Genericity Through Stratification

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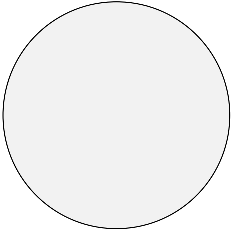
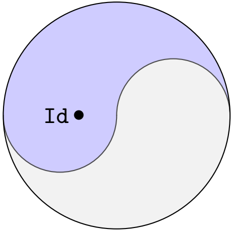
Logic in Computer Science
(LICS)
Tallinn, July 8, 2024

Meaningfulness: a Question of Taste ?



Meaningfulness: a Question of Taste ?

MEANINGFUL



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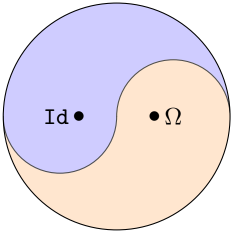

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Meaningfulness: a Question of Taste ?

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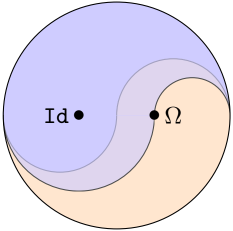

MEANINGLESS

Meaningfulness: a Question of Taste ?

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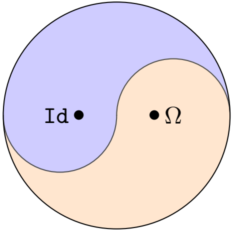

MEANINGLESS

Meaningfulness: a Question of Taste ?

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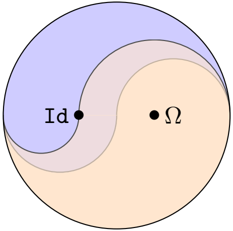

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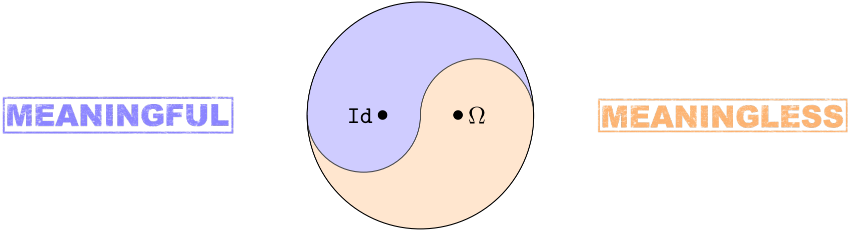
Meaningfulness: a Question of Taste ?



Key properties:

- (Operational and Logical Characterizations)
- Genericity Lemmas
- Consistency when equating all meaningless terms

Call-by-Name and Call-by-Value

Call-by-Name

Call-by-Value

Call-by-Name

NAME

Call-by-Value

VALUE

$(\lambda x.y\,\Omega)\,\Omega$

Ω

Call-by-Name and Call-by-Value

Call-by-Name

NAME

$$(\lambda x.y\,\Omega)\,\Omega$$

$$\downarrow$$

$$y\,\Omega$$

Call-by-Value

VALUE

$$\Omega \circlearrowleft$$

Call-by-Name and Call-by-Value

Call-by-Name

NAME

$$(\lambda x. y\, \Omega)\, \Omega$$

$$\downarrow$$

$$y\, \Omega$$

$$\not\downarrow$$

Call-by-Value

VALUE

$$\Omega \circlearrowleft$$

Call-by-Name and Call-by-Value

Call-by-Name

NAME

$$(\lambda x.y\,\Omega)\,\Omega$$

$$\downarrow$$

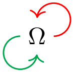
$$y\,\Omega$$

$$\not\downarrow$$

Call-by-Value

VALUE

$$(\lambda x.y\,\Omega)\,\Omega$$



Call-by-Name and Call-by-Value

Call-by-Name

NAME

$$(\lambda x.y\,\Omega)\,\Omega$$

$$\downarrow$$

$$y\,\Omega$$

$$\not\downarrow$$

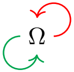
Call-by-Value

VALUE

$$(\lambda x.y\,\Omega)\,\Omega$$

$$\downarrow$$

$$(\lambda x.y\,\Omega)\,\Omega$$



Call-by-Name and Call-by-Value

Call-by-Name

NAME

$$(\lambda x. y\, \Omega)\, \Omega$$

$$\downarrow$$

$$y\, \Omega$$

$$\not\downarrow$$

Call-by-Value

VALUE

$$(\lambda x. y\, \Omega)\, \Omega$$

$$\downarrow$$

$$(\lambda x. y\, \Omega)\, \Omega$$

$$\downarrow$$

$$\vdots$$

$$\Omega$$

Call-by-Name and Call-by-Value

Call-by-Name

NAME

$$(\lambda x. y\,\Omega)\,\Omega$$

$$\downarrow_0$$

$$y\,\Omega$$

$$\not\downarrow_0$$

Call-by-Value

VALUE

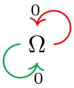
$$(\lambda x. y\,\Omega)\,\Omega$$

$$\downarrow_0$$

$$(\lambda x. y\,\Omega)\,\Omega$$

$$\downarrow_0$$

$$\vdots$$



Call-by-Name and Call-by-Value

Call-by-Name

NAME

$$(\lambda x. y\, \Omega)\, \Omega$$

$$\downarrow_0$$

$$y\, \Omega$$

$$\downarrow_1$$

$$y\, \Omega$$

Call-by-Value

VALUE

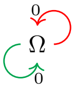
$$(\lambda x. y\, \Omega)\, \Omega$$

$$\downarrow_0$$

$$(\lambda x. y\, \Omega)\, \Omega$$

$$\downarrow_0$$

$$\vdots$$



Call-by-Name

NAME

$$(\lambda x.y\,\Omega)\,\Omega$$

$$\downarrow_0$$

$$y\,\Omega$$

$$\downarrow_1$$

$$y\,\Omega$$

$$\downarrow_1$$

$$\vdots$$

Call-by-Value

VALUE

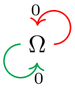
$$(\lambda x.y\,\Omega)\,\Omega$$

$$\downarrow_0$$

$$(\lambda x.y\,\Omega)\,\Omega$$

$$\downarrow_0$$

$$\vdots$$



Meaningfulness

Meaningfulness

MEANINGFUL

$\exists$ testing context $\mathtt{T}$, $\mathtt{T}\langle t \rangle \rightarrow^* \mathtt{Obs}$

Meaningfulness

MEANINGFUL

$\exists$ testing context $\mathtt{T}$, $\mathtt{T}\langle t \rangle \to^* \mathtt{Obs}$

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$\exists$ testing context $\mathtt{T}$, $\mathtt{T}\langle t \rangle \rightarrow^* \mathtt{Obs}$

Meaningfulness

MEANINGFUL

$\exists$ testing context $\mathtt{T}$, $\mathtt{T}\langle t\rangle \to^{*} \mathtt{Obs}$ where $\mathtt{T} ::= \diamond \mid (\lambda x.\mathtt{T})\, t \mid \mathtt{T}\, t$

Meaningfulness

MEANINGFUL

$\exists$ testing context $\mathtt{T},\ \mathtt{T}\langle t\rangle \to^* \mathtt{Obs}$ where $\mathtt{T} ::= \diamond \mid (\lambda x.\mathtt{T})\, t \mid \mathtt{T}\, t$

NAME $\exists\, \mathtt{T},\ \mathtt{T}\langle t\rangle \to^* \mathtt{Id}$

MEANINGFUL

$\exists$ testing context $\mathtt{T},\ \mathtt{T}\langle t\rangle \to^* \mathtt{Obs}$ where $\mathtt{T} ::= \diamond \mid (\lambda x.\mathtt{T})\, t \mid \mathtt{T}\, t$

NAME

$\exists\, \mathtt{T},\ \mathtt{T}\langle t\rangle \to^* \mathtt{Id}$

MEANINGFUL $\mathtt{Id}$ **MEANINGLESS** $\lambda x.\Omega,\ \Omega$

MEANINGFUL

$\exists$ testing context $\mathtt{T}$, $\mathtt{T}\langle t\rangle \to^{*} \mathtt{Obs}$ where $\mathtt{T} ::= \diamond \mid (\lambda x.\mathtt{T})\, t \mid \mathtt{T}\, t$

NAME

$\exists\, \mathtt{T}$, $\mathtt{T}\langle t\rangle \to^{*} \mathtt{Id}$

MEANINGFUL $\mathtt{Id}$ **MEANINGLESS** $\lambda x.\Omega$, Ω

- - - - - - - - - - - - - - - - - - - -

VALUE

$\exists\, \mathtt{T}$, $\mathtt{T}\langle t\rangle \to^{*} v$

MEANINGFUL

$\exists$ testing context $\mathtt{T}$, $\mathtt{T}\langle t\rangle \to^* \mathtt{Obs}$ where $\mathtt{T} ::= \diamond \mid (\lambda x.\mathtt{T})\, t \mid \mathtt{T}\, t$

NAME

$\exists\, \mathtt{T}$, $\mathtt{T}\langle t\rangle \to^* \mathtt{Id}$

MEANINGFUL $\mathtt{Id}$ **MEANINGLESS** $\lambda x.\Omega$, Ω

- - - - - - - - - - - - - - - - - - - -

VALUE

$\exists\, \mathtt{T}$, $\mathtt{T}\langle t\rangle \to^* v$

MEANINGFUL $\mathtt{Id}$, $\lambda x.\Omega$ **MEANINGLESS** Ω

Call-by-Name and Call-by-Value

Call-by-Name

NAME

$$(\lambda x. y\,\Omega)\,\Omega$$

$$\downarrow$$

$$y\,\Omega$$

$$\not\downarrow$$

Call-by-Value

VALUE

$$(\lambda x. y\,\Omega)\,\Omega$$

$$\downarrow$$

$$(\lambda x. y\,\Omega)\,\Omega$$

$$\downarrow$$

$$\vdots$$

Call-by-Name

NAME

$$(\lambda x. y\,\Omega)\,\Omega \qquad \bot$$

$$\downarrow$$

$$y\,\Omega$$

$$\not\downarrow$$

Call-by-Value

VALUE

$$(\lambda x. y\,\Omega)\,\Omega \qquad \bot$$

$$\downarrow$$

$$(\lambda x. y\,\Omega)\,\Omega$$

$$\downarrow$$

$$\vdots$$

Call-by-Name

$$(\lambda x.y\,\Omega)\,\Omega \qquad (\lambda x.y\,\Omega)\,\bot$$

$$\downarrow$$

$$y\,\Omega$$

$$\not\downarrow$$

Call-by-Value

$$(\lambda x.y\,\Omega)\,\Omega \qquad (\lambda x.\bot)\,\Omega$$

$$\downarrow$$

$$(\lambda x.y\,\Omega)\,\Omega$$

$$\downarrow$$

$$\vdots$$

Call-by-Name

NAME

$$\begin{array}{cc} (\lambda x.y\,\Omega)\,\Omega & (\lambda x.y\,\Omega)\,\bot \\ \downarrow & \downarrow \\ y\,\Omega & y\,\bot \\ \not\downarrow & \end{array}$$

Call-by-Value

VALUE

$$\begin{array}{cc} (\lambda x.y\,\Omega)\,\Omega & (\lambda x.\bot)\,\Omega \\ \downarrow & \downarrow \\ (\lambda x.y\,\Omega)\,\Omega & (\lambda x.\bot)\,\Omega \\ \downarrow & \\ \vdots & \end{array}$$

Call-by-Name and Call-by-Value

Call-by-Name

NAME

$$(\lambda x.y\,\Omega)\,\Omega \;\downarrow\; y\,\Omega \;\not\downarrow$$

$$(\lambda x.y\,\Omega)\,\bot \;\downarrow\; y\,\bot \;\not\downarrow$$

Call-by-Value

VALUE

$$(\lambda x.y\,\Omega)\,\Omega \;\downarrow\; (\lambda x.y\,\Omega)\,\Omega \;\downarrow\; \vdots$$

$$(\lambda x.\bot)\,\Omega \;\downarrow\; (\lambda x.\bot)\,\Omega \;\downarrow\; \vdots$$

Call-by-Name and Call-by-Value

Call-by-Name

NAME

$(\lambda x.y\,\Omega)\,\Omega$	$(\lambda x.y\,\Omega)\,\bot$
$\downarrow$	$\downarrow$
$y\,\Omega$	$y\,\bot$
$\not\downarrow$	$\not\downarrow$

Call-by-Value

VALUE

$(\lambda x.y\,\Omega)\,\Omega$	$(\lambda x.\bot)\,\Omega$
$\downarrow$	$\downarrow$
$(\lambda x.y\,\Omega)\,\Omega$	$(\lambda x.\bot)\,\Omega$
$\downarrow$	$\downarrow$
$\vdots$	$\vdots$

Lemma (Lifting) VALUE

Call-by-Name

NAME

$(\lambda x.y\,\Omega)\,\Omega$

$\downarrow$

$y\,\Omega$

$\not\downarrow$

$(\lambda x.y\,\Omega)\,\bot$

$\downarrow$

$y\,\bot$

$\not\downarrow$

Call-by-Value

VALUE

$(\lambda x.y\,\Omega)\,\Omega$

$\downarrow$

$(\lambda x.y\,\Omega)\,\Omega$

$\downarrow$

$\vdots$

$(\lambda x.\bot)\,\Omega$

$\downarrow$

$(\lambda x.\bot)\,\Omega$

$\downarrow$

$\vdots$

Lemma (Lifting) **VALUE**

$$t$$

$$\vee\!|$$

$$\mathbf{t} \longrightarrow \mathbf{u}$$

Call-by-Name

NAME

$$(\lambda x.y\,\Omega)\,\Omega \to y\,\Omega \not\to$$

$$(\lambda x.y\,\Omega)\,\bot \to y\,\bot \not\to$$

Call-by-Value

VALUE

$$(\lambda x.y\,\Omega)\,\Omega \to (\lambda x.y\,\Omega)\,\Omega \to \vdots$$

$$(\lambda x.\bot)\,\Omega \to (\lambda x.\bot)\,\Omega \to \vdots$$

Lemma (Lifting) VALUE

$$\begin{array}{ccc} t & \longrightarrow & u \\ \veebar & \rightsquigarrow & \veebar \\ \mathbf{t} & \longrightarrow & \mathbf{u} \end{array}$$

Call-by-Name

NAME

$$
\begin{array}{ccc}
(\lambda x.y\,\Omega)\,\Omega & & (\lambda x.y\,\Omega)\,\bot \\
\downarrow & \leftsquigarrow & \downarrow \\
y\,\Omega & & y\,\bot \\
\not\downarrow & & \not\downarrow
\end{array}
$$

Call-by-Value

VALUE

$$
\begin{array}{ccc}
(\lambda x.y\,\Omega)\,\Omega & & (\lambda x.\bot)\,\Omega \\
\downarrow & \leftsquigarrow & \downarrow \\
(\lambda x.y\,\Omega)\,\Omega & & (\lambda x.\bot)\,\Omega \\
\downarrow & \leftsquigarrow & \downarrow \\
\vdots & & \vdots
\end{array}
$$

Lemma (Lifting) **VALUE**

$$
\begin{array}{ccc}
t & \longrightarrow & u \\
\rotatebox{90}{$\leq$} & \rotatebox{90}{$\rightsquigarrow$} & \rotatebox{90}{$\leq$} \\
\mathbf{t} & \longrightarrow & \mathbf{u}
\end{array}
$$

Approximation on Meaningfulness

Meaningful (Quasi) Approximation:

$$t \ \text{MEANINGLESS} \quad \rightsquigarrow \qquad \mathcal{QA}(t) := \bot$$

Meaningful (Quasi) Approximation:

$$t \text{ MEANINGLESS} \quad \rightsquigarrow \quad \mathcal{QA}(t) := \bot$$

Lemma (Approximation) VALUE

$$\begin{array}{ccc} t & \longrightarrow & u \\ \vee\!\!| & & \vee\!\!| \\ \mathcal{QA}(t) & & \mathcal{QA}(u) \end{array}$$

Meaningful (Quasi) Approximation:

$$t \ \text{MEANINGLESS} \quad \rightsquigarrow \qquad \mathcal{QA}(t) := \bot$$

Lemma (Approximation) VALUE

$$\begin{array}{ccc} t & \longrightarrow & u \\ \vee\!\mid & \wr & \vee\!\mid \\ \mathcal{QA}(t) & \overset{*}{\longrightarrow} & \mathcal{QA}(u) \end{array}$$

Meaningful (Quasi) Approximation:

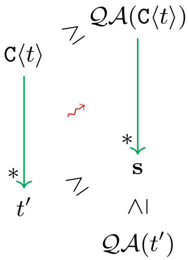
$$t \ \fbox{MEANINGLESS} \quad \rightsquigarrow \qquad \mathcal{QA}(t) := \bot$$

Lemma (Approximation) VALUE

$$\begin{array}{ccccc} t & \longrightarrow & u & & \\ \leq & \rightsquigarrow & \leq & & \\ \mathcal{QA}(t) & \longrightarrow^{*} & \mathbf{u} & \geq & \mathcal{QA}(u) \end{array}$$

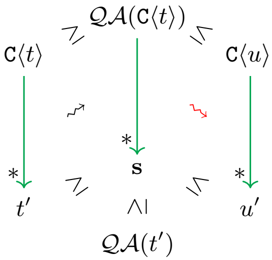
Variations on Genericity

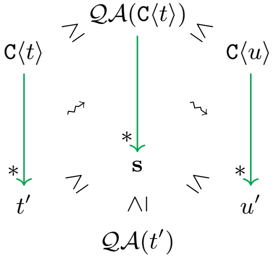
$$\mathtt{C}\langle t\rangle \;\xrightarrow{*}\; t'$$



$\mathcal{QA}(\mathtt{C}\langle t\rangle)$
$\mathtt{C}\langle t\rangle$
$*$
$*$
$\mathbf{s}$
t'
$\mathcal{QA}(t')$

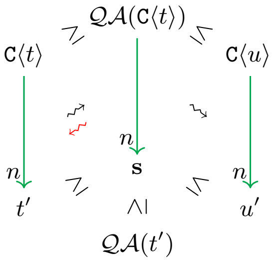
Variations on Genericity





Theorem ((Surface) Genericity) VALUE

Let t be MEANINGLESS *such that $\mathtt{C}\langle t\rangle$ has a $\rightarrow$-normal form. Then, there exists $n \in \mathbb{N}$ such that for any $u \in \Lambda$, there exists $\rightarrow$-normal forms t', u' such that $\mathtt{C}\langle t\rangle \rightarrow^* t'$ and $\mathtt{C}\langle u\rangle \rightarrow^* u'$.*

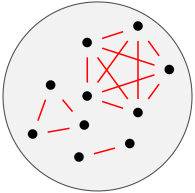


Theorem (Quantitative (Surface) Genericity) VALUE

Let t be MEANINGLESS *such that $\mathtt{C}\langle t\rangle$ has a $\rightarrow$-normal form. Then, there exists $n \in \mathbb{N}$ such that for any $u \in \Lambda$, there exists $\rightarrow$-normal forms t', u' such that $\mathtt{C}\langle t\rangle \rightarrow^n t'$ and $\mathtt{C}\langle u\rangle \rightarrow^n u'$.*

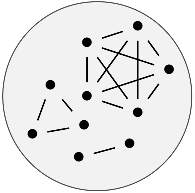
Theories of the λ-calculus

Theories: Equivalence relations on Λ.



Theories: Equivalence relations on Λ.

λ_{v}**-theories:** Contextually closed theory containing β_v.



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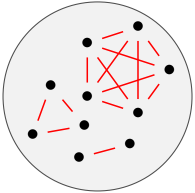

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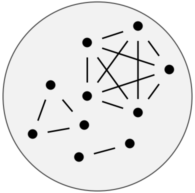
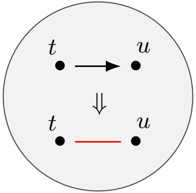
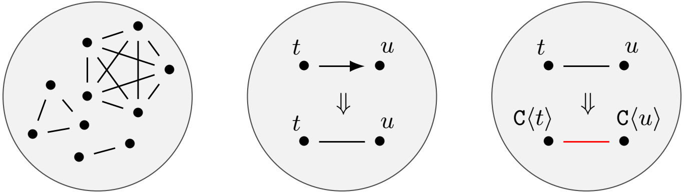




Theories: Equivalence relations on Λ.

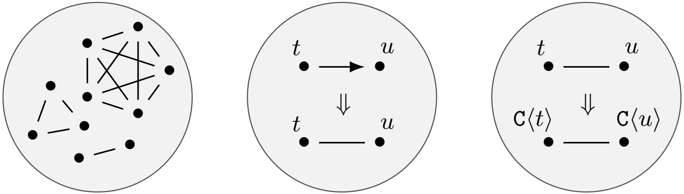
$\lambda_{\mathtt{v}}$**-theories:** Contextually closed theory containing β_v.



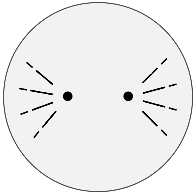
Theories of the λ-calculus

Theories: Equivalence relations on Λ.

λ_v**-theories:** Contextually closed theory containing β_v.



Consistent: There exists two distinct points.

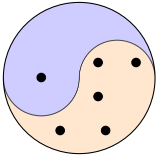


Theory $\mathcal{H}_{\mathtt{v}}$: Smallest Sensible $\lambda_{\mathtt{v}}$-Theory

Theory $\mathcal{H}_{\mathrm{v}}$: Smallest Sensible λ_{v}-Theory

Sensible Theory: λ_{v}-theory equating all MEANINGLESS terms.

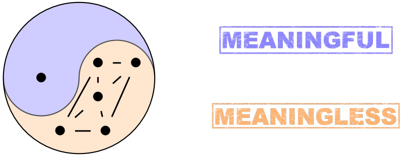
Sensible Theory: λ_v-theory equating all MEANINGLESS terms.



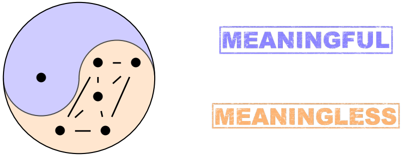
MEANINGFUL

MEANINGLESS

Sensible Theory: λ_{v}-theory equating all MEANINGLESS terms.



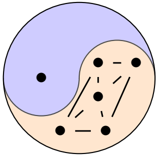
Sensible Theory: λ_v-theory equating all MEANINGLESS terms.



Theory $\mathcal{H}_v$: Smallest sensible λ_v-theory.

Theory $\mathcal{H}_{\text{v}}$: Smallest Sensible λ_{v}-Theory

Sensible Theory: λ_{v}-theory equating all MEANINGLESS terms.



MEANINGFUL

MEANINGLESS

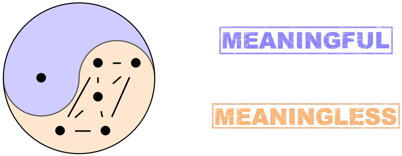
Theory $\mathcal{H}_{\text{v}}$: Smallest sensible λ_{v}-theory.

Theorem (Full Genericity) VALUE

Let $\mathtt{C}\langle t\rangle \to_{\omega}^{*} s$ *with* t MEANINGLESS *and* s *a* $\to_{\omega}$*-normal form, then for any* $u \in \Lambda$, $\mathtt{C}\langle u\rangle \to_{\omega}^{*} s$.

Theory $\mathcal{H}_{\mathrm{v}}$: Smallest Sensible λ_{v}-Theory

Sensible Theory: λ_{v}-theory equating all MEANINGLESS terms.



Theory $\mathcal{H}_{\mathrm{v}}$: Smallest sensible λ_{v}-theory.

Theorem (Full Genericity) VALUE

Let $\mathtt{C}\langle t\rangle \rightarrow_{\omega}^{*} s$ *with* t MEANINGLESS *and* s *a* $\rightarrow_{\omega}$*-normal form, then for any* $u \in \Lambda$, $\mathtt{C}\langle u\rangle \rightarrow_{\omega}^{*} s$.

Theorem VALUE

The theory $\mathcal{H}_{\mathrm{v}}$ *is consistent.*

Theory $\mathcal{H}_{\mathtt{v}}^{*}$: Maximal Consistent Extension of $\mathcal{H}_{\mathtt{v}}$

Theory $\mathcal{H}_{\mathrm{v}}^{*}$: Maximal Consistent Extension of $\mathcal{H}_{\mathrm{v}}$

Theory $\mathcal{H}_{\mathrm{v}}^{*}$: $t — u$

Theory $\mathcal{H}_{\mathtt{v}}^*$: Maximal Consistent Extension of $\mathcal{H}_{\mathtt{v}}$

Theory $\mathcal{H}_{\mathtt{v}}^*$: $t \mathrel{—} u$ when $\forall\ \mathtt{C},\ \mathtt{C}\langle t\rangle$ MEANINGFUL iff $\mathtt{C}\langle u\rangle$ MEANINGFUL.

Theory $\mathcal{H}_{\mathrm{v}}^{*}$: Maximal Consistent Extension of $\mathcal{H}_{\mathrm{v}}$

Theory $\mathcal{H}_{\mathrm{v}}^{*}$: $t — u$ when $\forall$ C, C$\langle t \rangle$ MEANINGFUL iff C$\langle u \rangle$ MEANINGFUL.

Corollary VALUE

The theory $\mathcal{H}_{\mathrm{v}}^{*}$ extends $\mathcal{H}_{\mathrm{v}}$.

Theory $\mathcal{H}_{\mathrm{v}}^*$: Maximal Consistent Extension of $\mathcal{H}_{\mathrm{v}}$

Theory $\mathcal{H}_{\mathrm{v}}^*$: $t \mathrel{—} u$ when $\forall\, \mathtt{C},\ \mathtt{C}\langle t\rangle$ MEANINGFUL iff $\mathtt{C}\langle u\rangle$ MEANINGFUL.

Theorem (Surface Genericity) VALUE

Let $\mathtt{C}\langle t\rangle$ be MEANINGFUL *with t* MEANINGLESS*, then for every $u \in \Lambda$, $\mathtt{C}\langle u\rangle$ is* MEANINGFUL.

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The theory $\mathcal{H}_{\mathrm{v}}^*$ extends $\mathcal{H}_{\mathrm{v}}$.

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The theory $\mathcal{H}_{\mathrm{v}}^*$ *extends* $\mathcal{H}_{\mathrm{v}}$.

Theorem VALUE

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Theory $\mathcal{H}_{\mathrm{v}}^*$: Maximal Consistent Extension of $\mathcal{H}_{\mathrm{v}}$

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Thank you !