functions on \( 2 \)).

**Theorem 11.** The interval \([C_M, \text{Par}(2)]\) contains exactly 25 partial clones and the interval \([C_D, \text{Par}(2)]\) contains exactly 33 partial clones on \( 2 \).

The intervals of partial clones \([C_M, \text{Par}(2)]\) and \([C_D, \text{Par}(2)]\) are completely described in [10] (see also [9]). D. Lau informed the second author that some of the results in [10] exist in the unpublished manuscript [18] by B. Strauch.

In view of results from [1], [5], [10], [18], [19], it was thought that if \( 2 \leq i \leq 5 \) and \( M_1, \ldots, M_i \) are non-Slupecki maximal partial clones on \( 2 \), then the interval \([M_1 \cap \cdots \cap M_i, \text{Par}(2)]\) is either finite or countably infinite. It is shown in [11] that the interval of partial clones \([pPol (\leq) \cap pPol (\neq), \text{Par}(2)]\) is infinite. This result is mentioned in Theorem 20.8 of [12] (with an independent proof given in [13]) and in chapter 8 of the PhD thesis [17]. However, it remained an open problem to determine whether \([pPol (\leq) \cap pPol (\neq), \text{Par}(2)]\) is countably or uncountably infinite.

The following relations, introduced in [2], are needed to settle this question. For \( n \geq 5 \) and \( n > k \geq 1 \) we denote by \( \sigma^n_k \subseteq 2^{2^n} \) the \((2n)\)-ary relation defined by
\[
\sigma^n_k := \{(x_1, \ldots, x_n, y_1, \ldots, y_n) \in 2^{2^n} \mid \\
\quad \forall i = 1, \ldots, n, x_i \neq y_i, \text{ and } \forall k = 1, \ldots, n, y_i+k \leq x_i\},
\]
where the subscripts \( i + j \) in the above definition are taken modulo \( n \).

Now for \( n \geq 5 \) and \( n > k \geq 1 \), we denote by \( \rho^n_k \subseteq 2^{4n} \) the \((4n)\)-ary relation defined by
\[
\rho^n_k := \{(x_1, \ldots, x_{2n}, y_1, \ldots, y_{2n}) \in 2^{4n} \mid \\
\quad (x_1, \ldots, x_n, y_1, \ldots, y_n) \in \sigma^n_k, \text{ and } \\
\quad (x_{n+1}, \ldots, x_{2n}, y_{n+1}, \ldots, y_{2n}) \in \sigma^n_k\}.
\]

By Lemma 5 we have that for all \( n \geq 5 \) and \( n > k \geq 1 \)
\[
pPol (\leq) \cap pPol (\neq) \subseteq pPol \sigma^n_k \cap pPol \sigma^n_k \subseteq pPol \rho^n_k.
\]

Denote by \( E_{\geq 4} := \{4, 6, 8, \ldots\} \) the set of all even integers greater or equal to 4 and denote by \( \mathcal{P}(E_{\geq 4}) \) the power set of \( E_{\geq 4} \). Furthermore, for every even integer \( k \geq 4 \), let \( n(k) := k(k+1)+1 \). Since \( pPol (\leq) \cap pPol (\neq) \subseteq pPol (\rho^n_k) \) for every \( n \geq 5 \) and every \( n > k \geq 1 \), we have that
\[
pPol (\leq) \cap pPol (\neq) \subseteq \bigcap_{t \in E_{\geq 4}} pPol \rho^{n(t)}(X)
\]
for every subset \( X \) of \( E_{\geq 4} \). It was shown in [2] that the map
\[
\chi: \mathcal{P}(E_{\geq 4}) \to [pPol (\leq) \cap pPol (\neq), \text{Par}(2)]
\]
defined by \( X \mapsto \chi(X) := \bigcap_{t \in E_{\geq 4}} pPol \rho^{n(t)} \) is one-to-one.

Hence we have the following result:

**Theorem 12.** The interval of partial clones \([pPol (\leq) \cap pPol (\neq), \text{Par}(2)]\) is of continuum cardinality on \( 2 \).

We conclude this survey with the following new result, which provides several examples of finite intervals of the form above.

**Theorem 13.** Let \( \theta \in \{\{0\}, \{1\}, \{(0,1)\}, \neq, \leq\} \) and \( \rho \in \{R_1, R_2\} \). Then the partial clone \( pPol \rho \cap pPol \theta \) is covered by the maximal partial clone \( pPol \theta \) over \( 2 \). In particular, each interval of partial clones of the form \([pPol \rho \cap pPol \theta, \text{Par}(2)]\) has size 2.

The proof is based on the following fact established after Lemma 3 in [8].

**Fact 14.** Let \( pPol \rho \) and \( pPol \theta \) be two distinct maximal partial clones on \( k \). Suppose that
\[
[pPol \rho \cap pPol \theta \subseteq pPol \lambda] \implies \quad [pPol \lambda \subseteq pPol \rho \text{ or } pPol \lambda = pPol \theta]
\]
holds for every irredudant relation \( \lambda \). Then the partial clone \( pPol \rho \cap pPol \theta \) is covered by the maximal partial clone \( pPol \theta \) on \( k \).

We need the following notation. For \( \psi = (v_1, \ldots, v_t) \in 2^t \), we define \( \ker(\psi) := \{(i,j) \in \{1, \ldots, t\}^2 \mid v_i = v_j\} \). Note that \( \ker(\psi) \) is a binary equivalence relation on the set \( \{1, \ldots, t\} \) with at most two blocks.

**Proof of Theorem 13.** Let \( \theta \in \{R_1, R_2\} \). We consider three cases:

a) \( pPol \{(0,1)\} \cap pPol \theta \) is covered by \( pPol \theta \). Let \( t \geq 1 \) and \( \lambda \) be a \( t \)-ary irredudant relation such that
pPol \{(0, 1)\} \cap pPol \theta \subseteq pPol \lambda.

By Lemma 5, there is a binary relation \( \varrho \) and a 4-ary relation \( \varrho_2 \), with \( \{\varrho_1, \varrho_2\} \) covering the set \( \{1, \ldots, t\} \) and such that

\[
\lambda = \{(x_1, \ldots, x_t) \in 2^t | \forall (j_1, j_2) \in \varrho_1, (x_{j_1}, x_{j_2}) \in \{(0, 1)\}, \text{ and} \forall (i_1, \ldots, i_4) \in \varrho_2, (x_{i_1}, x_{i_2}, x_{i_3}, x_{i_4}) \in \theta\}.
\]

Note that if \( \varrho_1 = \emptyset \), then \( \lambda \) can be defined from \( \theta \) and by Lemma 5 \( pPol \theta \subseteq pPol \lambda \), thus \( pPol \theta = pPol \lambda \) by the maximality of \( pPol \theta \). So assume \( \varrho_1 \neq \emptyset \). Without loss of generality, let \( (1, 2) \in \varrho_1 \), i.e., \( (x_1, x_2) = (0, 1) \) for every tuple \( (x_1, \ldots, x_t) \in \lambda \). Fix \( \psi = (0, 1, v_3, \ldots, v_t) \in \lambda \) and set

\[
\mu := \{(x_1, x_2) \in 2^2 \mid (x_1, x_2, x_{i_3}, \ldots, x_{i_t}) \in \lambda \}
\]

where, for \( j = 3, \ldots, t, i_j = 1 \) if \( (1, i_j) \in \ker(\psi) \) and \( i_j = 2 \) if \( (2, i_j) \in \ker(\psi) \). Then we have that \( pPol \lambda \subseteq pPol \mu \) by Lemma 5. As \( \psi = (0, 1, v_3, \ldots, v_t) \in \lambda \) we have \((0, 1) \in \mu \) and since every \((x_1, \ldots, x_t) \in \lambda \) satisfies \( x_1 = 0, x_2 = 1 \), we have that \( \mu = \{(0, 1)\} \). By Fact 14, \( pPol \{(0, 1)\} \cap pPol \theta \) is covered by \( pPol \theta \). The proof of the claim that \( pPol \{0\} \cap pPol \theta \) and \( pPol \{1\} \cap pPol \theta \) are covered by \( pPol \theta \) follows similarly.

b) \( pPol \{\neq\} \cap pPol \theta \) is covered by \( pPol \theta \). We proceed as in case a), and choose \( \psi = (v_1, v_2, \ldots, v_t) \in \lambda \). Then either \( (v_1, v_2) = (0, 1) \) or \( (v_1, v_2) = (1, 0) \). Suppose that \( (v_1, v_2) = (0, 1) \) and consider the map \( \tilde{\nu} = 0, \tilde{\nu} = 1 \). Then we have \( \tilde{\nu} \in pPol \lambda \) and so \( \tilde{\nu} \in pPol \theta \). Again consider the relation \( \mu \) defined in a). It is easy to see that \( \mu \) is the binary relation \( \neq \) and the rest of the proof is as above. The case \( (v_1, v_2) = (1, 0) \) follows similarly.

c) \( pPol \subseteq \cap pPol \theta \) is covered by \( pPol \theta \). Again proceed as in case a) with the assumption that \( (1, 2) \in \varrho_1 \). Note that in this case we have \( (0, 0, \ldots, 0, 1, \ldots, 1) \in \lambda \). Moreover since \( \lambda \) is irredundant, there is \( \psi = (v_1, v_2, \ldots, v_t) \in \lambda \) such that \( v_1 \neq v_2 \). As \( v_1 \leq v_2 \) we get \( (v_1, v_2) = (0, 1) \). Again consider the relation \( \mu \) as defined in case a). From \( \psi \in \lambda \) we obtain \( (0, 1) \in \mu \) and as \( (i, \ldots, i) \in \lambda \) we have \( (i, i) \in \mu \), for \( i = 0, 1 \). Note that \( (1, 0) \notin \mu \) since for every \( (x_1, x_2, \ldots, x_t) \in \lambda, x_1 \leq x_2 \). So \( \mu \) is the binary relation \( \leq \). The rest of the proof is as in case a).

\[ \square \]

Acknowledgments

Miguel Couceiro is supported by the internal research project FIR-MTH-PUL-09MRDO of the University of Luxembourg.

References