

# Promises and Infinite-Domain Constraint Satisfaction

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Currently hiring a PhD student!

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# Constraint Satisfaction Problems

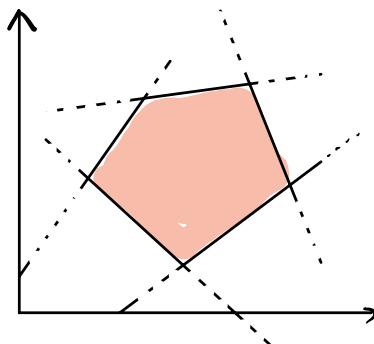
variables  $\rightsquigarrow$  domain satisfying some constraints

# Constraint Satisfaction Problems

Solve over  $\mathbb{Z}$ :

$$\begin{cases} 5x + y - z = 1 \\ x - y + z = 2 \end{cases}$$

Solve  $Ax \geq b$  over  $\mathbb{R}_{\geq 0}$ :



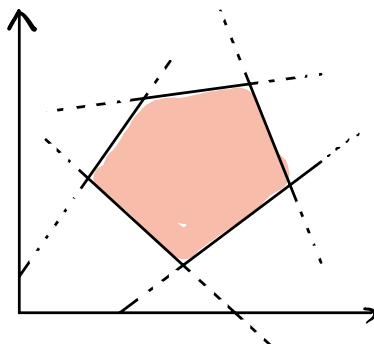
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$$\begin{cases} 5x + y - z = 1 \\ x - y + z = 2 \end{cases}$$

Solve  $Ax \geq b$  over  $\mathbb{R}_{\geq 0}$ :



Solve over  $\{\text{true}, \text{false}\}$ :

$$(p \vee q \vee \bar{r}) \wedge (\bar{r} \vee \bar{p}) \wedge (\bar{r} \vee \bar{q})$$

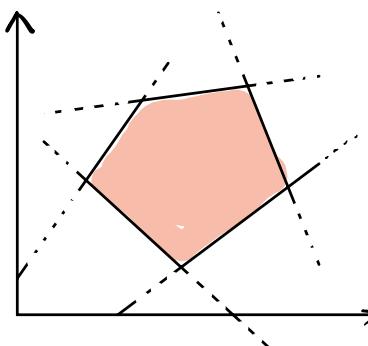
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Solve  $Ax \geq b$  over  $\mathbb{R}_{\geq 0}$ :



Solve over {true, false}:

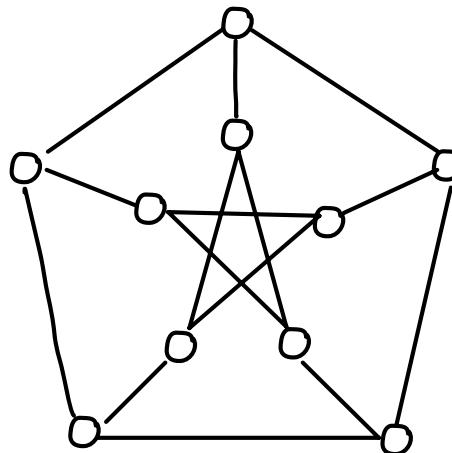
$$(p \vee q \vee \bar{r}) \wedge (\bar{r} \vee \bar{p}) \wedge (\bar{r} \vee \bar{q})$$

Solve over  $\{1, \dots, 9\}$ :

3			8	1		2
2		1		3	6	4
			2	4		
8	9				1	6
	6					5
7	2			4	9	
9		5	9			
	4		8	7	5	
6		1	7			3

variables  $\rightsquigarrow$  domain satisfying some constraints

"Solve" over {○, ○, ○}:



# Constraint Satisfaction Problems

Input:  $D \dots$  domain       $V \dots$  variables

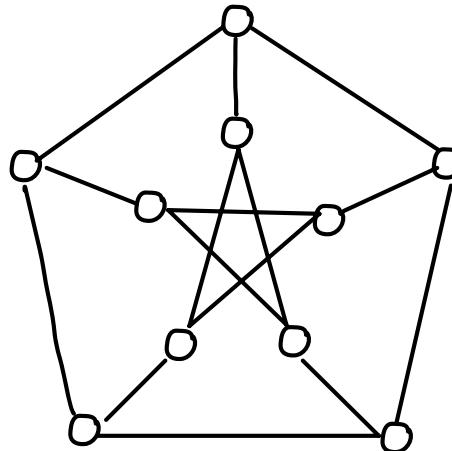
$C \dots$  constraints:  $(v_1, \dots, v_r) \rightarrow \{ \text{list of allowed assignments} \}$

Question:  $\exists h: V \rightarrow D$  satisfying all constraints?

Solve over  $\{1, \dots, 9\}$ :

3			8	1		2
2		1		3	6	4
			2	4		
8	9				1	6
	6					5
7	2			4	9	
9		5	8			
	4			7	5	
6		1	7			3

"Solve" over  $\{ \textcolor{brown}{0}, \textcolor{blue}{0}, \textcolor{green}{0} \}$ :



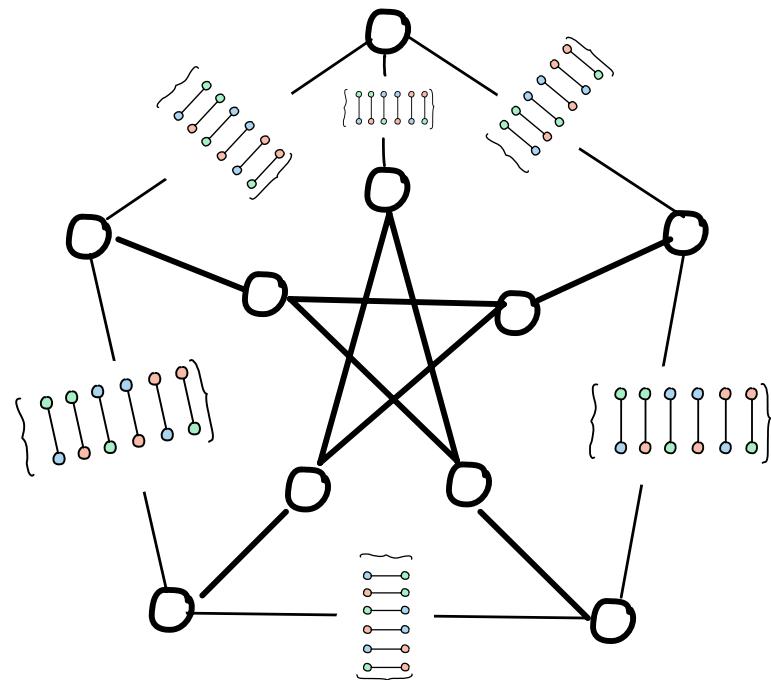
# Constraint Satisfaction Problems

Input:  $D \dots \text{domain}$        $V \dots \text{variables}$

$C \dots \text{constraints}: (v_1, \dots, v_r) \rightarrow \{\text{list of allowed assignments}\}$

Question:  $\exists h: V \rightarrow D$  satisfying all constraints?

$$D = \{ \textcolor{brown}{o}, \textcolor{blue}{o}, \textcolor{green}{o} \}$$



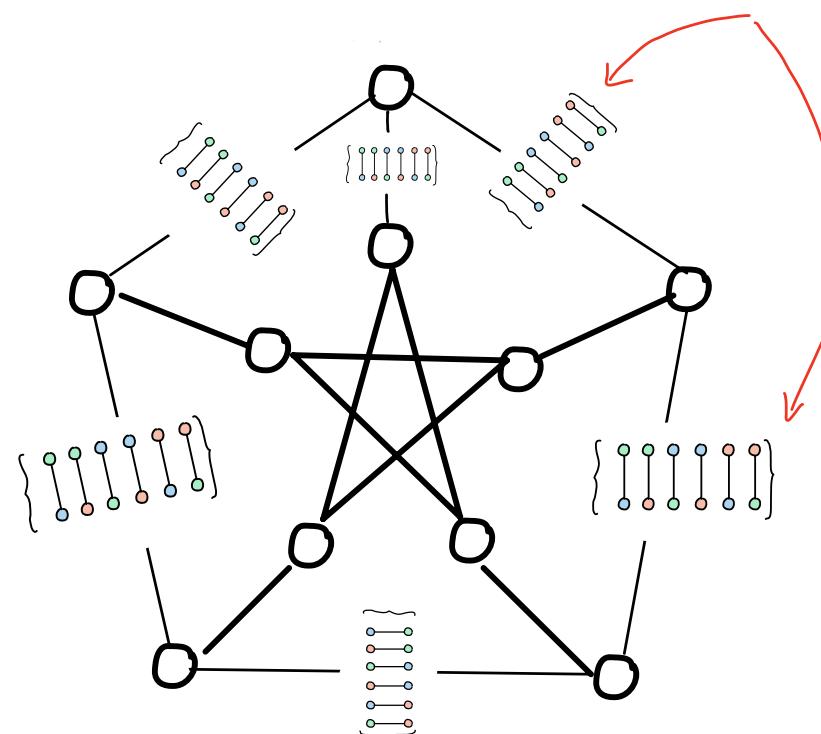
# Constraint Satisfaction Problems

Input of CSP( $D$ ):  $V \dots$  variables

C ... constraints:  $(v_1, \dots, v_r) \rightarrow E$

Question:  $\exists h: V \rightarrow D$  satisfying all constraints?

$$D = \{ \textcolor{brown}{o}, \textcolor{blue}{o}, \textcolor{green}{o} \}$$



all instances of 3-coloring  
use the same constraint relation  
 $E \subseteq D^2$

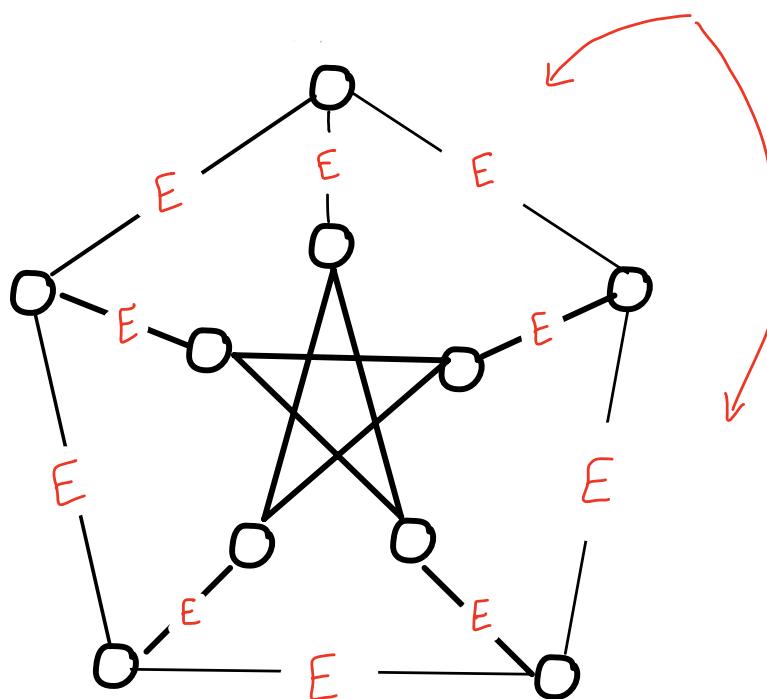
$$\mathbb{D} = (D, E)$$

# Constraint Satisfaction Problems

Input of CSP( $D$ ):  $V \dots$  variables  
 $C \dots$  constraints:  $(v_1, \dots, v_r) \rightarrow E$  } itself a relational structure  $\times$

Question:  $\exists h: V \rightarrow D$  satisfying all constraints? }  $\exists$  homomorphism  $X \rightarrow D$ ?

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# Constraint Satisfaction Problems

Input of  $CSP(D)$ :  $V \dots$  variables  
 $C \dots$  constraints:  $(v_1, \dots, v_r) \rightarrow E$  } itself a relational structure  $\times$

Question:  $\exists h: V \rightarrow D$  satisfying all constraints? }  $\exists$  homomorphism  $X \rightarrow D$ ?

3-COL

$$(\{\bullet, \circ, \textcolor{green}{\circ}\}; \{\bullet\bullet\bullet, \bullet\circ\circ, \circ\bullet\circ\})$$

1 in 3-SAT

$$(\{\text{True}, \text{False}\}; \left\{ \begin{pmatrix} \text{True} \\ \text{False} \end{pmatrix}, \begin{pmatrix} \text{False} \\ \text{True} \end{pmatrix}, \begin{pmatrix} \text{True} \\ \text{True} \end{pmatrix}, \begin{pmatrix} \text{False} \\ \text{False} \end{pmatrix} \right\})$$

Lin-Eq ( $\mathbb{F}_2$ )

$$(\{0, 1\}; \left\{ \begin{pmatrix} 1 \\ 0 \end{pmatrix}, \begin{pmatrix} 0 \\ 1 \end{pmatrix}, \begin{pmatrix} 1 \\ 1 \end{pmatrix}, \begin{pmatrix} 0 \\ 0 \end{pmatrix} \right\}, \{0\})$$

NOT-ALL-EQUAL-SAT

$$(\{\text{True}, \text{False}\}; \left\{ \begin{pmatrix} \text{True} \\ \text{False} \end{pmatrix}, \begin{pmatrix} \text{False} \\ \text{True} \end{pmatrix}, \begin{pmatrix} \text{False} \\ \text{False} \end{pmatrix}, \begin{pmatrix} \text{True} \\ \text{True} \end{pmatrix}, \begin{pmatrix} \text{True} \\ \text{False} \end{pmatrix}, \begin{pmatrix} \text{False} \\ \text{True} \end{pmatrix} \right\})$$

Horn-SAT

$$(\{\text{True}, \text{False}\}; \text{all except } \begin{pmatrix} \text{True} \\ \text{False} \end{pmatrix})$$

Theorem: (Bulatov - Zhuk '17)

For every finite  $D$ ,  $CSP(D)$  is in P or NP-complete.

# Extensions

High-dimensional  
constraints

Infinite  
Domains

Approximations  
(qualitative/quantitative)

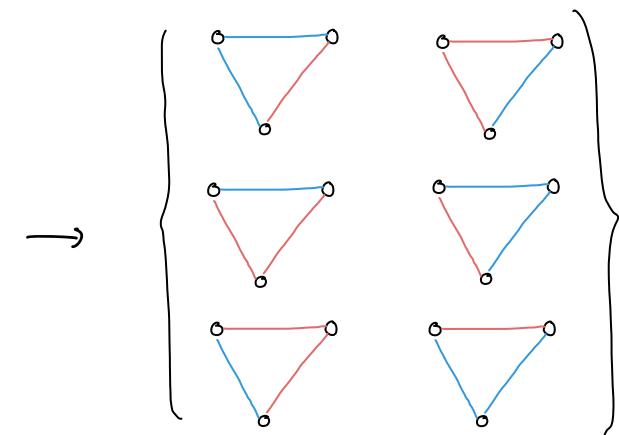
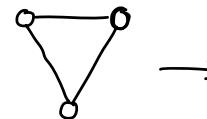
# Extensions

High-dimensional  
constraints

Infinite  
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Approximations  
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Find assignment edges  $\rightarrow \left\{ \begin{matrix} \text{o---o} \\ \text{o---o} \end{matrix} \right\}$  s.t.



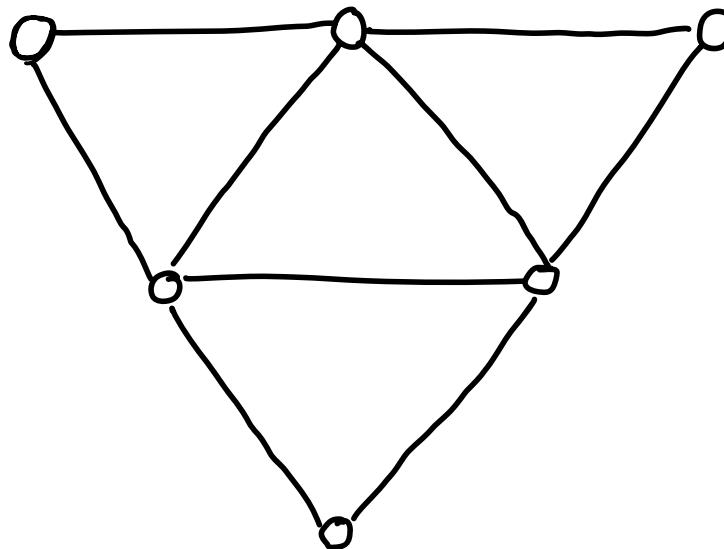
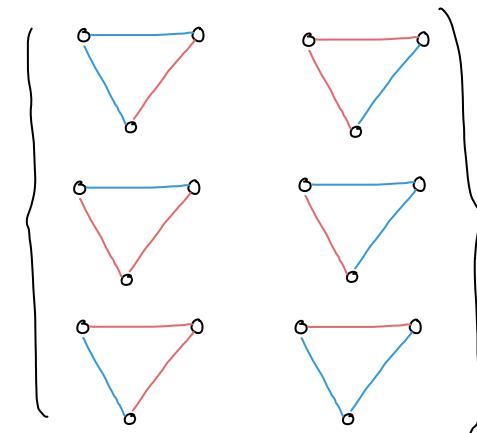
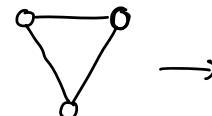
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Find assignment **edges**  $\rightarrow \left\{ \begin{array}{c} \text{o---o} \\ \text{o---o} \end{array} \right\}$  s.t.



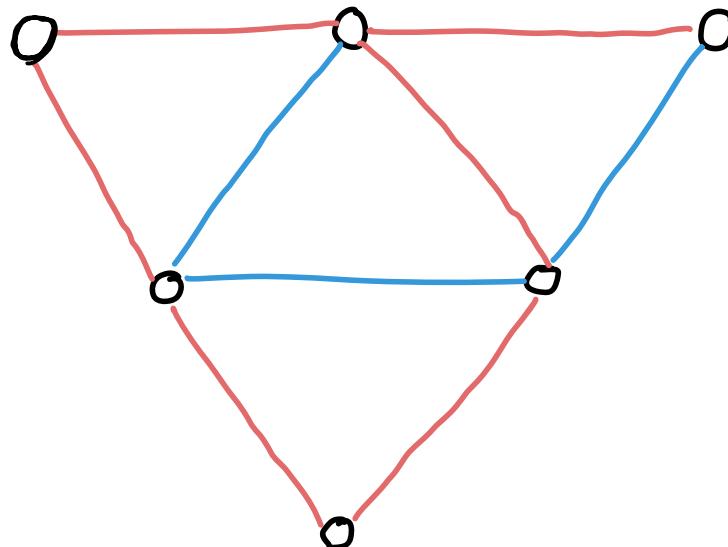
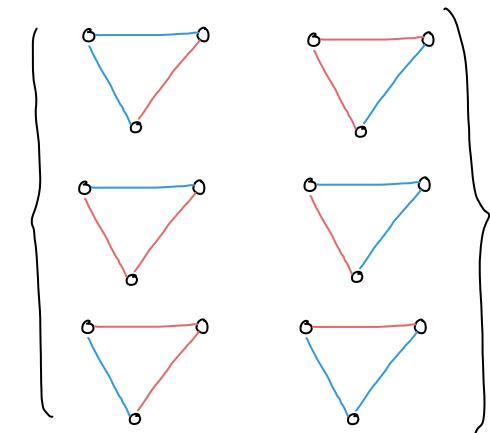
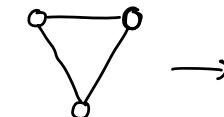
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High-dimensional  
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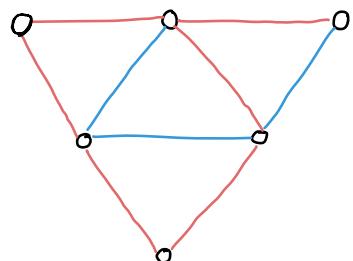
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High-dimensional  
constraints



Infinite  
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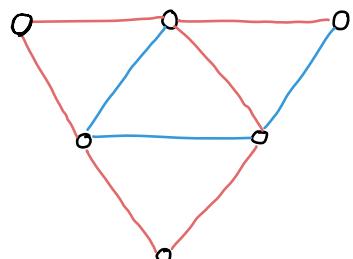
Domains and constraints are not part of the input  
~ they can be infinite!

Example:

$\exists h: V \rightarrow \mathbb{Q}$  satisfying some constraints  
 $(u, v, w) \rightarrow \{(a, b, c) \mid a < \max(b, c)\} ?$

# Extensions

High-dimensional  
constraints



Infinite  
Domains

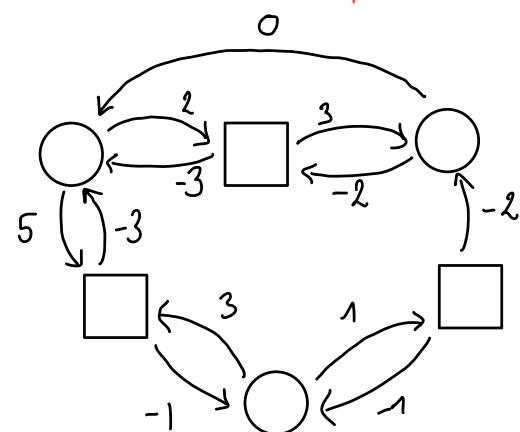
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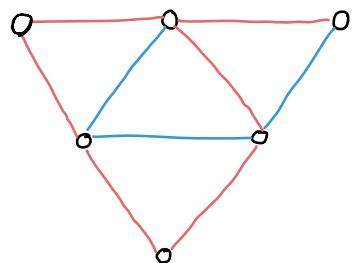
$\exists h: V \rightarrow \mathbb{Q}$  satisfying some constraints  
 $(u, v, w) \rightarrow \{(a, b, c) \mid a < \max(b, c)\} ?$

closely related to  
mean-payoff games, tropical linear programming

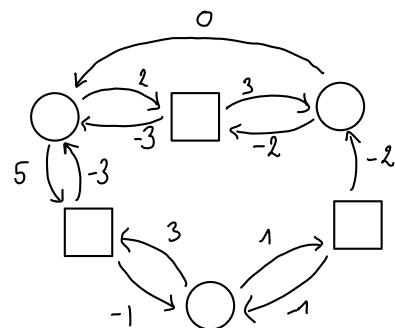


# Extensions

High-dimensional  
constraints



Infinite  
Domains

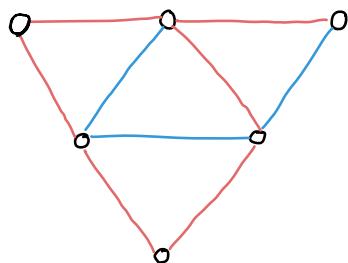


Approximations  
(qualitative/quantitative)

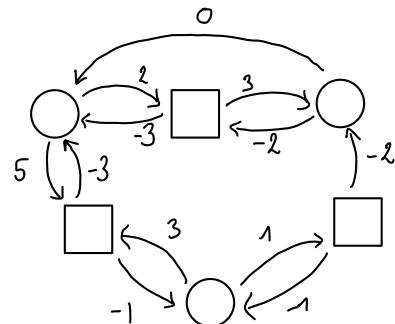
- satisfy as many constraints as possible
- satisfy all constraints in a weakened form

# Extensions

High-dimensional constraints



Infinite Domains

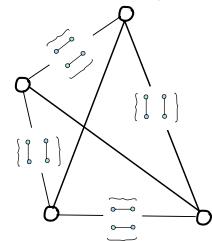


Approximations  
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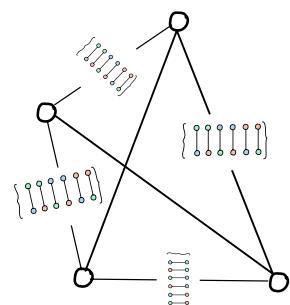
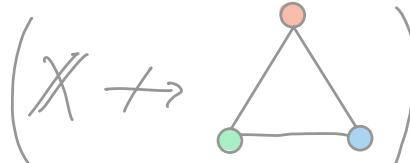
satisfy as many constraints as possible

satisfy all constraints in a weakened form

Yes-instances: strongly satisfiable

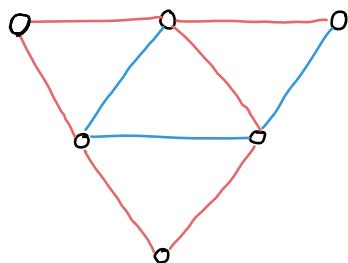


No-instances: not weakly satisfiable

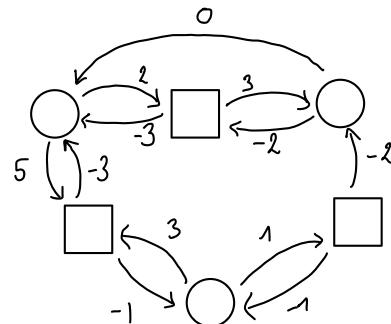


# Extensions

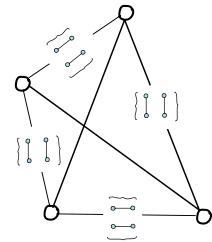
High-dimensional constraints



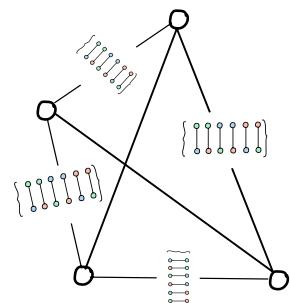
Infinite Domains



Yes-instances: strongly satisfiable



No-instances: not weakly satisfiable



Approximations  
(qualitative/quantitative)

satisfy as many constraints as possible

satisfy all constraints in a weakened form

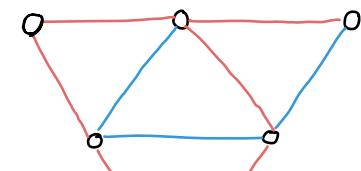
Denoted by

$\text{PCSP}(\text{Promise}, \text{Graph})$

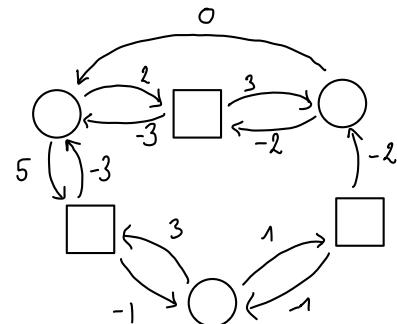
Promise

# Extensions

High-dimensional  
constraints



Infinite  
Domains

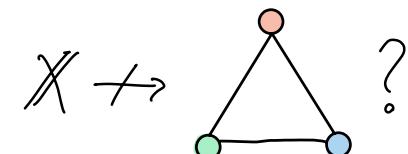
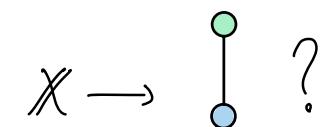


Very similar: in many cases, high-dimensional  
constraints are 1-dimensional constraints on  
an infinite set



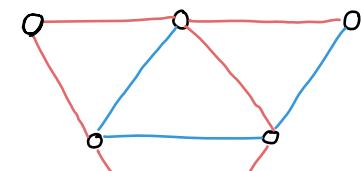
Fraïssé Theory of  
Generic structures

Approximations  
(qualitative/quantitative)

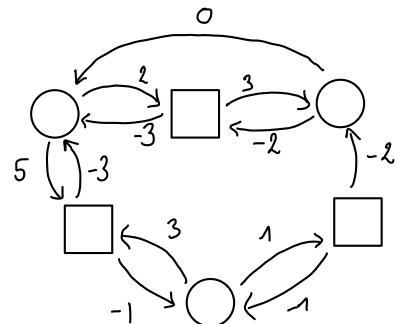


# Extensions

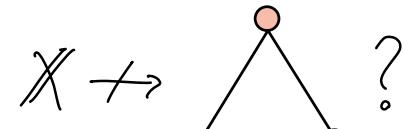
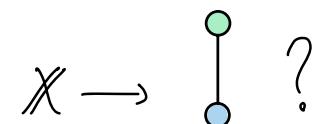
High-dimensional  
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Infinite  
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Approximations  
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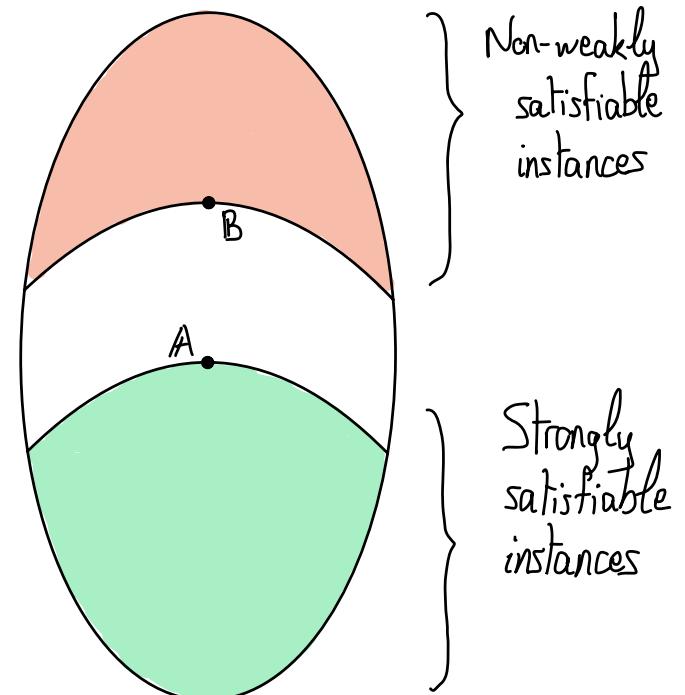
Connections?

Fraïssé Theory of  
Generic structures

# Logical Solvability of PCSPs

PCSP( $A, B$ ): Given  $X$ , decide if

- Yes:  $X$  is strongly satisfiable ( $X \rightarrow A$ )
- No:  $X$  is not weakly satisfiable ( $X \not\rightarrow B$ )



# Logical Solvability of PCSPs

PCSP( $A, B$ ): Given  $X$ , decide if

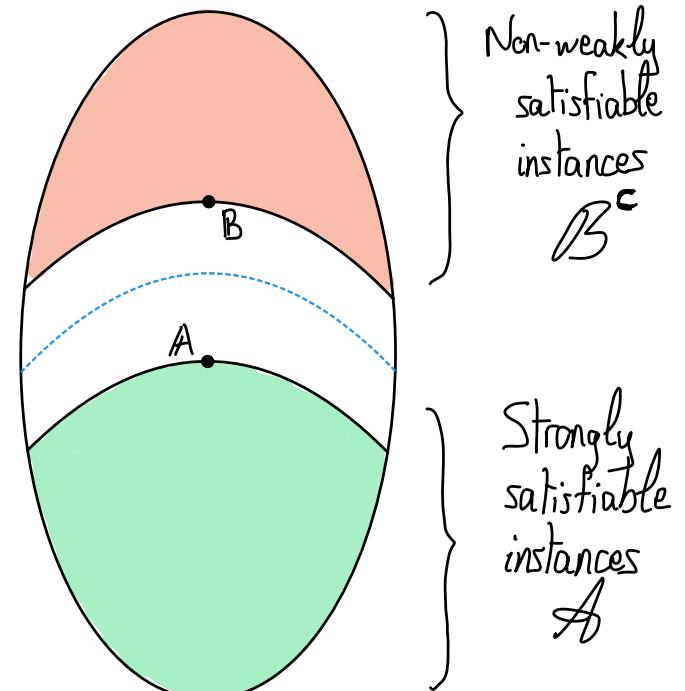
- Yes:  $X$  is strongly satisfiable ( $X \rightarrow A$ )
- No:  $X$  is not weakly satisfiable ( $X \not\rightarrow B$ )

An algorithm solving PCSP( $A, B$ ) realizes  
a separation between

$$\mathcal{A} = \{X \mid X \rightarrow A\}$$

and

$$\mathcal{B}^c = \{X \mid X \not\rightarrow B\}$$



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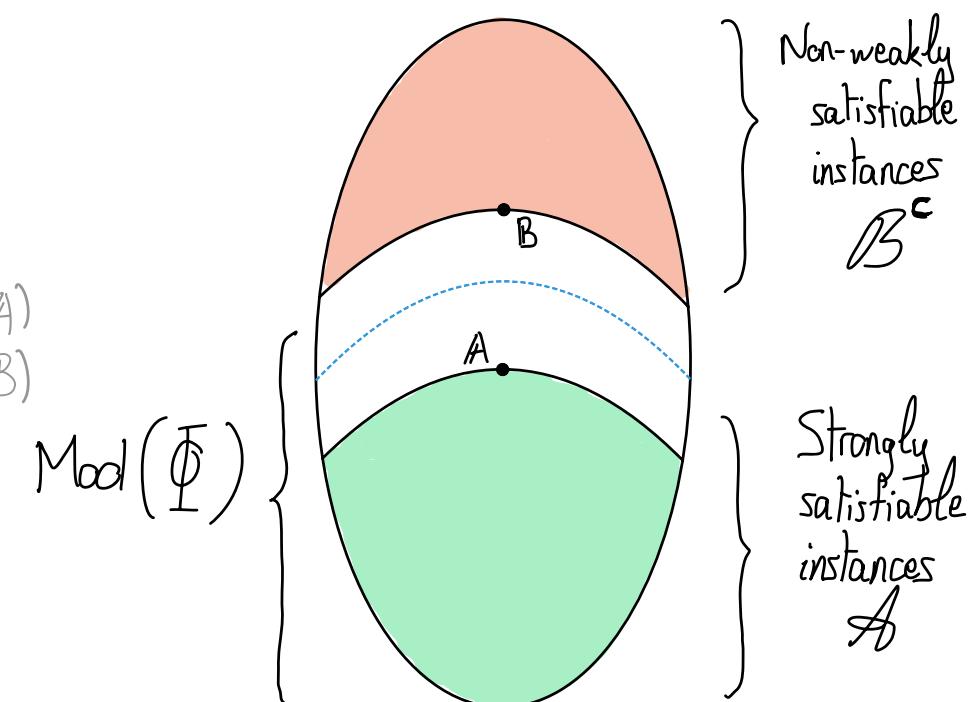
and

$$\mathcal{B}^c = \{X \mid X \not\rightarrow B\}$$

Questions: For a logic  $\mathcal{L}$  and fixed problem  
PCSP( $A, B$ ):

- is there a formula  $\Phi \in \mathcal{L}$  s.t.

$$\mathcal{A} \subseteq \text{Mod}(\Phi) \subseteq \mathcal{B} ?$$



# Logical Solvability of PCSPs

PCSP(A, B): Given  $\mathbb{X}$ , decide if

- Yes:  $\mathbb{X}$  is strongly satisfiable ( $\mathbb{X} \rightarrow A$ )
- No:  $\mathbb{X}$  is not weakly satisfiable ( $\mathbb{X} \not\rightarrow B$ )

An algorithm solving PCSP(A, B) realizes a separation between

$$\mathcal{A} = \{ \mathbb{X} \mid \mathbb{X} \rightarrow A \}$$

and

$$\mathcal{B}^c = \{ \mathbb{X} \mid \mathbb{X} \not\rightarrow B \}$$

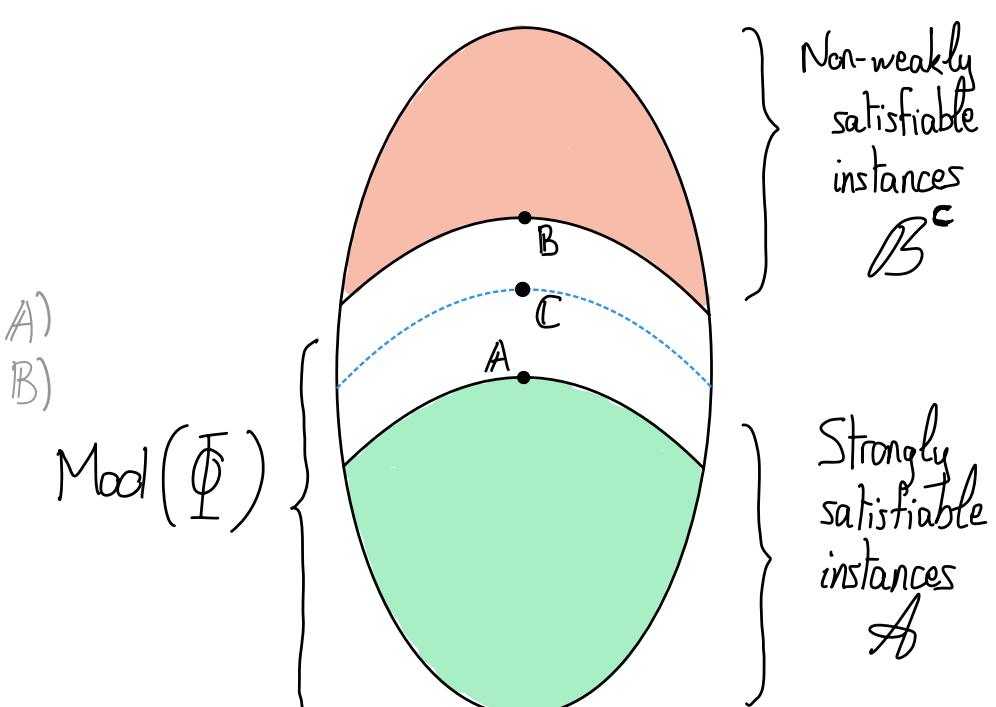
Questions: For a logic  $\mathcal{L}$  and fixed problem PCSP(A, B):

- is there a formula  $\Phi \in \mathcal{L}$  s.t.

$$\mathcal{A} \subseteq \text{Mod}(\Phi) \subseteq \mathcal{B} ?$$

- is there a (finite) structure  $\mathbb{C}$  s.t.

$$\mathcal{A} \subseteq \mathcal{C} \subseteq \mathcal{B} \text{ and } \text{CSP}(\mathbb{C}) \text{ definable in } \mathcal{L} ?$$



# Logical Solvability of PCSPs

PCSP(A, B): Given  $X$ , decide if

- Yes:  $X$  is strongly satisfiable ( $X \rightarrow A$ )
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An algorithm solving  $\text{PCSP}(A, B)$  realizes a separation between

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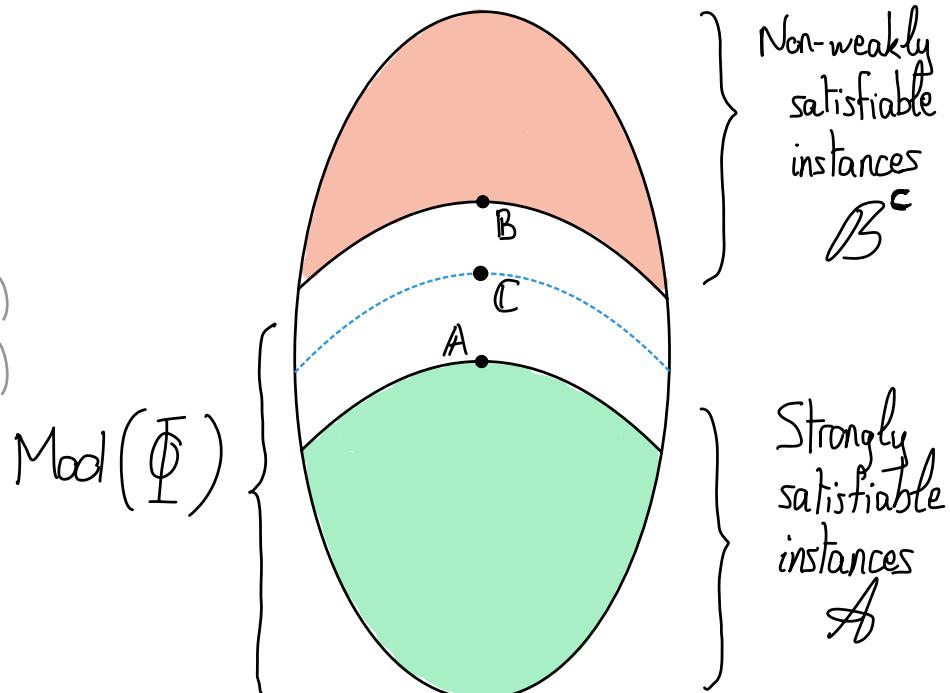
and

$$\mathcal{B}^c = \{X \mid X \not\rightarrow B\}$$

$$\text{PCSP}(A, B) \in L \iff$$

Questions: For a logic  $\mathcal{L}$  and fixed problem  $\text{PCSP}(A, B)$ :

- is there a formula  $\Phi \in \mathcal{L}$  s.t.  $\mathcal{A} \subseteq \text{Mod}(\Phi) \subseteq \mathcal{B}$  ?
- is there a (finite) structure  $C$  s.t.  $\mathcal{A} \subseteq C \subseteq \mathcal{B}$  and  $\text{CSP}(C)$  definable in  $\mathcal{L}$ ?



# Logical Solvability of PCSPs

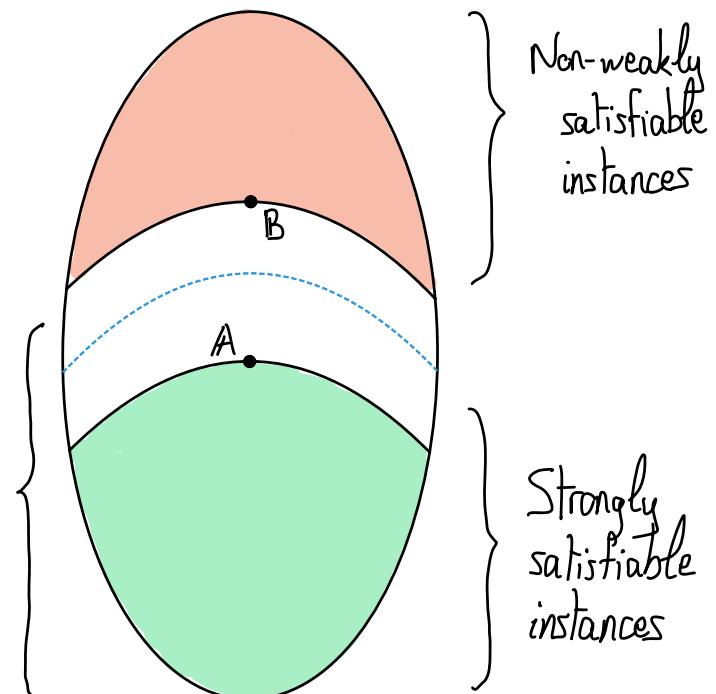
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- No:  $X$  is not weakly satisfiable ( $X \not\rightarrow B$ )

Example:  $A =$    
 $B =$

$\Phi$ :  
· no two consecutive edges of the same color  
· no edges of different colors arriving at a vertex  
· no edges of different colors leaving a vertex

$\text{Mod}(\emptyset)$



# Logical Solvability of PCSPs

PCSP( $A, B$ ): Given  $\mathbb{X}$ , decide if

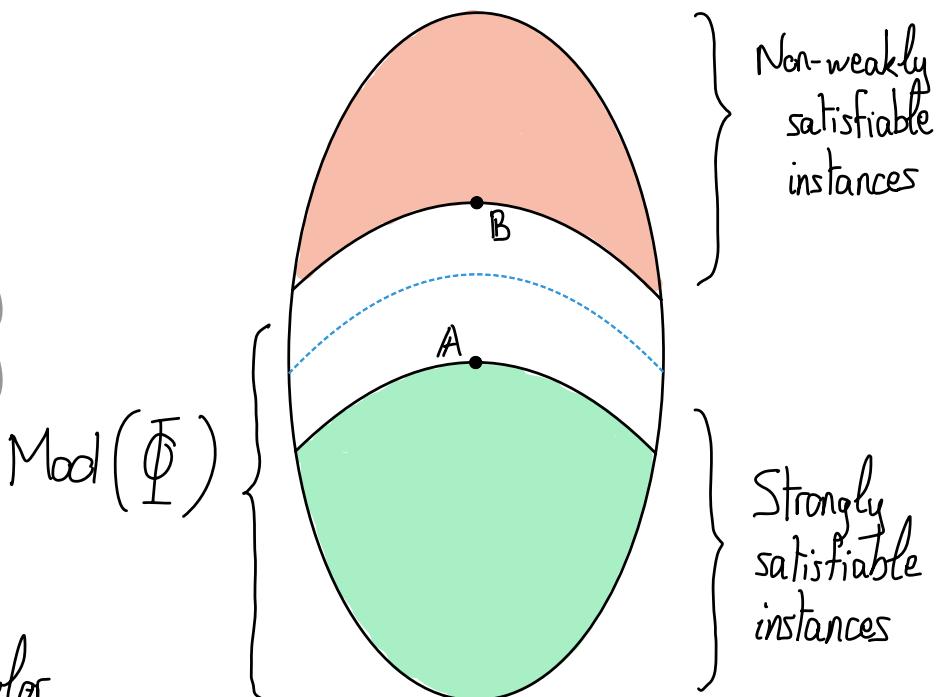
- Yes:  $\mathbb{X}$  is strongly satisfiable ( $\mathbb{X} \rightarrow A$ )
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Example:  $A = \text{o } \xrightarrow{\text{red}} \text{o } \xrightarrow{\text{blue}} \text{o } \xrightarrow{\text{red}} \text{o}$   
 $B = \text{o } \xrightarrow{\text{red}} \text{o } \xleftarrow{\text{red}} \text{o } \xleftarrow{\text{blue}} \text{o}$

$\Phi$ :  

- no two consecutive edges of the same color
- no edges of different colors arriving at a vertex
- no edges of different colors leaving a vertex

- If  $\mathbb{X}$  strongly satisfiable ( $\mathbb{X} \rightarrow A$ ) then  $\mathbb{X} \models \Phi$
- If  $\mathbb{X} \models \Phi$  then  $\mathbb{X}$  weakly satisfiable ( $\mathbb{X} \not\rightarrow B$ )



# Logical Solvability of PCSPs

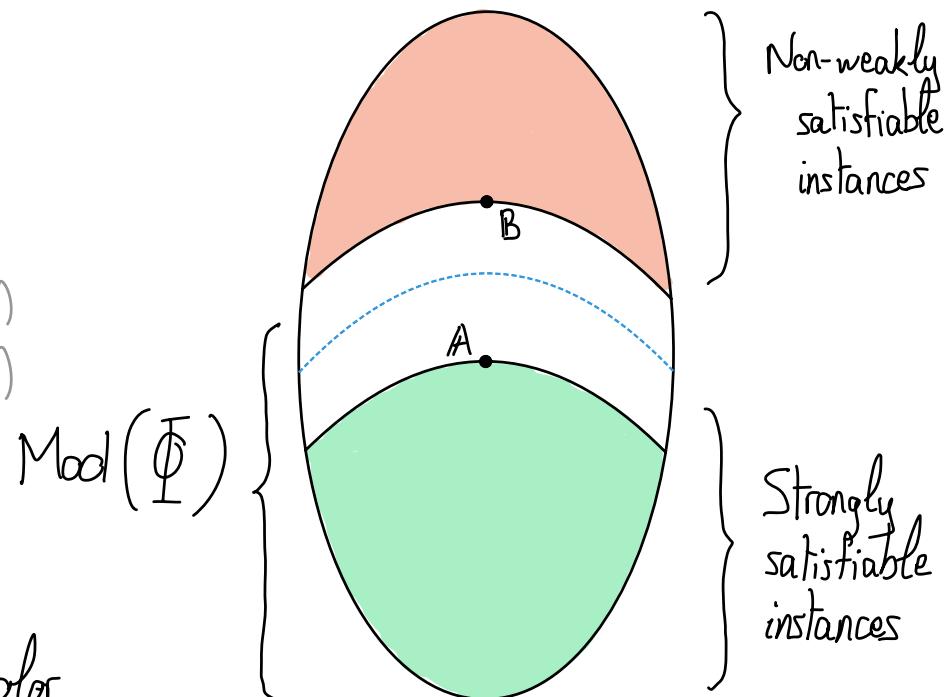
PCSP( $A, B$ ): Given  $\mathbb{X}$ , decide if

- Yes:  $\mathbb{X}$  is strongly satisfiable ( $\mathbb{X} \rightarrow A$ )
- No:  $\mathbb{X}$  is not weakly satisfiable ( $\mathbb{X} \not\rightarrow B$ )

Example:  $A = \text{o } \xrightarrow{\text{red}} \text{o } \xrightarrow{\text{blue}} \text{o } \xrightarrow{\text{red}} \text{o}$   
 $B = \text{o } \xrightarrow{\text{red}} \text{o } \xrightarrow{\text{red}} \text{o } \xleftarrow{\text{blue}} \text{o}$

$\Phi$ :  
 - no two consecutive edges of the same color  
 - no edges of different colors arriving at a vertex  
 - no edges of different colors leaving a vertex

- If  $\mathbb{X}$  strongly satisfiable ( $\mathbb{X} \rightarrow A$ ) then  $\mathbb{X} \models \Phi$
- If  $\mathbb{X} \models \Phi$  then  $\mathbb{X}$  weakly satisfiable ( $\mathbb{X} \not\rightarrow B$ )



(Exercise: no first-order formula characterizes strongly satisfiable instances )

" \_\_\_\_\_ " weakly \_\_\_\_\_ . \_\_\_\_\_ )

## The case of first-order logic

The result For every  $\text{PCSP}(A, B)$ , the following are equivalent:

- $\text{PCSP}(A, B)$  is first-order solvable,
- there exists a structure  $C$  s.t.  $A \rightarrow C \rightarrow B$  and  $\text{CSP}(C)$  is first-order definable,
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## The proof

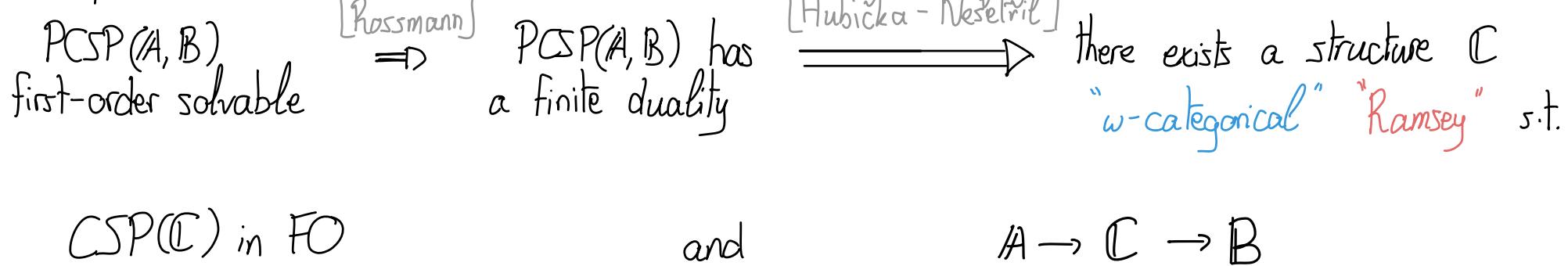
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$\xrightarrow{\text{[Larose-Loten-Tardieu]}}$

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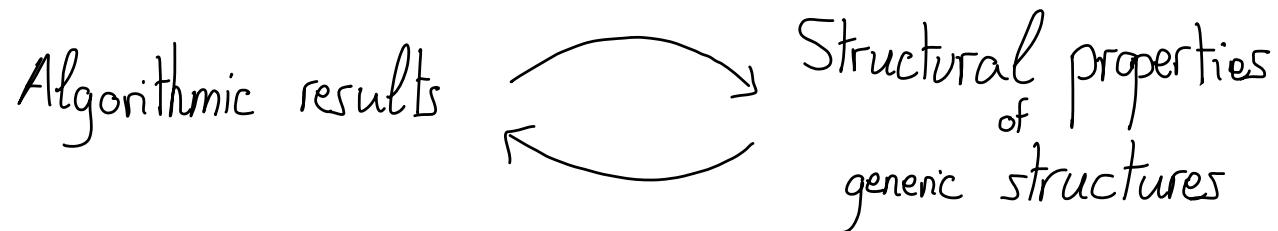
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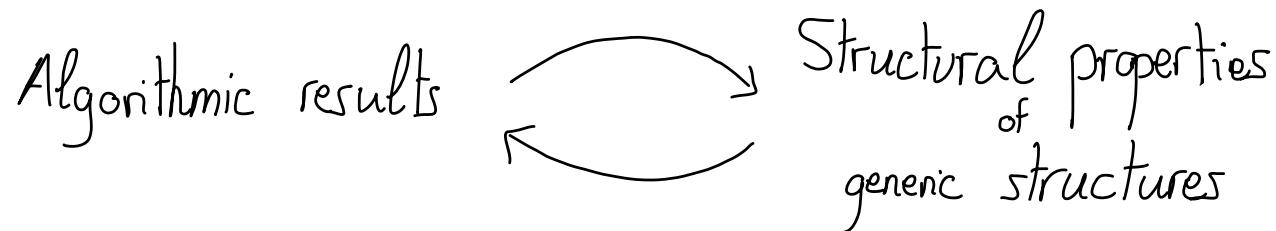
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Open: · Consistency, Sherali-Adams, and Lasserre hierarchies  
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Thank You!

(Did I mention I'm hiring?)