A Feferman-Vaught Decomposition Theorem for Weighted MSO Logic

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QuantLA

formula β $\xleftrightarrow{\text{satisfaction}}$ structure $\mathcal{A}$

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Feferman-Vaught theorem

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$\Uparrow$

combine answers

$\nearrow$ $\nwarrow$

questions about $\mathcal{A}$ questions about $\mathcal{B}$

$\sigma = (\mathsf{Rel}, \mathsf{ar})$	signature
$\mathsf{Rel} = \{R_1, \ldots, R_m\}$	relation symbols
$\mathsf{ar}\colon \mathsf{Rel} \to \mathbb{N}$	arity function

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$\mathcal{A} = (A, \mathcal{I})$	σ-structure
A	finite universe
$\mathcal{I}(R) \subseteq A^{\mathsf{ar}(R)}$ $(R \in \mathsf{Rel})$	interpretation

Disjoint union $\mathcal{A} \sqcup \mathcal{B}$ of σ-structures

$A \sqcup B$	universe
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MSO(σ) logic

$$\beta ::= R(x_1, \ldots, x_n) \;\mid\; x \in X \;\mid\; \neg\beta \;\mid\; \beta \vee \beta \;\mid\; \exists x.\beta \;\mid\; \exists X.\beta$$

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Propositional formulas Prop

$$P ::= x_i \;\mid\; y_i \;\mid\; P \vee P \;\mid\; P \wedge P$$

Given

signature σ $\beta \in \mathrm{MSO}(\sigma)$

Classical Feferman-Vaught Theorem

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such that for all structures $\mathcal{A}$,$\mathcal{B}$

$\mathcal{A} \sqcup \mathcal{B} \models \beta$ iff $P(x_1, \ldots, x_n, y_1, \ldots, y_n) = \mathtt{true}$

where $x_i = \mathtt{true}$ iff $\beta_i^{\mathbb{1}} \models \mathcal{A}$

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qualitative answers $\longrightarrow$ quantitative answers

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Example $(\mathbb{N}_0, +, \cdot, 0, 1)$

$[\![\bigoplus x. \bigoplus y.\text{edge}(x, y)]\!]$ $=$ number of edges

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wMSO(σ, S) logic [Droste and Gastin, ICALP '05]

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Example $(\mathbb{R} \cup \{-\infty\}, \max, +, -\infty, 0)$ $\quad \mathrm{clique}(X) \in \mathrm{MSO}$

largest clique

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$\langle\!\langle E \rangle\!\rangle : S^n \times S^n \to S$

$$\langle\!\langle x_1 \oplus y_2 \rangle\!\rangle(\bar{s}, \bar{t}) = s_1 \oplus t_2$$

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there exist

$n \geq 1$ $\qquad$ $\bar{\beta}^{1}, \bar{\beta}^{2} \in \mathsf{MSO}(\sigma)^n$ $\qquad$ $P \in \mathsf{Prop}$

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such that for all structures $\mathcal{A}$,$\mathcal{B}$

$$\mathcal{A} \sqcup \mathcal{B} \models \beta \quad \text{iff} \quad P(x_1, \ldots, x_n, y_1, \ldots, y_n) = \mathtt{true}$$

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$\bar{\varphi}^{\mathbb{1}} = \bar{\varphi}^{2} = (\varphi_{|b-b|}, \varphi_{|a|}) \qquad E = (x_1 \oplus y_1) \otimes (x_2 \oplus y_2)$

Results of the paper: overview

- restrictions on product quantifiers necessary

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- specific semirings no restrictions

  De Morgan algebras, locally finite semirings

Restriction

$$\psi ::= \beta \mid s \mid \psi \oplus \psi \mid \psi \otimes \psi$$
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fails for

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$\bigotimes x. \bigotimes y.1$	$\|A\|^2$	$(\mathbb{R} \cup \{-\infty\}, \max, +, -\infty, 0)$

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$$f : \left[\frac{X}{2}\right] \to \{1, \dots, k\}$$

Then

$$\exists Y \subseteq X \text{ infinite} \quad \text{with} \quad f\restriction_{\left[\frac{Y}{2}\right]} \equiv \text{constant}$$

Restriction: $(\mathbb{R} \cup \{\infty\}, \textsc{max}, +, \infty, 0)$

assume

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$$\mathcal{S}_l = (\{1, \ldots, l\}, \emptyset)$$

Restriction: $(\mathbb{R} \cup \{\infty\}, \textsc{max}, +, \infty, 0)$

assume

$$[\![\bigotimes x. \bigotimes y.1]\!](\mathcal{S}_l \sqcup \mathcal{S}_m) = \langle\!\langle E \rangle\!\rangle([\![\bar{\varphi}^1]\!](\mathcal{S}_l), [\![\bar{\varphi}^2]\!](\mathcal{S}_m)) \qquad \forall l, m$$

$$\mathcal{S}_l = (\{1, \ldots, l\}, \emptyset)$$

Restriction: $(\mathbb{R} \cup \{\infty\}, \max, +, \infty, 0)$

assume

$$[\![\bigotimes x. \bigotimes y.1]\!](\mathcal{S}_l \sqcup \mathcal{S}_m) = \langle\!\langle E \rangle\!\rangle([\![\bar{\varphi}^1]\!](\mathcal{S}_l), [\![\bar{\varphi}^2]\!](\mathcal{S}_m)) \qquad \forall l, m$$

$$\mathcal{S}_l = (\{1, \ldots, l\}, \emptyset)$$

$$(l+m)^2 \qquad = [\![\bigotimes x. \bigotimes y.1]\!](\mathcal{S}_l \sqcup \mathcal{S}_m)$$

RESTRICTION: $(\mathbb{R} \cup \{\infty\}, \text{MAX}, +, \infty, 0)$

assume

$$[\![\bigotimes x. \bigotimes y.1]\!](\mathcal{S}_l \sqcup \mathcal{S}_m) = \langle\!\langle E \rangle\!\rangle([\![\bar{\varphi}^1]\!](\mathcal{S}_l), [\![\bar{\varphi}^2]\!](\mathcal{S}_m)) \qquad \forall l, m$$

$$\mathcal{S}_l = (\{1, \ldots, l\}, \emptyset)$$

$$E = \bigoplus_{i=1}^{k} \left(x_1^{g_{1,i}} \otimes \ldots \otimes x_n^{g_{n,i}} \otimes y_1^{h_{1,i}} \otimes \ldots \otimes y_n^{h_{n,i}} \right) \qquad \text{wlog}$$

$$(l + m)^2 \qquad = [\![\bigotimes x. \bigotimes y.1]\!](\mathcal{S}_l \sqcup \mathcal{S}_m)$$

assume

$$[\![\bigotimes x. \bigotimes y.1]\!](\mathcal{S}_l \sqcup \mathcal{S}_m) = \langle\!\langle E \rangle\!\rangle([\![\bar{\varphi}^{1}]\!](\mathcal{S}_l), [\![\bar{\varphi}^{2}]\!](\mathcal{S}_m)) \qquad \forall l, m$$

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$$E = \bigoplus_{i=1}^{k} \left(x_1^{g_{1,i}} \otimes \dots \otimes x_n^{g_{n,i}} \otimes y_1^{h_{1,i}} \otimes \dots \otimes y_n^{h_{n,i}} \right) \qquad \text{wlog}$$

$$a_{li} = ([\![\bar{\varphi}_1^{1}]\!](\mathcal{S}_l))^{g_{1,i}} \otimes \dots \otimes ([\![\bar{\varphi}_n^{1}]\!](\mathcal{S}_l))^{g_{n,i}}$$
$$b_{mi} = ([\![\bar{\varphi}_1^{2}]\!](\mathcal{S}_m))^{h_{1,i}} \otimes \dots \otimes ([\![\bar{\varphi}_n^{2}]\!](\mathcal{S}_m))^{h_{n,i}}$$

$$(l + m)^2 \qquad = [\![\bigotimes x. \bigotimes y.1]\!](\mathcal{S}_l \sqcup \mathcal{S}_m)$$

RESTRICTION: $(\mathbb{R} \cup \{\infty\}, \text{MAX}, +, \infty, 0)$

assume

$$[\![\bigotimes x. \bigotimes y.1]\!](\mathcal{S}_l \sqcup \mathcal{S}_m) = \langle\!\langle E \rangle\!\rangle([\![\bar{\varphi}^{\mathbb{1}}]\!](\mathcal{S}_l), [\![\bar{\varphi}^{\mathbb{2}}]\!](\mathcal{S}_m)) \qquad \forall l, m$$

$$\mathcal{S}_l = (\{1, \ldots, l\}, \emptyset)$$

$$E = \bigoplus_{i=1}^{k} \left(x_1^{g_{1,i}} \otimes \ldots \otimes x_n^{g_{n,i}} \otimes y_1^{h_{1,i}} \otimes \ldots \otimes y_n^{h_{n,i}} \right) \qquad \text{wlog}$$

$$a_{li} = ([\![\bar{\varphi}_1^{\mathbb{1}}]\!](\mathcal{S}_l))^{g_{1,i}} \otimes \ldots \otimes ([\![\bar{\varphi}_n^{\mathbb{1}}]\!](\mathcal{S}_l))^{g_{n,i}}$$

$$b_{mi} = ([\![\bar{\varphi}_1^{\mathbb{2}}]\!](\mathcal{S}_m))^{h_{1,i}} \otimes \ldots \otimes ([\![\bar{\varphi}_n^{\mathbb{2}}]\!](\mathcal{S}_m))^{h_{n,i}}$$

$$(l + m)^2 = [\![\bigotimes x. \bigotimes y.1]\!](\mathcal{S}_l \sqcup \mathcal{S}_m) = \max_{i=1}^{k} \; a_{li} + b_{mi}$$

assume

$$[\![\bigotimes x. \bigotimes y.1]\!](\mathcal{S}_l \sqcup \mathcal{S}_m) = \langle\!\langle E \rangle\!\rangle([\![\bar{\varphi}^1]\!](\mathcal{S}_l), [\![\bar{\varphi}^2]\!](\mathcal{S}_m)) \qquad \forall l, m$$

$$\mathcal{S}_l = (\{1, \ldots, l\}, \emptyset)$$

$$E = \bigoplus_{i=1}^{k} \left(x_1^{g_{1,i}} \otimes \ldots \otimes x_n^{g_{n,i}} \otimes y_1^{h_{1,i}} \otimes \ldots \otimes y_n^{h_{n,i}} \right) \qquad \text{wlog}$$

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$$b_{mi} = ([\![\bar{\varphi}_1^2]\!](\mathcal{S}_m))^{h_{1,i}} \otimes \ldots \otimes ([\![\bar{\varphi}_n^2]\!](\mathcal{S}_m))^{h_{n,i}}$$

$$(l+m)^2 = [\![\bigotimes x. \bigotimes y.1]\!](\mathcal{S}_l \sqcup \mathcal{S}_m) = \max_{i=1}^{k} a_{li} + b_{mi}$$

Restriction: $(\mathbb{R} \cup \{\infty\}, \textsc{max}, +, \infty, 0)$

$$(l + m)^2 = \max_{i=1}^{k} a_{li} + b_{mi} \qquad \forall l, m$$

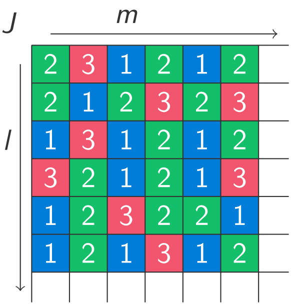
Restriction: $(\mathbb{R} \cup \{\infty\}, \max, +, \infty, 0)$

$$(l+m)^2 = \max_{i=1}^{k} a_{li} + b_{mi} \qquad \forall l, m$$

choose j_{lm} with $(l+m)^2 = a_{l j_{lm}} + b_{m j_{lm}}$

$$(l+m)^2 = \max_{i=1}^{k} a_{li} + b_{mi} \qquad \forall l, m$$

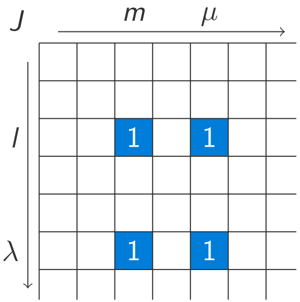
choose j_{lm} with $(l+m)^2 = a_{l j_{lm}} + b_{m j_{lm}}$



Restriction: $(\mathbb{R} \cup \{\infty\}, \max, +, \infty, 0)$

$$(l+m)^2 = \max_{i=1}^{k} a_{li} + b_{mi} \qquad \forall l, m$$

choose j_{lm} with $(l+m)^2 = a_{lj_{lm}} + b_{mj_{lm}}$

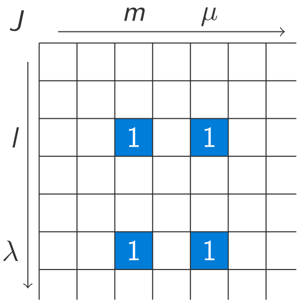


Restriction: $(\mathbb{R} \cup \{\infty\}, \max, +, \infty, 0)$

$$(l+m)^2 = \max_{i=1}^{k} a_{li} + b_{mi} \qquad \forall l, m$$

choose j_{lm} with $(l+m)^2 = a_{lj_{lm}} + b_{mj_{lm}}$

$$(l+m)^2 = a_{l1} + b_{m1}$$



$$(l+m)^2 = \max_{i=1}^{k} a_{li} + b_{mi} \qquad \forall l, m$$

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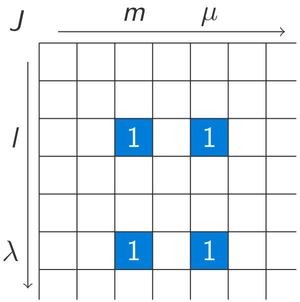
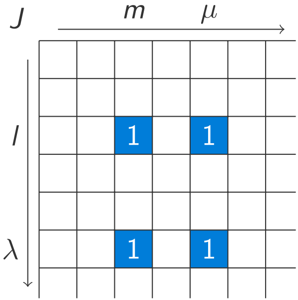


$$(l+m)^2 = a_{l1} + b_{m1}$$

$$(\lambda+m)^2 = a_{\lambda 1} + b_{m1}$$

$$(l+m)^2 = \max_{i=1}^{k} a_{li} + b_{mi} \qquad \forall l, m$$

choose j_{lm} with $(l+m)^2 = a_{l j_{lm}} + b_{m j_{lm}}$



$$(l+m)^2 = a_{l1} + b_{m1}$$

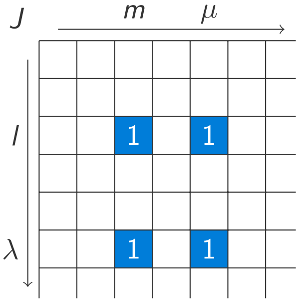
$$(\lambda+m)^2 = a_{\lambda 1} + b_{m1}$$

$$(l+\mu)^2 = a_{l1} + b_{\mu 1}$$

Restriction: $(\mathbb{R} \cup \{\infty\}, \max, +, \infty, 0)$

$$(l+m)^2 = \max_{i=1}^{k} a_{li} + b_{mi} \qquad \forall l, m$$

choose j_{lm} with $(l+m)^2 = a_{lj_{lm}} + b_{mj_{lm}}$



$$(l+m)^2 = a_{l1} + b_{m1}$$

$$(\lambda+m)^2 = a_{\lambda 1} + b_{m1}$$

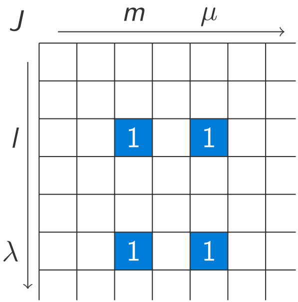
$$(l+\mu)^2 = a_{l1} + b_{\mu 1}$$

$$(\lambda+\mu)^2$$

Restriction: $(\mathbb{R} \cup \{\infty\}, \max, +, \infty, 0)$

$$(l+m)^2 = \max_{i=1}^{k} a_{li} + b_{mi} \qquad \forall l, m$$

choose j_{lm} with $(l+m)^2 = a_{lj_{lm}} + b_{mj_{lm}}$



$$(l+m)^2 = a_{l1} + b_{m1}$$

$$(\lambda+m)^2 = a_{\lambda 1} + b_{m1}$$

$$(l+\mu)^2 = a_{l1} + b_{\mu 1}$$

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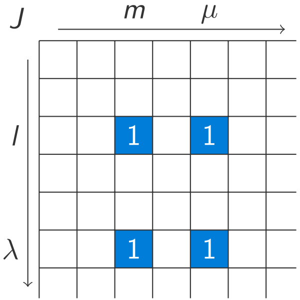


$$(l+m)^2 = a_{l1} + b_{m1}$$

$$(\lambda+m)^2 = a_{\lambda 1} + b_{m1}$$

$$(l+\mu)^2 = a_{l1} + b_{\mu 1}$$

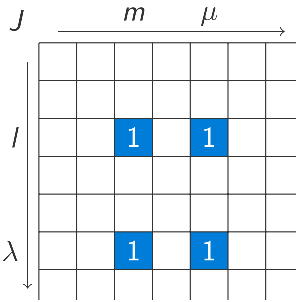
$$(\lambda+\mu)^2 = a_{\lambda 1} + b_{\mu 1}$$

$$= (\lambda+m)^2 - b_{m1} + (l+\mu)^2 - a_{l1}$$

Restriction: $(\mathbb{R} \cup \{\infty\}, \max, +, \infty, 0)$

$$(l+m)^2 = \max_{i=1}^{k} a_{li} + b_{mi} \qquad \forall l, m$$

choose j_{lm} with $(l+m)^2 = a_{lj_{lm}} + b_{mj_{lm}}$



$$(l+m)^2 = a_{l1} + b_{m1}$$

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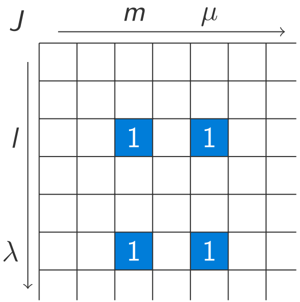
$$(l+\mu)^2 = a_{l1} + b_{\mu 1}$$

$$\begin{aligned}(\lambda+\mu)^2 &= a_{\lambda 1} + b_{\mu 1} \\ &= (\lambda+m)^2 - b_{m1} + (l+\mu)^2 - a_{l1} \\ &= (\lambda+m)^2 + (l+\mu)^2 - (l+m)^2\end{aligned}$$

RESTRICTION: $(\mathbb{R} \cup \{\infty\}, \max, +, \infty, 0)$

$$(l+m)^2 = \max_{i=1}^{k} a_{li} + b_{mi} \qquad \forall l, m$$

choose j_{lm} with $(l+m)^2 = a_{l j_{lm}} + b_{m j_{lm}}$



$$(l+m)^2 = a_{l1} + b_{m1}$$

$$(\lambda+m)^2 = a_{\lambda 1} + b_{m1}$$

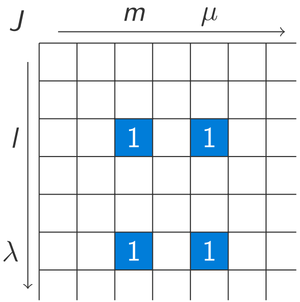
$$(l+\mu)^2 = a_{l1} + b_{\mu 1}$$

$$\begin{aligned}
(\lambda+\mu)^2 &= a_{\lambda 1} + b_{\mu 1} \\
&= (\lambda+m)^2 - b_{m1} + (l+\mu)^2 - a_{l1} \\
&= (\lambda+m)^2 + (l+\mu)^2 - (l+m)^2 \\
&\vdots \\
&= (\lambda+\mu)^2 - 2(\lambda-l)(\mu-m)
\end{aligned}$$

Restriction: $(\mathbb{R} \cup \{\infty\}, \max, +, \infty, 0)$

$$(l+m)^2 = \max_{i=1}^{k} \; a_{li} + b_{mi} \qquad \forall l, m$$

choose j_{lm} with $(l+m)^2 = a_{l j_{lm}} + b_{m j_{lm}}$



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$$\begin{aligned}(\lambda+\mu)^2 &= a_{\lambda 1} + b_{\mu 1} \\ &= (\lambda+m)^2 - b_{m1} + (l+\mu)^2 - a_{l1} \\ &= (\lambda+m)^2 + (l+\mu)^2 - (l+m)^2 \\ &\vdots \\ &< (\lambda+\mu)^2\end{aligned}$$

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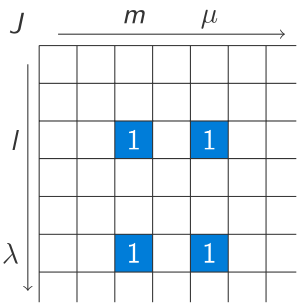
$$(l+m)^2 = \max_{i=1}^{k} a_{li} + b_{mi} \qquad \forall l, m$$

choose j_{lm} with $(l+m)^2 = a_{lj_{lm}} + b_{mj_{lm}}$



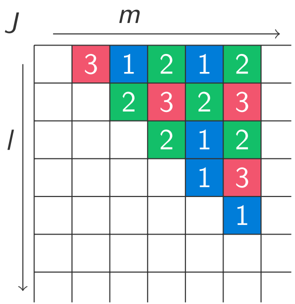
Ramsey: define $f : \binom{\mathbb{N}}{2} \to \{1, \ldots, k\}$

$\{l, m\} \mapsto j_{lm}$ for $l < m$

Restriction: $(\mathbb{R} \cup \{\infty\}, \max, +, \infty, 0)$

$$(l+m)^2 = \max_{i=1}^{k} a_{li} + b_{mi} \qquad \forall l, m$$

choose j_{lm} with $(l+m)^2 = a_{l j_{lm}} + b_{m j_{lm}}$



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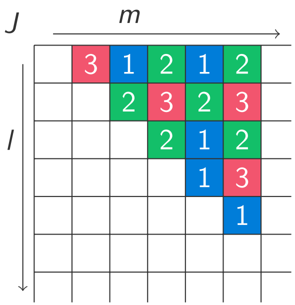


Ramsey: define $f : \binom{\mathbb{N}}{2} \to \{1, \ldots, k\}$

$\{l, m\} \mapsto j_{lm}$ for $l < m$

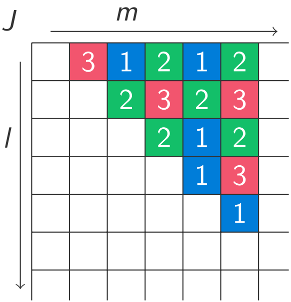
Let

$Y \subseteq \mathbb{N}$ infinite with $f{\restriction}_{\binom{Y}{2}} \equiv j$

Restriction: $(\mathbb{R} \cup \{\infty\}, \max, +, \infty, 0)$

$$(l+m)^2 = \max_{i=1}^{k} \; a_{li} + b_{mi} \qquad \forall l, m$$

choose j_{lm} with $(l+m)^2 = a_{l j_{lm}} + b_{m j_{lm}}$



Ramsey: define $f : \binom{\mathbb{N}}{2} \to \{1, \dots, k\}$

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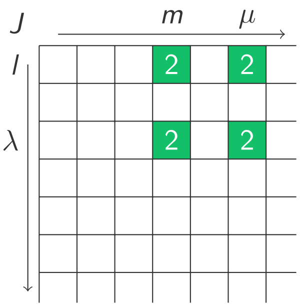
Let

$Y \subseteq \mathbb{N}$ infinite with $f\restriction_{\binom{Y}{2}} \equiv j$

$l < \lambda < m < \mu \in Y$

$$(l+m)^2 = \max_{i=1}^{k} \; a_{li} + b_{mi} \qquad \forall l, m$$

choose j_{lm} with $(l+m)^2 = a_{l j_{lm}} + b_{m j_{lm}}$



Ramsey: define $f : \left[\binom{\mathbb{N}}{2}\right] \to \{1, \ldots, k\}$

$\{l, m\} \mapsto j_{lm}$ for $l < m$

Let

$Y \subseteq \mathbb{N}$ infinite with $f\restriction_{\left[\binom{Y}{2}\right]} \equiv j$

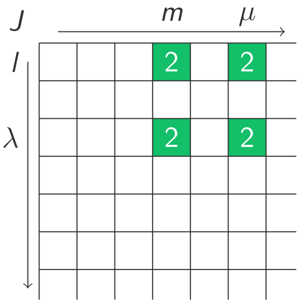
$l < \lambda < m < \mu \in Y$

$j_{lm} = j_{l\mu} = j_{\lambda m} = j_{\lambda\mu}$

RESTRICTION: $(\mathbb{R} \cup \{\infty\}, \max, +, \infty, 0)$

$$(l+m)^2 = \max_{i=1}^{k} \; a_{li} + b_{mi} \qquad \forall l, m$$

choose j_{lm} with $(l+m)^2 = a_{l j_{lm}} + b_{m j_{lm}}$



Ramsey: define $f : \left[\mathbb{N} \atop 2\right] \to \{1, \ldots, k\}$

$\{l, m\} \mapsto j_{lm}$ for $l < m$

Let

$Y \subseteq \mathbb{N}$ infinite with $f\restriction_{\left[Y \atop 2\right]} \equiv j$

$l < \lambda < m < \mu \in Y$

$j_{lm} = j_{l\mu} = j_{\lambda m} = j_{\lambda\mu}$ $\implies$ contradiction