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► **To cite this version:**

| Bruno Courcelle. On betweenness in order-theoretic trees. 2021. hal-03175157v1

**HAL Id: hal-03175157**

**<https://hal.science/hal-03175157v1>**

Preprint submitted on 19 Mar 2021 (v1), last revised 7 Sep 2022 (v5)

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# On betweenness in order-theoretic trees

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March 19, 2021

**Abstract** : An *order-theoretic tree* is a partial order such that the set of nodes larger than any node is linearly ordered. Rooted trees, ordered by the ancestor relation, are order-theoretic trees.

The ternary relation  $B(x, y, z)$  of *betweenness* states that  $y$  is between  $x$  and  $z$ , in some sense. For linear and partial orders, for finite and order-theoretic trees, it has been characterized in *first-order* or *monadic second-order* logic. In an order-theoretic tree,  $B(x, y, z)$  means that  $x < y < z$  or  $z < y < x$  or  $x < y \leq x \sqcup z$  or  $z < y \leq x \sqcup z$  where  $x \sqcup z$  is the least upper-bound of incomparable  $x$  and  $z$ .

We prove that the class of the *induced substructures* of the betweenness structures of countable order-theoretic trees is *monadic second-order definable*. The proof uses *partitioned probe cographs*, a variant of cographs, and their known five *bounds*, *i.e.*, the five minimal excluded induced subgraphs, up to isomorphism.

This article links two apparently unrelated topics: cographs and order-theoretic trees.

## Introduction

The ternary relation  $B(x, y, z)$  of *betweenness* expresses that  $y$  is between  $x$  and  $z$ , in some structure, such as a tree or a graph. *Betweenness* has been already characterized by *first-order* or *monadic second-order* sentences for linear and partial orders [7, 9, 16], for certain finite graphs [1, 2], for finite trees and for infinite trees of various kinds [3, 5, 6].

An *order-theoretic tree* (an *O-tree* for short) is a partial order  $T = (N, \leq)$  such that  $\{x \in N \mid x \geq y\}$  is linearly ordered for any  $y$ , a notion studied by Fraïssé [12]. If  $T$  is finite, we have a forest ordered by the ancestor relation. The set of rational numbers is an order-theoretic tree although no node has an immediate ancestor. We used order-theoretic trees previously to define the modular decomposition and the rank-width of countable graphs [3, 8].

The *betweenness structure* of an O-tree  $T = (N, \leq)$  is  $(N, B_T)$  such that

$$B_T(x, y, z) :\iff x \neq y \neq z \neq x \wedge [(x < y \leq x \sqcup z) \vee (z < y \leq x \sqcup z)]$$

where  $x \sqcup z$  denotes the least upper-bound of  $x$  and  $z$ . If  $x \sqcup z$  does not exist, there is no triple  $(x, y, z)$  in  $B_T$ . An *induced betweenness* is a induced substructure of such  $(N, B_T)$ .

In [3, 6] we have characterized several types of betweenness structures, in particular the betweenness structures of order-theoretic trees by *monadic second-order sentences*. We conjectured that the class **IBO** of *induced* betweenness structures in O-trees is monadic second-order definable too. We prove a slight weakening of this property by allowing the defining monadic second-order sentence to use the finiteness set predicate  $Fin(X)$ , expressing that the set  $X$  is finite.

Our proof uses the fact that *partitioned probe cographs*, have exactly five known bounds [15]. A *bound* is a minimal induced subgraph not in a given *hereditary* class, *i.e.*, closed under taking induced subgraphs (see Pouzet [17]). A *probe cograph* is obtained from a cograph by choosing a partition of its vertex set into two sets and by removing the edges having their two ends in one of the two sets. In a partitioned probe cograph, we keep track of the partition by means of a labelling of the vertices. A *probe cograph* is obtained from a partitioned probe cograph by forgetting the partition. The path  $P_5$  is a probe cograph. The path  $P_6$  is a bound of probe cographs.

The class of probe cographs is hereditary. As it is *2-well-quasi-ordered* [10, 17], it has finitely many bounds. They are not completely known but we define an algorithm based on monadic second-order logic and clique-width decompositions that could compute them. Unfortunately, it is intractable.

This article links two apparently unrelated notions: betweenness in order-theoretic trees and certain graphs defined from cographs. To give an intuition about this link, we observe that the cocomparability graph of an order-theoretic tree is a graph without induced  $P_4$ , hence, is a finite or infinite cograph (Proposition 3.5).

**Summary:** Section 1 reviews partial orders, graphs, clique-width and usual trees. Section 2 defines and studies p-cographs. Section 3 defines order-theoretic trees. Section 4 proves the monadic second-order characterization of **IBO**. Section 5 examines the bounds of the class of probe cographs.

## 1 Definitions and notation

All graphs, trees, partial orders and relational structures are countable which means finite or countably infinite. We denote  $[k] := \{1, \dots, k\}$ . Two sets  $A$  and  $B$  *overlap* if  $A \cap B$ ,  $A - B$  and  $B - A$  are not empty. In some cases, we denote by  $A \uplus B$  the union of two sets to stress that they are disjoint. Isomorphism of graphs, combinatorial and logical structures is denoted by  $\simeq$ .

### Partial orders

For partial orders  $\leq, \preceq, \sqsubseteq, \dots$  we denote respectively by  $<, \prec, \sqsubset, \dots$  the corresponding strict partial orders. We write  $x \perp y$  if  $x$  and  $y$  are incomparable for the considered order.

Let  $P = (V, \leq)$  be a partial order. For  $X, Y \subseteq V$ , the notation  $X < Y$  means that  $x < y$  for every  $x \in X$  and  $y \in Y$ . We write  $X < y$  instead of  $X < \{y\}$  and similarly for  $x < Y$ . We use similar notation for  $\leq$  and  $\perp$ . The least upper-bound of  $x$  and  $y$  is denoted by  $x \sqcup y$  if it exists and is then called their *join*.

If  $X \subseteq V$ , then we define  $N_{\leq}(X) := \{y \in V \mid y \leq X\}$  and similarly for  $N_{<}$ . We define  $\downarrow(X) := \{y \in V \mid y \leq x \text{ for some } x \in X\}$ . We have  $N_{\leq}(X) \leq X$ ,  $N_{\leq}(\emptyset) = V$ , and  $\downarrow(\emptyset) = \emptyset$ . We also define  $L_{\geq}(X) := \{y \in V \mid y \geq X\}$ , and similarly  $L_{>}(X)$ . We write  $L_{\geq}(x)$  (resp.  $L_{\geq}(x, y)$ ) if  $X = \{x\}$  (resp.  $X = \{x, y\}$ ) and similarly for  $L_{>}$ .

An *embedding* of a partial order  $P = (N, \leq)$  into another one  $P' = (N', \leq')$  is an injective mapping  $j : N \rightarrow N'$  such that  $j(x) \leq' j(y)$  if and only if  $x \leq y$ . It is a *join-embedding* if  $j(x) \sqcup' j(y) = j(x \sqcup y)$  whenever  $x$  and  $y$  have a join in  $P$ . We write  $P \subseteq_j P'$  if the inclusion mapping is a join-embedding.

## Graphs

In this article, graphs are undirected and simple, which means without loops and parallel (multiple) edges. We denote respectively by  $P_n, C_n, K_n$  a path, a cycle, a clique with  $n$  vertices.

The notation  $u - v$  designates an edge with ends  $u$  and  $v$ . As a property, it means also "there is an edge between  $u$  and  $v$ ". We say then that  $u$  and  $v$  are *adjacent* or *are neighbours*. The notation  $u - v - w - x$  shows the vertices of a path of 4 vertices. The notation  $u - v - w - x - u$  shows the vertices of a 4-cycle.

Induced subgraph inclusion is denoted by  $\subseteq_i$  and  $G[X]$  is the induced subgraph of a graph  $G = (V, E)$  having the vertex set  $X$  and then,  $G - x := G[V - \{x\}]$ .

We denote by  $G \oplus H$  the union of disjoint graphs  $G$  and  $H$ . This operation does not modify the possibly existing vertex-labels. Then,  $G \otimes H$  is  $G \oplus H$  augmented with edges between any vertex of  $G$  and any of  $H$ .

The *diameter* of a connected graph is the maximal *distance* between two vertices, *i.e.*, the minimum number of edges of a path between them.

By a *class* of graphs, we mean a set closed under isomorphism. A class  $\mathcal{C}$  is *hereditary* if it is closed under taking induced subgraphs. Its *bounds* are then the graphs  $G$  not in  $\mathcal{C}$  such that  $G - x \in \mathcal{C}$  for each vertex  $x$ . They form the class  $Bnd(\mathcal{C})$ . If the graphs in  $Bnd(\mathcal{C})$  are finite and are finitely many up to isomorphism, then  $\mathcal{C}$  is FO-definable (see below) and recognizable in polynomial time.

## Rooted trees

A *tree* is a connected graph without cycles. It is convenient to call *nodes* the vertices of a tree. A *rooted tree* is a triple  $T = (N_T, E_T, r)$  such that  $(N_T, E_T)$  is a tree and  $r \in N$ . It can be defined as the partial order  $(N_T, \leq_T)$  such that

$x \leq_T y$  if and only if  $y$  is on the path from the *root*  $r$  to  $x$ . A *leaf* is a minimal node,  $L_T$  denotes the set of leaves. The other nodes are *internal*. We will always handle rooted trees  $T$  as partial order  $(N_T, \leq_T)$ , and in Section 3, we will define certain generalized trees, called *O-trees*, as partial orders [12].

A node  $x$  is a *son* of  $y$  if  $x <_T y$  and there is no node  $z$  such that  $x <_T z <_T y$ . The *degree* of a node is the number of its sons. A node of degree 0 is thus a leaf.

The *subtree* of a rooted tree  $T$  issued from a node  $u$  is  $T/u := (N_{T \leq}(u), \leq)$  where  $\leq$  is the restriction of  $\leq_T$  to  $N_{T \leq}(u)$ .

A *rooted forest*  $F$  is the union of pairwise disjoint rooted trees and  $Rt_F$  denotes the set of roots of its trees.

A finite rooted tree  $T$  can be denoted linearly by  $\tilde{T}$  defined as follows: If  $T$  has root  $r$  and subtrees  $T_1, \dots, T_p$  issued from the sons of the root, then  $\tilde{T} := r(\tilde{T}_1, \dots, \tilde{T}_p)$ . If  $T$  is reduced to  $r$ , then  $\tilde{T} := r$ . The order of the sequence  $T_1, \dots, T_p$  is irrelevant as trees are only ordered by the ancestor relation. In some cases, we can replace in this notation a node by its label.

### Logic

We will use relational structures of the following types :  $(N, \leq)$  to describe a partial order, a rooted tree or an order-theoretic tree,  $(V, \text{edg})$  to describe a graph with set  $V$  of vertices, and  $\text{edg}(x, y)$  means that there is an edge between  $x$  and  $y$ . Betweenness structures are of the form  $(N, B)$  where  $B$  is a ternary relation. Vertex or node labellings are formalized by additional unary relations. If  $S$  is a relational structure with domain  $N$  and  $X \subseteq N$ , then  $S[X]$  denotes the induced substructure with domain  $X$  and  $\subseteq_i$  denotes an induced inclusion of relations.

Properties will be expressed by first-order (FO) or monadic-second order (MSO) sentences. A *sentence* is a formula without free variables. For example, that a graph  $G$  has no induced subgraph isomorphic to a finite graph  $H$  is FO expressible. That a graph  $G$  is not connected is expressed in its representing structure  $(V, \text{edg})$  by the following MSO sentence:

$$\exists X[(\exists x.x \in X) \wedge (\exists y.y \notin X) \wedge (\forall x, y(x \in X \wedge y \notin X) \implies \neg \text{edg}(x, y)].$$

See the book [9] for a detailed study of monadic second-order logic.

We abbreviate *first-order* into FO and *monadic second-order* into MSO. We consider classes of finite or countably infinite structures. Such a class is *MSO* (or *FO*) *definable* if it is the class of finite or countably infinite models of an MSO (or FO) sentence.

The *finiteness set predicate*  $Fin(X)$  expresses that a set  $X$  is finite. The finiteness of a set  $X \subseteq N$  is not MSO expressible, unless some linear order on  $N$  can be defined by MSO formulas (see Example 1.6 in [6]). This is the case for example if  $N$  is the set of nodes of a ternary tree. An  $MSO_{fin}$ -sentence is an MSO-sentence where  $Fin(X)$  can be used.

All trees, graphs and relational structures are finite or countably infinite.

## 2 Cographs and related notions

In this section all graphs and trees are finite.

### Definition 2.1 : Cographs

(a) A graph is a *cograph* if and only if it can be generated from isolated vertices by the operations  $\oplus$  and  $\otimes$  if and only if it has no induced path  $P_4$ . There are many other characterizations [18]. The family of cographs is hereditary. only bound is  $P_4$ .

(b) The cycle  $a - b - c - d - a$  is defined by the term  $(a \oplus c) \otimes (b \oplus d)$ . To define it up to isomorphism, that is, without naming the vertices, we will use the term  $(\bullet \oplus \bullet) \otimes (\bullet \oplus \bullet)$ . We can use the notation  $t_1 \oplus t_2 \oplus \dots \oplus t_n$  because the operation  $\oplus$  is associative, and similarly for  $\otimes$ . We can also use the notation  $\oplus(t_1, t_2, \dots, t_n)$  or  $\otimes(t_1, t_2, \dots, t_n)$  if we consider  $t$  as a rooted tree whose internal vertices are labelled by  $\oplus$  or  $\otimes$ .

(c) The syntactic tree of term defining a cograph  $G = (V, E)$  is called a  $\{\oplus, \otimes\}$ -tree. It is a rooted tree whose set of leaves is  $V$  and whose internal nodes are of degree at least 2 and labelled by  $\oplus$  or  $\otimes$ .

### Definition 2.2 : 2-graphs

A *2-graph* is a graph  $(V, E)$  equipped with a bipartition  $V_1 \uplus V_2$  of its vertex set  $V$ . We will say that  $x \in V_i$  is an *i-vertex*. The *type* of a finite path  $x_1 - x_2 - \dots - x_n$  in a 2-graph is the word  $b_1 b_2 \dots b_n$  over  $\{1, 2\}$  such that, for each  $i$ ,  $x_i$  is a  $b_i$ -vertex.  $\square$

### Definitions 2.3 : Probe cographs

(a) A *partitioned probe cograph* (a *pp-cograph* in short) is a 2-graph obtained from a cograph  $(V, E)$  by choosing a bipartition  $V_1 \uplus V_2$  of  $V$  and removing the edges between its 1-vertices.

(b) A *probe cograph* (a *p-cograph* in short) is obtained from a pp-cograph by forgetting the bipartition (and the corresponding labelling of its vertices by 1 or 2).

(c) A bipartition of a graph (or a vertex-labelling by 1 or 2) is *good* if it makes it into a pp-cograph.

(d) Partitioned probe cographs can be defined by terms, similar to those that define cographs, using the operation  $\oplus$  and the operation  $\otimes$  that we redefine as follows for 2-graphs:  $G \otimes H$  is  $G \oplus H$  augmented with all edges between an  $i$ -vertex of  $G$  and a  $j$ -vertex of  $H$ , provided  $i$  and  $j$  are not both 1. It is associative. A nullary symbol  $\bullet_i(x)$  defines  $x$  as an isolated  $i$ -vertex.

The path  $P_4 = a - b - c - d$  with labelling of type 1212 is a pp-cograph defined by the term  $\bullet_1(c) \otimes ([\bullet_1(a) \otimes \bullet_2(b)] \oplus \bullet_2(d))$ . To define it up to isomorphism, we can use the term  $\bullet_1 \otimes ([\bullet_1 \otimes \bullet_2] \oplus \bullet_2)$ . Note that  $\bullet_1(x) \otimes \bullet_1(y)$  and  $\bullet_1(x) \oplus \bullet_1(y)$  define the same 2-graph. See also Example 2.5(1).  $\square$

We review some results from [10, 15].

**Proposition 2.4 :** (1) The class of partitioned probe cographs is hereditary. Its bounds are the paths of types 2222, 1222, 2122 or 21212 and the 2-graph  $Q$  defined as the path  $a - b - c - d - e$  of type 12221 augmented with the edge  $b - d$ . Its graphs can be recognized in linear time.

(2) The class of probe cographs is hereditary and has finitely many bounds. Its graphs can be recognized in linear time.

An immediate consequence of interest for the present article is that pp-cographs are definable among 2-graphs by a first-order (FO) sentence, effectively constructed from the five *known* bounds. Probe cographs are so but the corresponding FO sentence is not known, because the complete list of bounds is not either. However, their bounds are definable in monadic second-order (MSO) logic by a known sentence, obtained from the FO sentence that defines the pp-cographs. We will discuss these points in Section 5.

**Examples 2.5:** (1) The path  $P_4$  is not a cograph. It has good labellings of types 1212 and 1221. Its labellings of type 1222, 2122 and 2222 are not good.

(2) The labelled path  $P_5 = a - b - c - d - e$  of type 12121 is a pp-cograph defined by the term  $\bullet_1(c) \otimes [(\bullet_1(a) \otimes \bullet_2(b)) \oplus (\bullet_1(e) \otimes \bullet_2(d))]$ . No other labelling of it is good, which follows from Proposition 2.4(1).

(3) The path  $P_6 = a - b - c - d - e - f$  is not a p-cograph. Assume it has a good labelling. The induced path  $a - b - c - d - e$  must have type 12121 and  $f$  must have label 2. But then  $b - c - d - e - f$  has type 21212, which is not possible by (1). It follows that a p-cograph has no induced  $P_6$ . Hence, a connected p-cograph cannot have diameter 5 or more because otherwise, it would contain an induced path  $P_6$ . Furthermore,  $P_6$  is a bound of p-cographs.

(4) All graphs having at most 5 vertices except the cycle  $C_5$  are p-cographs.  $\square$

### 3 Order-theoretic trees

**Definition 3.1:** (a) An *order-theoretic forest* (an *O-forest* in short) is a partial order  $J = (N, \leq)$  such that, for each  $x \in N$ , the set  $L_{\geq}(x) := \{y \mid y \geq x\}$  is linearly ordered. An O-forest is an *O-tree* if every two nodes have an upper-bound. An O-tree is a *join-tree* if every two elements  $x$  and  $y$  have a least upper-bound, denoted by  $x \sqcup y$  and also called their *join*. An O-tree may have no largest node. Its largest node if it exists is called the *root*. If  $x \sqcup y$  and  $y \sqcup z$  are defined, then so is  $x \sqcup z$  and it belongs to  $\{x \sqcup y, y \sqcup z\}$ .

(b) If  $u < w$ , then we say that  $w$  is an *ancestor* of  $u$ .

(c) A *line* in an O-forest  $(N, \leq)$  is a subset  $L$  of  $N$  that is linearly ordered and *convex*, *i.e.*, is such that  $z \in L$  if  $x, y \in L$  and  $x < z < y$ .

(d) A *leaf* is a minimal node. It has *degree* 0; the set of leaves is denoted by  $L_J$ .

(e) A node  $x$  has *degree* 1 if there is  $y < x$  such that every node  $z < x$  is comparable with  $y$ . For finite forests, this is equivalent to the definition in

Section 1. If we delete nodes of degree 1 of an O-forest  $J$ , we obtain a (possibly empty) O-forest  $J'$  such that  $J' \subseteq_j J$  because a node of degree 1 is not the join of any two incomparable nodes.  $\square$

**Definition 3.2 :** *Substitutions of lines in O-forests.*

Let  $J = (N, \leq)$  be an O-forest and, for each  $x \in N$ , let  $(A_x, \leq_x)$  be a (possibly empty or singleton) linearly ordered set. These sets are assumed to be pairwise disjoint. We let  $J' = J[A_x/x; x \in N] := (N', \leq')$  be the partial order such that :

$N'$  is the union of the sets  $A_x$ ,

$u \leq' v$  if and only if either  $u \leq_x v$ , or  $u \in A_x, v \in A_y$  and  $x < y$ .

It is an O-forest in which each nonempty  $A_x$  is a line.

**Definitions 3.3 :** *The join-completion of an O-forest.*

Let  $J = (N, \leq)$  be an O-forest and  $\mathcal{K}$  be the set of upwards closed lines  $L_{\geq}(x, y) := L_{\geq}(x) \cap L_{\geq}(y)$  for all (possibly equal) nodes  $x, y$ . If  $x$  and  $y$  have a join, then  $L_{\geq}(x, y) = L_{\geq}(x \sqcup y)$ . If they have no upper-bound, then  $L_{\geq}(x, y)$  is empty.

The family  $\mathcal{K}$  is countable. We let  $h : N \rightarrow \mathcal{K}$  map  $x$  to  $L_{\geq}(x)$  and  $\widehat{J} := (\mathcal{K}, \supseteq)$ . We call  $\widehat{J}$  the *join-completion* of  $J$  because of the following proposition, stated with these hypotheses and notation.

**Proposition 3.4** [6] : The partially ordered set  $\widehat{J} := (\mathcal{K}, \supseteq)$  is a join-tree and  $h$  is a join-embedding  $J \rightarrow \widehat{J}$ .  $\square$

If we identify  $x \in N$  with  $h(x) = L_{\geq}(x)$ , we have a join-preserving inclusion  $J \subseteq_j \widehat{J}$ . The join of  $h(x)$  and  $h(y)$  is  $L_{\geq}(x, y)$ .

The following side proposition shows that cographs arise naturally from O-forests. We recall that  $\perp$  denotes incomparability.

**Proposition 3.5:** The cocomparability graph  $CC(J) := (N, \perp)$  of a finite forest  $J = (N, \leq)$  is a cograph.

**Proof sketch:** First we consider the cocomparability graph  $CC(T) = (N, \perp)$  of a finite rooted tree  $T = (N, \leq)$  is a cograph. If  $T = a(T_1, \dots, T_n)$  and  $n \geq 2$ , then  $CC(T) = a \oplus (CC(T_1) \otimes \dots \otimes CC(T_n))$ . If  $n = 1$ , we have  $CC(T) = a \oplus CC(T_1)$ .  $\square$

If we define as a cograph an infinite graph without induced path  $P_4$ , then this proposition extends to countable O-forests.



## 4 Betweenness in order-theoretic trees

We will consider ternary structures  $S = (N, B)$ . If  $n > 2$ , the notation  $\neq(x_1, x_2, \dots, x_n)$  means that  $x_1, x_2, \dots, x_n$  are pairwise distinct, hence it abbreviates an FO formula. If  $n > 3$ , then  $B^+(x_1, x_2, \dots, x_n)$  abbreviates the FO formula

$$B(x_1, x_2, x_3) \wedge B(x_2, x_3, x_4) \wedge \dots \wedge B(x_{n-2}, x_{n-1}, x_n)$$

and  $A(x_1, x_2, x_3)$  abbreviates

$$B(x_1, x_2, x_3) \vee B(x_2, x_1, x_3) \vee B(x_1, x_3, x_2).$$

**Definitions and background 4.1 :** *O-forests and their betweenness relations.*

(a) The *betweenness relation* of an O-forest  $J = (N, \leq)$  is the ternary relation  $B_J \subseteq N^3$  such that :

$$B_J(x, y, z) : \iff \neq(x, y, z) \wedge ([x < y \leq x \sqcup z] \vee [z < y \leq x \sqcup z]).$$

If  $x \sqcup z$  is undefined, then  $B_J(x, y, z)$  holds for no triple  $(x, y, z)$ . If  $x < y < z$ , we have  $B_J(x, y, z)$ .

We denote by **BO** the class of betweenness structures  $(N, B_J)$  of O-forests  $J = (N, \leq)$ .

(b) The following related classes have been considered in [5, 6].

**IBO** is the class of induced substructures of the structures in **BO**.

**QT** (for *quasi-trees*) is the class of betweenness structures of join-trees.

**IBQT** is the class of induced substructures of structures in **QT**.

We have the following proper inclusions :

$$\mathbf{QT} \subset \mathbf{IBQT} \cap \mathbf{BO},$$

$$\mathbf{IBQT} \subset \mathbf{IBO} \text{ and}$$

$$\mathbf{BO} \subset \mathbf{IBO}.$$

The classes **IBQT** and **BO** are incomparable, and for finite structures, we have **QT** = **BO**.

(c) The betweenness relation  $B$  of a rooted tree  $T = (N, \leq)$ , (hence,  $(N, B) \in \mathbf{QT}$ ) satisfies the following properties for all  $x, y, z, u \in N$ :

$$A1 : B(x, y, z) \Rightarrow \neq(x, y, z).$$

$$A2 : B(x, y, z) \Rightarrow B(z, y, x).$$

$$A3 : B(x, y, z) \Rightarrow \neg B(x, z, y).$$

$$A4 : B(x, y, z) \wedge B(y, z, u) \Rightarrow B^+(x, y, z, u).$$

$$A5 : B(x, y, z) \wedge B(x, u, y) \Rightarrow B^+(x, u, y, z).$$

$$A6 : B(x, y, z) \wedge B(x, u, z) \Rightarrow y = u \vee B^+(x, u, y, z) \vee B^+(x, y, u, z).$$

$$A7 : \neq(x, y, z) \Rightarrow A(x, y, z) \vee \exists w [B(x, w, y) \wedge B(y, w, z) \wedge B(x, w, z)].$$

Conversely, every ternary structure satisfying these properties is in **QT** [3]. Furthermore, the class **IBQT** is FO definable (this is not immediate), and the class **BO** is MSO definable [5, 6]. The case of **IBO** was left as a conjecture. We will prove the following.

**Theorem 4.2** : The class **IBO** is  $\text{MSO}_{fin}$ -definable.

We will consider ternary structures  $(N, B)$  that always satisfy the FO-expressible properties A1-A6. These properties hold in every structure in **IBO** but do not characterize this class (Proposition 3.22 of [6]).

#### 4.1 Preliminary results on IBO

**Defintion 4.3** : The *Gaifman graph* of a ternary structure  $S = (N, B)$  is the graph  $Gf(S)$  whose vertex set is  $N$  and that has an edge  $u - v$  if and only if  $u$  and  $v$  belong to some triple in  $B$ . We say that  $S$  is *connected* if  $Gf(S)$  is. If it is not, then  $S$  is the disjoint union of the induced structures  $S[X]$  for all connected components  $X \subseteq N$  of  $Gf(S)$ .

**Lemma 4.4:** (1) A structure  $S$  is in **IBO** if and only if its connected components are.

(2) If a structure  $S$  in **IBO** is connected, then it is an induced betweenness relation of an O-tree.

**Proof:** (1) The "only if" direction is clear by the definitions. Conversely, assume that each connected component of a ternary structure  $S = (N, B)$  is in **IBO**. For each of them  $S[X]$ , let  $U_X := (M_X, \leq_X)$  be a defining O-forest (we have  $M_X \supseteq X$ ). We assume them pairwise disjoint. We let  $\mathbb{N}^R$  be  $\mathbb{N}$  ordered by reversing the natural order and assumed to be disjoint from each  $M_X$ . We let  $W$  be the union of  $\mathbb{N}^R$  and the  $U_X$ 's ordered as follows :

$$\begin{aligned} x \leq_W y \text{ if and only if} \\ x \leq y \text{ in } \mathbb{N}^R \text{ or } x \leq_X y \text{ for some component } X, \text{ or } x \text{ is in some } M_X \\ \text{and } y \in \mathbb{N}. \end{aligned}$$

Then  $W$  is an O-tree and  $B = B_W \cap N^3$ .

(2) Let  $S = (N, B)$  such that  $B = B_U \cap N^3$  for some O-forest  $U = (M, \leq)$ . Let  $M'$  be the union of the lines  $L_{\geq}(x)$  of  $U$  for all  $x \in N$ . Then  $U' := U[M']$  is an O-forest and  $B = B_{U'} \cap N^3$ . We prove that it is an O-tree if furthermore  $S$  is connected. If  $x$  and  $y$  belong to a triple in  $B$ , then they have an upper-bound in  $M'$  by the definition of  $B_U$  and, furthermore, any  $x' \geq x$  and  $y' \geq y$  also have an upper-bound in  $M'$ . Let  $u, v \in M'$ . There is a path  $x_1 - x_2 - \dots - x_n$  in  $Gf(S)$  such that  $u \geq x_1$  and  $v \geq x_n$ . Hence we have  $z_1, z_2, \dots, z_{n-1}$  such that  $z_1$  is an upper-bound of  $u$  and  $x_2, z_2$  is an upper-bound of  $z_1$  and  $x_3, \dots, z_{n-1}$  is an upper-bound of  $z_{n-2}$  and  $v \geq x_n$ . We have  $z_{n-1} \geq u$ . Hence,  $U'$  is an O-tree.  $\square$

The converse of Assertion (2) may be false: consider a star  $T = (N, \leq)$  with root  $r$  and  $S := (N - \{r\}, B)$  where  $B := B_T[(N - \{r\})]$ . Then,  $S$  is in **IBO**, defined from a tree, but not connected as  $B$  is empty.

**Definition 4.5 :** *Marked join-trees and related notions*

(a) A *marked join-tree* is a 4-tuple  $T = (M, \leq, M_\oplus, M_\otimes)$  such that  $(M, \leq)$  is a join-tree and  $M_\oplus, M_\otimes$  are disjoint subsets of  $M$  that contain no leaf. We let  $V_T := M - (M_\oplus \uplus M_\otimes)$ . Its *size* is  $|M|$ .

(b) We define the *betweenness relation*  $B_T \subseteq V_T^3$  of  $T$  as follows:

$$B_T(x, y, z) : \iff \begin{aligned} & \neq (x, y, z) \wedge x \sqcup_T z \notin M_\oplus \wedge \\ & ([x < y \leq x \sqcup_T z] \vee [z < y \leq x \sqcup_T z]). \end{aligned}$$

The join  $x \sqcup_T z$  is always defined as  $T$  is a join-tree. We have  $B_T(x, y, z)$  if  $x < y < z$ .

We let  $S_T := (V_T, B_T)$  be the *betweenness structure* of  $T$ . The Gaifman graph of  $S_T$  has vertex set  $V_T$ .

(c) If we delete from  $T$  all nodes of degree 1 belonging to  $M_\oplus \uplus M_\otimes$ , we obtain a marked join-tree having the same betweenness structure and that join-embeds into  $T$  (cf. Definition 3.1(e)). We call *reduced* such a marked join-tree.

**Lemma 4.6 :** Let  $T = (M, \leq, M_\oplus, M_\otimes)$  be a marked join-tree.

(1) If  $U = (N, \leq, N_\oplus, N_\otimes)$  join-embeds in  $T$ , then  $B_U = B_T[N \cap V_T]$ .

(2) If  $X \subseteq V_T$  and  $B = B_T[X]$ , then there exists  $U$  as (1) such that  $B_U = B$ .

(3) If  $T_1, \dots, T_n, \dots$  is a sequence of marked join-trees such that  $T_i \subseteq_j T_{i+1}$  and  $T$  is the union of the  $T_i$ 's, then  $B_T$  is the union of the increasing sequence  $B_{T_1} \subseteq_i B_{T_2} \subseteq_i \dots B_{T_n} \subseteq_i \dots$

**Proof :** (1) Since  $U$  join-embeds in  $T$ , if  $x, y \in N \cap V_T$ , then  $x \sqcup_U y = x \sqcup_T y$  and this join belongs to  $M_\oplus$  (resp.  $M_\otimes$ ) if and only if it belongs to  $N_\oplus$  (resp.  $N_\otimes$ ). The result follows from the definitions.

(2) Let  $T = (M, \leq, M_\oplus, M_\otimes)$  be a marked join-tree and  $N \subseteq M$ . Let us remove from  $T$  all subtrees  $T/u$  that contain no node of  $N$ . We obtain  $U = (N', \leq, N_\oplus, N_\otimes)$ , a marked join-tree that join-embeds in  $T$  and  $V_U = N \cap V_T$ . Hence we have  $B = B_T[N] = B_U$  by (1).

(3) We have  $T_n \subseteq_j T$  for each  $n$ . The result follows.  $\square$

**Proposition 4.7 :** (1) A structure  $S = (N, B)$  is in **IBO** if and only if is  $B = B_T$  for a marked join-tree  $T = (M, \leq, M_\oplus, M_\otimes)$  such that  $V_T = N$ .

(2) If  $N$  is finite, then  $T$  can be chosen finite of size at most  $2|N| - 1$ .

**Proof:** (1) "If" Let  $S_T := (V_T, B_T)$  be defined from a marked join-tree  $T = (M, \leq, M_\oplus, M_\otimes)$ . We will construct an O-tree  $U = (W, \leq')$  such that  $M - M_\oplus \subseteq W$  and  $B_U[V_T] = B_T$ .

For each node  $x$  in  $M_\oplus$ , we let  $\mathbb{N}_x^R$  be an isomorphic copy of  $\mathbb{N}$  ordered by reversing the natural ordering. Hence  $\mathbb{N}_x^R$  has no least element. We choose these copies pairwise disjoint and disjoint with  $M$ .

We define  $U := T[\mathbb{N}_x^R/x; x \in M_\oplus]$ . It is an O-tree by Definition 3.2 (where substitutions are defined).

If  $x \sqcup_T z \in M_\oplus$ , then  $x$  and  $z$  have no join in  $U$ .

Let  $x, y, z \in V_T$  be such that  $B_T(x, y, z)$  holds. If  $x < y < z$  or  $z < y < x$  in  $T$ , then the same holds in  $U$  and  $B_U(x, y, z)$  holds. Otherwise,  $x$  and  $z$  are incomparable and  $x < y \leq x \sqcup_T z > z$  or  $x < x \sqcup_T z \geq y > z$ . Then,  $x \sqcup_T z$  is either in  $V_T$  or is labelled by  $\otimes$ . In both cases,  $x \sqcup_T z$  is the join of  $x$  and  $z$  in  $U$ . Hence,  $B_U(x, y, z)$  holds.

Conversely, assume that  $x, y, z \in V_T$  and  $B_U(x, y, z)$  holds. If  $x < y < z$  or  $z < y < x$  in  $U$ , then the same holds in  $T$  and  $B_T(x, y, z)$  holds. Otherwise,  $x$  and  $z$  are incomparable and  $x < y \leq x \sqcup_U z > z$  or  $x < x \sqcup_U z \geq y > z$ . Then  $x$  and  $z$  have a join  $m$  in  $T$ . It must be in  $V_T \cup M_\otimes$ , otherwise,  $x \sqcup_U z$  does not exist because it would be the minimal element of  $\mathbb{N}_m^R$ . Hence  $B_T(x, y, z)$  holds. Hence  $S \in \mathbf{IBO}$ .

"Only if" Conversely, assume that  $S = (N, B)$  in  $\mathbf{IBO}$  is defined from an O-tree  $U = (M, \leq)$  such that  $N \subseteq M$  and  $B = B_U \cap N^3$ . We can assume that for every  $y \in M$ , we have  $x \leq y$  for some  $x \in N$ : if this is not the case, we replace  $M$  by the union  $M'$  of the upwards closed lines  $L_{U \geq}(x)$  for all  $x \in N$  and, letting  $U' := (M', \leq)$ , we have  $N \subseteq M'$  and  $B = B_{U'} \cap N^3$ .

Let  $W = (P, \leq)$  be the join-completion of  $U$ , cf Definition 3.3. We label by  $\otimes$  a node in  $M - N$ , and by  $\oplus$  a node in  $P - M$ . These latter nodes have been added to  $U$  in place of missing joins, according to Proposition 3.4.

*Claim :*  $B = B_W$ .

*Proof :*  $B \subseteq B_W$ . Let  $B(x, y, z)$ . If  $x < y < z$  or  $z < y < x$  in  $U$  then the same holds in  $W$  and  $B_W(x, y, z)$  holds.

Otherwise,  $x$  and  $z$  are incomparable and  $x < y \leq x \sqcup z > z$  or  $x < x \sqcup z \geq y > z$  in  $U$ . Then  $x \sqcup z$  is in  $N$  or is labelled by  $\otimes$  in  $W$ . Hence,  $B_W(x, y, z)$  holds. Then  $x \sqcup z$  is not labelled by  $\oplus$ .

Conversely, assume that  $B_W(x, y, z)$  holds. A similar proof establishes that  $B(x, y, z)$  holds.  $\square$

If  $S = (N, B)$  in  $\mathbf{IBO}$  is defined from an O-forest  $U = (M, \leq)$  as opposed to an O-tree, then its connected components are defined by O-trees. For each of them, we have a marked join-tree. We put them together in a marked join-tree with a root labelled by  $\oplus$ . (Similar to the proof of Lemma 4.4(2)).

(2) Let  $S = (N, B)$  in  $\mathbf{IBO}$  be finite and defined from a marked join-tree  $T = (M, \leq, M_\oplus, M_\otimes)$  such that  $N = V_T$  and  $B = B_T$ . By removing the nodes in  $M_\oplus \cup M_\otimes$  of degree 1, we obtain a reduced marked join-tree that defines  $S$  and has at most  $2|N| - 1$  nodes.  $\square$

**Remark 4.8 :** We observed in Proposition 2.15 of [6] that a finite structure in  $\mathbf{IBO}$  may not be defined from any *finite* O-forest  $U$  (cf. Definition 4.1). Marked join-trees remedy this "defect" and yield Proposition 4.7, a key fact for our proof.

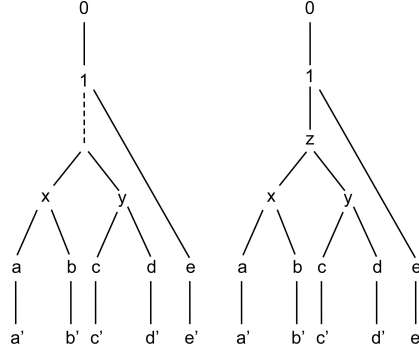


Figure 1: See Examples 4.9. In the O-tree to the left we have  $0 > 1 > 2 > 3 > \dots > n > \dots$  above  $x$  and  $y$ .

**Example 4.9 :** We consider  $S = (N, B)$  in **IBO** defined from the infinite O-tree on the left of Figure 1 where  $N = \{0, a, a', b, b', c, c', d, d', e, e'\}$ . We have:

- (a)  $B(a', a, 0), B(b', b, 0), B(c', c, 0), B(d', d, 0), B(e', e, 0),$
- (b)  $B^+(a', a, b, b'), B^+(c', c, d, d'), B^+(a', a, e, e'), B^+(b', b, e, e'),$   
 $B^+(c', c, e, e')$  and  $B^+(d', d, e, e')$ .

We do not have  $B^+(a', a, c, c')$  because  $a$  and  $c$  have no join, as the dotted line represents  $\mathbb{N}^R$ .

The right part shows a finite marked join-tree  $T = (M, \leq, M_\oplus, M_\otimes)$  where  $z$  has been added as join of  $x$  and  $y$  and the nodes  $2, 3, \dots, n, \dots$  of degree 1 above  $z$  have been deleted (cf. Definition 3.1 for the degree).

We have  $M = N \cup \{1, x, y, z\}, M_\oplus = \{z\}, M_\otimes = \{1, x, y\}$  and  $B_T = B$ .  $\square$

**Proposition 4.10 :**  $S$  is in **IBO** if and only if each of its finite substructures is.

**Proof :** The "only if" direction is clear as, by its definition, the class **IBO** is hereditary, *i.e.*, closed under taking induced substructures.

"If" direction. First, some observations. If  $S = (V_T, B)$  is defined from a marked join-tree  $T = (N, \leq, N_\oplus, N_\otimes)$  and  $S' \subseteq_i S$ , then the restriction  $T'$  of  $T$  to  $\{x \in N \mid x \geq y \text{ for some } y \in V_T\}$  is a marked join-tree that defines  $S'$ . By reducing it (Definition 4.5(c)), we get  $T'' \subseteq_j T$  that defines  $S'$ .

By Proposition 4.7, each finite structure  $S = (N, B)$  in **IBO** of size  $m = |N|$  is defined by marked join-trees of size at most  $2m - 1$ . We let  $J(S)$  be the finite set of all such join-trees, up to isomorphism.

For proving the statement, we let  $S = (N, B)$  be infinite. It is the union of an increasing sequence  $S_1 \subseteq_i S_2 \subseteq_i \dots \subseteq_i S_n \subseteq_i \dots$  of finite induced substructures that we assume to be in **IBO**.

We will use the following version of Koenig's Lemma. Let  $A_1, A_2, \dots, A_n, \dots$  be an infinite sequence of pairwise disjoint finite sets, and  $A$  be their union. Let  $R \subseteq A \times A$  be such that for every  $b$  in  $A_n, n > 1$ , there is  $a \in A_{n-1}$  such that  $(a, b) \in R$ . Then, there exists an infinite sequence  $a_1, \dots, a_n, \dots$  such that  $(a_{n-1}, a_n) \in R$  for each  $n > 1$ .

The finite sets  $J(S_n)$  are pairwise disjoint. We define

$$R := \{(T, T') \mid T \in J(S_{n-1}), T' \in J(S_n), n > 1 \text{ and } T \subset_j T'\}.$$

It follows from Lemma 4.6(2) that if  $T' \in J(S_n)$  and  $n > 1$ , we have  $(T, T') \in R$  for some  $T \in J(S_{n-1})$ .

Hence, there is an infinite sequence of marked join-trees trees

$$T_1 \subset_j T_2 \subset_j \dots \subset_j T_n \subset_j \dots \text{ such that } T_n \in J(S_n) \text{ for each } n.$$

By Lemma 4.6(3), their union is a marked join-tree  $T$  such that  $T_n \subset_j T$  for each  $n$ . We obtain an increasing sequence of finite marked join-trees whose union is a marked join-tree that defines  $S$ . Hence  $S \in \mathbf{IBO}$ .  $\square$

The proof of Theorem 4.2 reduces to that of the following proposition.

**Proposition 4.11:** There is an MSO-sentence that characterizes the finite connected structures in  $\mathbf{IBO}$  among the finite ternary structures.

**Proof of Theorem 4.2, assuming proved Proposition 4.11 :** Let  $\varphi$  be the MSO sentence such that, for every finite ternary structure  $S = (N, B)$  :

$$S \models \varphi \text{ if and only if } S \text{ is connected and in } \mathbf{IBO}.$$

Consider the MSO<sub>fin</sub> sentence  $\psi$  :

$$\forall X. (\gamma(X) \wedge \text{Fin}(X) \implies \varphi[X]),$$

where  $\gamma(X)$  expresses that  $X$  is connected in the Gaifman graph  $Gf(S)$  and  $\varphi[X]$  is the relativization of  $\varphi$  to  $X$ .

*Relativizing* a sentence to a set, here  $X$ , is a classical construction in monadic second-order logic, see *e.g.* [9], Section 5.2.1. If  $S = (N, B)$  is a ternary structure and  $X \subseteq N$ , then  $S \models \varphi[X]$  if and only if  $S[X] \models \varphi$ .

We prove that  $S \models \psi$  if and only if  $S$  is in  $\mathbf{IBO}$ .

If  $S$  is in  $\mathbf{IBO}$ , then every induced substructure  $S[X]$ , in particular every finite and connected one satisfies  $\varphi$ , hence  $S \models \psi$ .

Conversely, assume that  $S \models \psi$ . Let  $X$  be a finite subset of  $N$ . If it is connected in  $Gf(S)$ , then  $\varphi[X]$  holds hence  $S[X]$  is in  $\mathbf{IBO}$ . Otherwise, it is a disjoint union of connected sets in  $Gf(S)$ . For each of them, say  $Y$ , the validity of  $\psi$  implies that  $\varphi[Y]$  holds,  $S[Y]$  is in  $\mathbf{IBO}$  and so are  $S[X]$  by Lemma 4.4(1) and  $S$  by Proposition 4.10.  $\square$

## 4.2 Overview of the proof of Proposition 4.11

For proving Proposition 4.11, we will handle finite graphs, trees, forests and structures  $(N, B)$ . We need some definitions.

**Definition 4.12** : *Rooted forests compatible with a ternary relation.*

A rooted forest  $T = (N, \leq_T)$  is *compatible with a relation*  $B \subseteq N^3$  satisfying Axioms A1-A6 if, for all  $x, y, z \in N$  :

- (i) if  $B(x, y, z)$  holds, then  $x <_T y$  or  $z <_T y$ ,
- (ii) if  $B(x, y, z)$  and  $x <_T y >_T z$  hold, then  $y = x \sqcup_T z$ .
- (iii) if  $x <_T z$ , then  $B(x, y, z)$  holds if and only if  $x <_T y <_T z$ .  $\square$

**Lemma 4.13** : Let  $S = (N, B) \in \mathbf{IBO}$  be finite, connected and defined from a finite reduced marked join-tree  $U = (N \uplus N_{\oplus} \uplus N_{\otimes}, \leq_U, N_{\oplus}, N_{\otimes})$ .

(1) Then  $T := U[N] = (N, \leq_T)$  is a finite rooted forest compatible with  $B$ , where  $\leq_T$  is the restriction of  $\leq_U$  to  $N$ .

(2) The order  $\leq_T$  is FO definable in the structure  $(N, B, R)$  where  $R$  is the set of roots of  $T$ .  $\square$

The forest  $T$  is not necessarily a tree because the root of  $U$  need not be in  $N$ . This root cannot be labelled by  $\oplus$ , otherwise  $S$  is not connected (we exclude the trivial case where  $N$  is singleton).

**Proof** : (1) Let  $S, T, U$  as in the statement.

(i) If  $B(x, y, z)$  holds, then:

- either  $x <_U y <_U z$  or  $z <_U y <_U x$
- or  $x \perp_U z \wedge (x <_U y \leq_U x \sqcup_U z \vee z <_U y \leq_U x \sqcup_U z)$ ,
- where in the latter case,  $x \sqcup_U z \in N \cup N_{\otimes}$ .

In all cases, we have  $x <_U y$  or  $z <_U y$ , hence  $x <_T y$  or  $z <_T y$ .

(ii) If  $B(x, y, z)$  and  $x <_T y >_T z$  hold, then the above description of  $B(x, y, z)$  shows that  $y \leq_U x \sqcup_U z$ . As we have  $x <_U y >_U z$  we must have  $y = x \sqcup_U z$ . If  $y$  is not  $x \sqcup_T z$ , we have  $m \in N$ , such that  $x < m, z < m < y$  in  $T$  and in  $U$ . But then  $y$  is not the join of  $x$  and  $z$  in  $U$ . Hence,  $y = x \sqcup_T z$ .

(iii) Clear from the definitions because  $\leq_T$  is the restriction of  $\leq_U$  to  $N$ .

(2) If  $R = \{r\}$ , then  $x \leq_T y$  if and only if  $x = y$  or  $y = r$  or  $B(x, y, r)$  holds.

Otherwise, the root of  $U$  is in  $N_{\otimes}$  and has degree at least 2. Let  $x$  and  $y$  be not in  $R$ .

*Claim* : (a) If  $r \in R$ , we have  $x <_T r$  if and only if  $B(x, r, r')$  holds for some  $r' \in R$ .

(b) We have  $x <_T y$  if and only if  $B(x, y, r)$  holds for some  $r \in R$ .

*Proof:* (a) Assume that  $x <_T r$ . There is  $r' \in R$  such that  $r \sqcup_U r'$  has label  $\otimes$ . Hence  $B(x, r, r')$  holds.

Conversely, if  $B(x, r, r')$  holds for some  $r' \in R$ , we have  $x <_T r$  or  $r' <_T r$  because  $T$  is compatible with  $B$ . As  $r$  and  $r'$  are different and are distinct roots of  $T$ , they are incomparable and we have  $x <_T r$ .

(b) If  $x <_T y$ , we have  $x <_T y <_T r$  for some  $r \in R$ . Hence  $B(x, y, r)$  holds since  $T$  is compatible with  $B$ .

Conversely, if  $B(x, y, r)$  holds for some  $r \in R$ , then, we have  $x <_T y$  or  $r <_T y$ . The latter is not possible as  $r$  is a root.  $\square$

Let  $\psi(R, x, y)$  be the following FO formula (an FO formula may have free set variables and use atomic formulas  $x \in X$ ):

$$\begin{aligned} x = y \vee [x \neq y \wedge \exists r (R = \{r\} \wedge [y = r \vee B(x, y, r)])] \\ \vee [x \neq y \wedge \exists r, r' \in R (y = r \wedge B(x, y, r'))] \\ \vee [x \neq y \wedge y \notin R \wedge \exists r \in R. B(x, y, r)]. \end{aligned}$$

By the claim, it defines  $x \leq_T y$  since  $R$  is the set of roots of  $T$ .

We let  $\varphi(R)$  be the FO formula relative to ternary structures  $S = (N, B)$  expressing the following:

" $R \subseteq N$  and the binary relation  $x \leq y$  on  $N$  defined by  $S \models \psi(R, x, y)$  is a partial order and  $T := (N, \leq)$  is a forest that is compatible with  $B$  and whose set of roots is  $R$ ".  $\square$

**Proposition 4.14 :** Let  $S = (N, B)$  satisfy properties A1-A6.

(1) For every  $R \subseteq N$  such that  $S \models \varphi(R)$ , if we let  $\leq$  be defined by  $\psi(R, x, y)$ , then  $T := (N, \leq)$  is a rooted forest compatible with  $B$ .

(2) Every rooted forest  $T := U[N]$  defined from a finite marked join-tree  $U = (N \uplus N_{\oplus} \uplus N_{\otimes}, \leq_U, N_{\oplus}, N_{\otimes})$  such that  $B_U = B$  is described by the formulas  $\varphi(R)$  and  $\psi(R, x, y)$ .

**Proof :** The first assertion follows from the definition of  $\varphi$ . The second one follows from Lemma 4.13(2).  $\square$

All rooted forests  $T$  compatible with  $B$  of potential interest for checking that  $S$  is in **IBO** can be described in terms of their sets of roots  $R$  by the existential MSO formula  $\exists R. \varphi(R)$ .

We will construct MSO formulas to "check" that a "guessed" forest  $T$  satisfies additional requirements implying that  $T := U[N]$  for some finite marked join-tree  $U$  witnessing that  $S \in \mathbf{IBO}$ .

In some  $T$  that has been "guessed", we will insert (if possible) nodes labelled by  $\oplus$  or  $\otimes$  so as to make it into the desired marked join-tree  $U$ . We will insert nodes in  $T$  in the following cases:



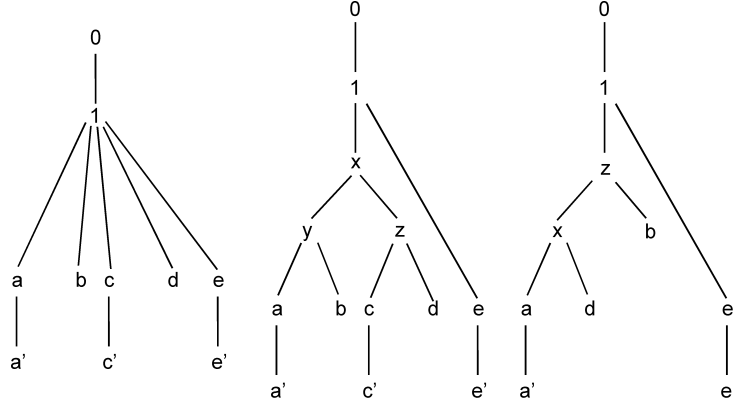


Figure 2: Example 4.15

(1) If  $a' < a$ ,  $b \perp a$ ,  $B(a', a, b)$  holds and there is no  $x$  in  $T$  such that  $\{a, b\} < x$  and  $B(a, x, b)$  holds, then we insert  $a \sqcup_U b$  labelled by  $\otimes$  such that  $a \sqcup_U b < m$  where  $m$  is any upper-bound in  $T$  of  $\{a, b\}$ .

(2) If  $a' < a$ ,  $b \perp a$  but  $B(a', a, b)$  does not hold, then we insert  $a \sqcup_U b$  as above labelled by  $\oplus$ .

In Case (1)  $a$  and  $b$  may have a join  $m$  in  $T$  but we need to insert a "new join"  $a \sqcup_U b < m$ .

**Example 4.15** : The left part of Figure 2 shows a rooted tree  $T$  constructed from the following facts relative to  $N := \{a', a, b, c', c, d, e', e, 1, 0\}$  :

- (a)  $B^+(a', a, 1, 0)$ ,  $B(b, 1, 0)$ ,  $B^+(c', c, 1, 0)$ ,  $B(d, 1, 0)$ ,  $B^+(e', e, 1, 0)$ ,
- (b)  $B^+(a', a, c, c')$ ,  $B(a', a, d)$ ,  $B(b, c, c')$ ,
- (c)  $B^+(a', a, 1, e, e')$ ,  $B^+(b, 1, e, e')$ ,  $B^+(c', c, 1, e, e')$  and  $B^+(d, 1, e, e')$ .

Facts (b) indicate the need of joins  $a \sqcup c$ ,  $a \sqcup d$ , and  $b \sqcup c$  labelled by  $\otimes$  in the marked join-tree  $U$  to be constructed. These joins are all equal to  $x$  in the tree in the middle of Figure 2. The absence of facts  $B(a', a, b)$  and  $B(c', c, d)$  indicates the need of  $\oplus$ -labelled joins  $y$  and  $z$ , respectively between  $a, b$  and  $x$ , and between  $c, d$  and  $x$ . However, no triple in  $B$  necessitates that  $b$  and  $d$  have a  $\otimes$ -labelled join. A corresponding marked join-tree is shown in the middle of Figure 2.

Consider now  $N' := \{a', a, b, d, e', e, 1, 0\} \subseteq N$  and  $B' := B[N']$ . We get a marked join-tree for  $B'$  by deleting  $c, c'$  and  $z$  from the previous one. However, another one shown to the right, that defines  $(N', B')$  where  $x$  is labelled by  $\otimes$  and  $z$  by  $\oplus$ .  $\square$

We need more definitions. We let  $B, T, U$  and  $R$ , be as above in Lemma 4.13.

**Definitions 4.16 :** *Cographs and pp-cographs defined from  $T$  and, either  $U$  or  $B$ .*

(a) For each node  $x$  of  $T$  with sons  $y_1, \dots, y_s, s \geq 2$ , we define  $y_i \sim_x y_j$  if and only if  $i = j$  or  $y_i \sqcup_U y_j \neq x$  so that this join has label  $\otimes$  or  $\oplus$ . It is easy to see that  $\sim_x$  is an equivalence relation.

We have  $y_i \sim_x y_j$  if and only if  $B(y_i, x, y_j)$  does not hold, by (ii) of compatibility, Definition 4.12.

(b) For each class  $C$  of the equivalence relation  $\sim_x$ , we define  $G_{x,C}$  as the 2-graph  $(C, E, C_1, C_2)$  such that:

$y \in C_2$  if and only if  $y' < y$  for some  $y' \in N$ ,

$y - z$  is an edge if and only if  $y$  or  $z$  is in  $C_2$  and  $y \sqcup_U z$  has label  $\otimes$ .

There are no edges between vertices in  $C_1$ . Hence  $G_{x,C}$  is a pp-cograph. We obtain a cograph if we add edges  $y - z$  such that  $y$  and  $z$  are in  $C_1$  and  $y \sqcup_U z$  has label  $\otimes$ .

(c) Let  $R = \{r_1, \dots, r_p\}, p \geq 2$ . We let  $G_{root}$  be the 2-graph  $(R, E, R_1, R_2)$  defined as  $G_{x,C}$  above, where  $R$  replaces  $C$  and  $y \in R_2$  if and only if  $y' < y$  for some  $y' \in N$ . It is also a pp-cograph.  $\square$

**Lemma 4.17 :** The edges  $y - z$  of  $G_{x,C}$  and  $G_{root}$  are characterized by the FO formula  $(\exists y' < y, B(y', y, z)) \vee (\exists z' < z, B(z', z, y))$ .

**Proof :** Consider  $x \in N$  and sons  $y$  and  $z$  of  $x$  in a class  $C$  of  $\sim_x$ .

Let  $y - z$  be an edge of  $G_{x,C}$  such that  $y \in C_2$  and  $y \sqcup_U z$  has label  $\otimes$ . Then  $B_U(y', y, z)$  holds for all  $y' < y$  and so does  $B(y', y, z)$  as  $B = B_U$ .

Conversely, if  $y' < y \wedge B(y', y, z)$  holds, then the join  $y \sqcup_U z$  must have label  $\otimes$  or be in  $N$ . But in the latter case, it must be  $x$  as  $y$  and  $z$  are sons of  $x$ . Hence, we have  $B(y, x, z)$  but then we do not have  $y \sim_x z$ . Hence,  $y - z$  is an edge of  $G_{x,C}$ .

The proof is similar for  $G_{root}$ . The join  $y \sqcup_U z$  cannot be in  $N$  as  $y, z$  are distinct roots.  $\square$

It follows that the 2-graphs  $G_{root}$  and  $G_{x,C}$  can be defined from  $B$  and  $T$  only, without using  $U$  that we are actually looking for. Furthermore, they can be described by FO formulas in the structure  $(N, B, R)$ .

**Proposition 4.18 :** Let  $S = (N, B)$  and  $T = (N, \leq)$  be defined for some  $R$  satisfying  $\varphi(R)$  by the formula  $\psi(R, x, y)$ .

(1) There exists a marked join-tree  $U \supseteq T$  such that  $B = B_U$  if and only if the 2-graphs  $G_{root}$  and  $G_{x,C}$  are pp-cographs.

(2) This condition is FO expressible in the structure  $(N, B, \leq)$ .

**Proof:** (1) The "only if" direction follows from the previous constructions.

Conversely, assume that each 2-graph  $G_{x,C}$  (determined solely from  $T$  and  $B$  by Lemma 4.17) as in the statement is a pp-cograph. By adding some edges between its 1-vertices, we can get a cograph  $H_{x,C} \supseteq G_{x,C}$ . It is defined by an

$\{\oplus, \otimes\}$ -tree  $t_{x,C}$  (Definition 2.1(c)), a rooted tree whose internal nodes are labelled by  $\oplus$  or  $\otimes$  and whose set of leaves is  $C$ .

Similarly, if  $T$  has several roots and  $G_{root}$  is a pp-cograph, there is a cograph  $H_{root} \supseteq G_{root}$  defined by a  $\{\oplus, \otimes\}$ -tree  $t_{root}$  whose set of leaves is  $R$ .

By inserting in  $T$  the internal nodes of  $t_{x,C}$  between  $x$  and the nodes in  $C$ , for all relevant pairs  $(C, x)$ , and those of  $t_{root}$  above the roots of  $T$ , we get a marked join-tree  $U$  such that  $U \supseteq T = U[N]$  and  $B = B_U$ .

This can be formalized as follows. By bottom-up induction, we define marked join-trees  $T_x$  and  $T_{x,C}$  for each  $x$  in  $N$  and equivalence class  $C$  of the relation  $\sim_x$ . We assume that the trees  $t_{x,C}$  and  $t_{root}$  are pairwise disjoint.

(a) If  $x$  is a leaf, then  $T_x := x$ . There is no set  $C$  to consider.

Otherwise,  $T_x := x(\dots, T_{x,C}, \dots)$  where the list covers all equivalence classes  $C$  of  $\sim_x$ . (We use the linear notation of finite rooted trees defined in Section 1).

(b) If  $C = \{y\}$ , then  $T_{x,C} := T_y$ .

Otherwise, we use the  $\{\oplus, \otimes\}$ -tree  $t_{x,C}$  as follows:  $T_{x,C} := t_{x,C}[\dots, T_y/y, \dots]$ , denoting the substitution in  $t_{x,C}$  of  $T_y$  for each  $y \in C$  (it is a leaf of  $t_{x,C}$ ).

(c) To complete the construction, we define  $U := T_r$  if  $T$  is a tree with root  $r \in N$ .

Otherwise,  $U := t_{root}[\dots, T_r/r, \dots]$  denoting the substitution in  $t_{root}$  of  $T_r$  for each leaf  $r \in R$  (it is a leaf of  $t_{root}$ ).

It is clear that  $U$  is a marked join-tree  $(N \uplus N_{\oplus} \uplus N_{\otimes}, \leq_U, N_{\oplus}, N_{\otimes})$  and that  $T = U[N]$ .

*Claim :*  $B_U = B$ .

*Proof :* Note that  $\leq_T$  is the restriction of  $\leq_U$  to  $N$ .

If  $x$  and  $z$  are comparable, then  $(x, y, z) \in B_U$  if and only if  $x <_U y <_U z$  if and only if  $x <_T y <_T z$  if and only if  $(x, y, z) \in B$  since  $T$  is compatible with  $B$ .

We now assume  $x \perp z$  and  $(x, y, z) \in B$ .

Let  $u := x \sqcup_U z$ . By the compatibility of  $T$  with  $B$  (point (ii)), we have  $x <_T y$  or  $z <_T y$ .

(a) If  $u \in N$ , then  $u = x \sqcup_T z$ . Again by compatibility (point (i)), we do not have  $u <_T y$ . Hence, we have  $x <_T y \leq_T u >_T z$  or  $z <_T y \leq_T u >_T x$ . The same inequalities hold with  $\leq_U$  hence  $(x, y, z) \in B_U$ .

(b) Otherwise,  $u$  has label  $\oplus$  or  $\otimes$ . Let  $x'$  be maximal in  $N$  such that  $x \leq x'$  and  $z'$  be similar for  $z$ .

(b.1) If  $x'$  and  $z'$  have no upper-bound in  $T$ , they are distinct roots and  $u$  is an internal node of  $G_{root}$ .

As noted above, we have  $x <_T y$  or  $z <_T y$ . Assume the first, wlog. Then  $x <_T y \leq_T x'$ .

If  $u$  has label  $\otimes$  then  $B_U(x, y, z)$  holds by the definition of  $B_U$ .

(If  $u$  has label  $\oplus$  then  $B_U(x, y, z)$  does not hold, but the definition of the edges of  $G_{root}$  gives that  $B_U(x, y, z)$  does not hold.)

(b.2) If  $x'$  and  $z'$  have a least upper-bound  $m$  in  $T$ , then,  $u <_U m$ . We have two cases:

*Case 1* :  $B(x, m, z)$  holds. We cannot have  $y >_T m$ , hence, we have  $x <_T y \leq_T m >_T z$  or  $z <_T y \leq_T m >_T x$ . The same inequalities hold with  $\leq_U$ , hence  $(x, y, z) \in B_U$ .

*Case 2* : if  $B(x, m, z)$  does not hold. Then  $x' \sim_m z'$  (we cannot have  $B(x', m, z')$ ) and so  $x'$  and  $z'$  belong to a same class  $C$  of  $\sim_m$ . Then we use the same argument as above with  $G_{m,C}$  instead of  $G_{root}$ .

The proof that  $B_U \subseteq B$  is similar.  $\square$

This completes the proof of Assertion (1).

(2) The following facts can be expressed in the structure  $(N, \leq, B)$  such that  $S = (N, B)$  satisfies A1-A6 and  $T = (N, \leq)$  is a forest compatible with  $B$  by MSO formulas that are easy to write explicitly:

$\alpha(R, R_1, R_2)$  :  $R$  is the set of root of  $T$ , it is not singleton and  $(R_1, R_2)$  is its partition defined in Definition 4.16(c).

$\beta(x, y, z)$  :  $y < x \wedge z < x \wedge y \sim_x z$ , ( $y$  and  $z$  are sons of  $x$  in  $T$ ) cf. Definition 4.16(a).

$\gamma(x, C, C_1, C_2)$  :  $C$  is a set of sons of  $x$  and an equivalence class of  $\sim_x$ ,  $(C_1, C_2)$  is its partition defined in Definition 4.16(b).

$\eta(R, y, z)$  :  $y - z$  is an edge of  $G_{root}$ .

$\eta'(x, C, y, z)$  :  $y - z$  is an edge of  $G_{x,C}$ .

$\pi(R)$  :  $R$  is not singleton and  $G_{root}$  is a pp-cograph (we use  $\alpha$  and  $\eta$ ).

$\pi'(x, C, y, z)$  :  $G_{x,C}$  is well-defined and is a pp-cograph (we use  $\gamma$  and  $\eta'$ ).

It is MSO expressible in  $(N, B, \leq)$  by Proposition 2.4(1) whether the 2-graphs  $G_{root}$  and  $G_{x,C}$  are all pp-cographs. The condition of Assertion (1) is thus MSO expressible in the structure  $(N, B, \leq)$  by an MSO sentence  $\mu$ .  $\square$

**Proof of Proposition 4.11:** We must prove that an MSO-sentence can characterize the finite connected structures in **IBO** among the finite ternary structures. There is an MSO sentence  $\chi$  expressing that a ternary structure  $S = (N, B)$  is connected and satisfies A1-A6. The sentence over  $S = (N, B)$  defined as  $\exists R(\varphi(R) \wedge \mu'(R))$  where  $\mu'$  translates  $\mu$  (of Proposition 4.18(2)) by using  $\psi(R, x, y)$  to define  $\leq$  expresses well that  $S$  is in IBO by Proposition 4.18(1).  $\square$

## 5 Clique-width and the bounds of probe cographs

We discuss some properties of probe cographs. We first review clique-width.

**Definition 5.1** : *Clique-width*.

(a) Simple loop-free undirected graphs are built with the help of vertex labels (in addition to the labels of 2-graphs). Each vertex has a *label* in a set  $L$ . The nullary symbol  $\mathbf{a}(x)$  where  $a \in L$ , denotes the isolated vertex  $x$  labelled by  $a$ . The operations are the union  $\oplus$  of disjoint graphs, the unary operations  $add_{a,b}$  for  $a, b \in L, b \neq a$ , that adds an edge between each  $a$ -labelled vertex and each  $b$ -labelled vertex (unless they are already adjacent), the unary operation  $relab_{a \rightarrow b}$  that changes every vertex label  $a$  into  $b$ .

(b) A term over the above defined operations is *well-formed* if no two occurrences of nullary symbols denote the same vertex (so that the graphs defined by two arguments of any operation  $\oplus$  are disjoint). We call them the *clique-width terms*. Each term  $t$  denotes a vertex labelled graph  $\mathbf{val}(t)$  whose vertices are those specified by the nullary symbols of  $t$ . Its *width* is the number of labels that occur in  $t$ . The *clique-width* of a graph  $G$  without labels from  $L$  (but possibly with labels from another set like  $\{1, 2\}$ ), denoted by  $cwd(G)$ , is the least width of a term  $t$  that denotes some vertex labelling of  $G$ .

(c) Clique-width terms may contain redundancies: for example  $add_{a,b}(add_{c,d}(add_{a,b}(G))) = add_{c,d}(add_{a,b}(G))$  and  $relab_{a \rightarrow b}(relab_{a \rightarrow c}(G)) = relab_{a \rightarrow c}(G)$  for every graph  $G$ . It follows that each graph of clique-width at most  $k$  is defined by infinitely many terms written a fixed set  $L$  of  $k$  labels. However, one can "normalize" these terms so that we avoid these redundancies. This is done in Proposition 2.121 of [9]. Let us call *normal* such a term. It follows that for each graph of clique-width at most  $k$  there is a finite number of normal terms that define it and use the labels in  $L := [k]$ . Furthermore, the set  $N_k$  of normal terms that use the labels in  $[k]$  is recognizable by a finite automaton, see [9].  $\square$

**Proposition 5.2 :** The maximal clique-width of a probe cograph is 4.

**Proof :** The upper-bound, observed in [10], is easy to establish. The bound 4 is reached by the probe cograph defined by the term :

$$[\bullet_1(1) \oplus (\bullet_1(2) \otimes \bullet_2(7)) \oplus (\bullet_1(3) \otimes \bullet_2(8))] \otimes \\ [\bullet_1(4) \oplus (\bullet_1(5) \otimes \bullet_2(9)) \oplus (\bullet_1(6) \otimes \bullet_2(10))]$$

shown in Figure 1, where the leaves 1,...,6 define 1-vertices and the leaves 7 to 10 (written in Italcs) define 2-vertices. It has clique-width<sup>1</sup> 4.  $\square$

**Proposition 5.3:** Apart from  $P_6$ , the finitely many bounds of probe cographs have diameter at most 4 and clique-width bounded by 8. They are connected and MSO definable.

**Proof :** Since the class of probe cographs is closed under disjoint union, their bounds are connected.

We have observed that  $P_6$  of diameter 5 is a bound. Any other graph of diameter at least 5 contains properly an induced path  $P_6$ , hence cannot be a bound.

If a graph has  $G - x$  has clique-width  $k$ , then  $G$  has clique-width at most  $2k$  [13]. Hence, as probe cographs have clique-width at most 4, their bounds have clique-width at most 8.

If  $\mathcal{C}$  is an hereditary class of graphs, then its bounds form the class:

$$\underline{Bnd(\mathcal{C}) := \{G \mid G \notin \mathcal{C} \text{ and } G - x \in \mathcal{C} \text{ for each vertex } x \text{ of } G\}}.$$

<sup>1</sup>The verification has been done by using the software TRAG [11] that is accessible on-line. It is based on [14].

If  $\mathcal{C}$  is defined by an MSO sentence  $\theta$ , then  $Bnd(\mathcal{C})$  is defined by the MSO sentence :

$$\neg\theta \wedge \forall X(\theta[X] \text{ and } "X \text{ is the set of all vertices minus one"}).$$

By Proposition 2.4(1) the class of pp-cographs is FO definable. Hence, the class of probe cographs is MSO definable, because an existential set quantification is useful to guess a good labelling of the given graph. The corresponding MSO sentence is known from the knowledge of the bounds of pp-cographs. However, the class of probe cographs is FO-definable by Proposition 2.4(2), but we do not know the corresponding sentence as the bounds of probe cographs are not completely known.  $\square$

**Theorem 5.4 :** There is an algorithm that can compute the finitely many bounds of the class of probe cographs. An upper-bound to their sizes is computable.

**Proof sketch :** By Proposition 5.3, we can construct effectively a monadic second-order sentence  $\xi$  that defines the class  $\mathcal{B}$  of bounds of probe cographs among finite graphs. By Theorem 6.35 of [9] or an algebraic version of it in terms of recognizable sets (Corollary 5.59), one can build a finite automaton  $\mathcal{A}$  that recognizes the set of normal terms of width at most 8 that define the graphs in  $\mathcal{B}$ . Then  $L(\mathcal{A})$  is finite as we know that  $\mathcal{B}_{\approx}$  is. However, several terms in  $L(\mathcal{A})$  may define isomorphic graphs. As  $L(\mathcal{A})$  is finite, one can list its elements and thus the graphs it defines after removing isomorphic duplicates.

The monadic second-order sentence  $\xi$  can be replaced by  $\xi \wedge \delta$  where  $\delta$  is the first-order sentence expressing that a graph is connected and its diameter<sup>2</sup> is at most 4. We obtain in this way a more restrictive set  $L(\mathcal{A})$  without missing any graph in  $\mathcal{B}$  except  $P_6$ , but we know it.

*Pumping lemmas* are classical tools of language theory by which one can bound the sizes of the terms of a finite recognizable set, without listing them. However the obtained bound would be ridiculous huge.  $\square$

This decision procedure is actually intractable, because of the complexity of the sentence  $\xi$  and the size of the corresponding automata, needing to handle terms with 8 labels.

For the reader interested in determining exactly the bounds of probe cographs, we indicate those we know. We denote by  $\overline{G}$  the edge-complement of a graph  $G$ .

**Proposition 5.5 :** The following graphs of clique-width 3 are bounds for probe cographs:

- (1) The standard graphs  $C_5, P_6, C_6, \overline{C_6}$ .
- (2) Three graphs obtained by substituting  $K_2$  (an edge) to one or two vertices of a path  $P_4$  or  $P_5$ . See Figure 3.

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<sup>2</sup>The graphs having a universal vertex have diameter  $\leq 2$ . The bounds on diameter and clique-width do not prove Conjecture 2.16.

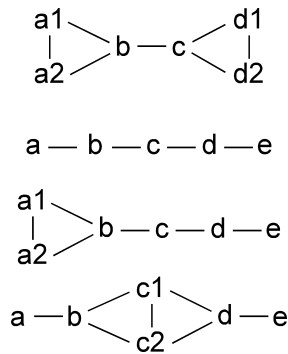


Figure 3: The graphs of Proposition 5.5(2). The second one,  $P_5$ , is a probe cograph.

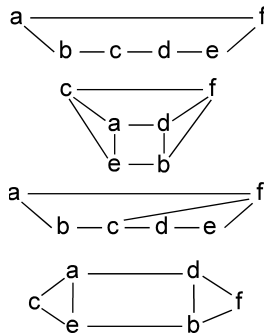


Figure 4: The bounds  $C_6, \overline{C_6}, D$  and  $\overline{D}$  of Proposition 5.5(3).

(3) The graph  $D$  obtained from the cycle  $C_6 = a - b - c - d - e - f - a$  by adding the edge  $c - f$  and its complement  $\overline{D}$  obtained from  $C_6$  by adding two edges. Its clique-width is 3. See Figure 4.

(4) Graphs obtained from the "house" by substituting edges. See Figure 5.

**Proof hints:** (2) The path  $P_5$  has a unique good labelling. If we substitute  $K_2$  for a 1-vertex, we obtain a bound.

(4) A good labelling of the house, to the left of Figure 5 must label  $c$  by 1 and either  $b$  or  $d$  by 1. We obtain two bounds, by substituting  $K_2$  to  $c$  or, to  $b$  and  $d$ .  $\square$

We do not know any graph of clique-width 4 or more that is a bound for probe cographs. Hence, for now, we are far from the upper-bound 8 of Proposition 5.3.

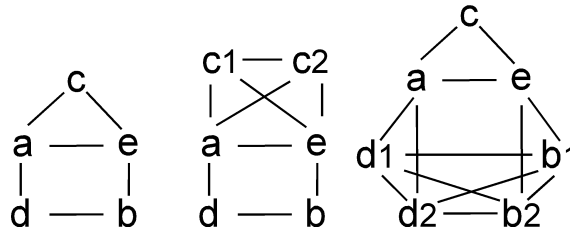


Figure 5: The "house" to the left, a probe cograph, and two bounds, cf. Proposition 5.5(4).

## 6 Conclusion

We review two open problems.

**Problem 1** : What can be said about the bounds of the class of probe cographs?

MSO logic is of no help.

**Problem 2** : Does there exist a *monadic second-order transduction*, cf. Chapter 7 of [9], that transforms a finite ternary structure assumed to be in **IBO** into a finite marked join-tree defining it?

We recall that in [6], we studied four classes of betweenness structures (cf. Definition 4.1) : **QT**, **IBQT**, **BO** and **IBO**. Each betweenness structure  $S = (N, B)$  is defined from a labelled O-tree, say  $T = (M, \leq, N_{\oplus}, N_{\otimes})$ . This description covers all cases, although labels are useless in some cases.

The question is whether some witnessing  $T$  can be defined by monadic second-order formulas in the given structure  $S$ , in technical words, by a monadic second-order transduction. A FO transduction exists for **QT** and MSO transductions exist for **IBQT** and **BO**.

Theorem 4.2 establishes that the class **IBO** is MSO definable, without building an associated MSO transduction. As a finite structure in **IBO** having  $n$  elements can be defined from a marked rooted tree with at most  $2n$  nodes, it is not hopeless to find such a transduction (an MSO transduction transforms a structure with  $n$  elements into one with at most  $kn$  elements, for some fixed  $k$ .)

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