

ORACLES AND CHOICE SEQUENCES FOR TYPE-THEORETIC PRAGMATICS

CMU POP SEMINAR

Jon Sterling

October 8, 2015

joint work with Darryl McAdams

INTRODUCTION

[[*A woman walked in.*]]



[[*A woman walked in.*]]

▽

($\Sigma p \in \textit{Woman}$)

[[*A woman walked in.*]]

∇

$(\Sigma p \in \textit{Woman}) \textit{WalkedIn}(p)$

[[*She sat down*]]



[[*She sat down*]]

▽

SatDown(???)

[[*A woman walked in. She sat down*]]



[[A woman walked in. She sat down]]

▽

$(\Sigma x \in (\Sigma p \in \text{Woman}) \text{WalkedIn}(p))$

[[A woman walked in. She sat down]]

▽

$(\Sigma x \in (\Sigma p \in \text{Woman}) \text{WalkedIn}(p)) \text{SatDown}(???)$

[[A woman walked in. She sat down]]

▽

$(\Sigma x \in (\Sigma p \in \text{Woman}) \text{WalkedIn}(p)) \text{SatDown}(\pi_1(x))$

THE **require** ORACLE: STATICS

require : (0;1)

(operator)

require $x : A$ **in** $N \stackrel{\text{def}}{=} \textbf{require}(A; x.N)$

(notation)

require : (0;1)

(operator)

require $x : A$ **in** $N \stackrel{\text{def}}{=} \text{require}(A; x.N)$

(notation)

$$\frac{\Gamma \vdash M \in A \quad \Gamma, x : A \vdash N \in B}{\Gamma \vdash \text{require } x : A \text{ in } N \in B}$$

(require)

[[A woman walked in. She sat down]]

∇

$(\Sigma x \in (\Sigma p \in Woman) WalkedIn(p)) SatDown(???)$

[[A woman walked in. She sat down]]

▽

$(\Sigma x \in (\Sigma p \in \text{Woman}) \text{WalkedIn}(p))$ **require** $y : \text{Woman}$ **in** $\text{SatDown}(y)$

The meaning of a sentence is a logical proposition.

~~The meaning of a sentence is a logical proposition.~~

~~The meaning of a sentence is a logical proposition.~~

The meaning of a sentence is a type-theoretic expression which may evaluate to a canonical proposition.

~~The meaning of a sentence is a logical proposition.~~

The meaning of a sentence is a type-theoretic expression which may evaluate to a canonical proposition.

~~The meaning of a sentence is a logical proposition.~~

The meaning of a sentence is a type-theoretic expression which may evaluate to a canonical proposition.

What we want:

$(\Sigma x \in (\Sigma p \in \text{Woman}) \text{WalkedIn}(p)) \text{ require } y : \text{Woman in SatDown}(y)$

\sim

$(\Sigma x \in (\Sigma p \in \text{Woman}) \text{WalkedIn}(p)) \pi_1(x)$

~~The meaning of a sentence is a logical proposition.~~

The meaning of a sentence is a type-theoretic expression which may evaluate to a canonical proposition.

What we want:

$(\Sigma x \in (\Sigma p \in \text{Woman}) \text{WalkedIn}(p))$ **require** $y : \text{Woman}$ **in** $\text{SatDown}(y)$

\sim

$(\Sigma x \in (\Sigma p \in \text{Woman}) \text{WalkedIn}(p)) \pi_1(x)$

where $M \sim N \stackrel{\text{def}}{=} (M \leq N) \ \& \ (N \leq M)$

$$\frac{M \in A \quad [M/x] N \Downarrow N'}{\text{require } x : A \text{ in } N \Downarrow N'} \quad (??)$$

$$\frac{M \in A \quad [M/x] N \Downarrow N'}{\text{require } x : A \text{ in } N \Downarrow N'} \quad (??)$$

[[*The President ran a marathon*]]



[[*The President ran a marathon*]]

▽

require $x : \textit{President}$ **in** $(\Sigma y \in \textit{Marathon}) \textit{Ran}(x; y)$

A POSITIVE EXAMPLE

require $x : \textit{President}$ **in** $(\Sigma y \in \textit{Marathon}) \textit{Ran}(x; y)$

require $x : \textit{President}$ **in** $(\Sigma y \in \textit{Marathon}) \textit{Ran}(x; y)$

\Downarrow

$(\Sigma y \in \textit{Marathon}) \textit{Ran}(\textit{Obama}; y)$

A NEGATIVE EXAMPLE

A NEGATIVE EXAMPLE

[[*The unicorn ran a marathon*]]



$\llbracket \textit{The unicorn ran a marathon} \rrbracket$

∇

require $x : \textit{Unicorn}$ **in** $(\Sigma y \in \textit{Marathon}) \textit{Ran}(x; y)$

[[*The unicorn ran a marathon*]]

∇

require $x : \textit{Unicorn}$ **in** $(\Sigma y \in \textit{Marathon}) \textit{Ran}(x; y)$

(not a proposition)

IS require COMPUTATIONALLY EFFECTIVE?

Yes, but we need two things:

Yes, but we need two things:

1. judgments shall be local / sensitive to knowledge

Yes, but we need two things:

1. judgments shall be local / sensitive to knowledge
2. non-determinism must be eliminated

Yes, but we need two things:

1. judgments shall be local / sensitive to knowledge (via forcing)
2. non-determinism must be eliminated

Yes, but we need two things:

1. judgments shall be local / sensitive to knowledge (via forcing)
2. non-determinism must be eliminated

$$w \Vdash \mathcal{I}$$

Yes, but we need two things:

1. judgments shall be local / sensitive to knowledge (via forcing)
2. non-determinism must be eliminated (via choice sequences)

$$w \Vdash \mathcal{I}$$

Yes, but we need two things:

1. judgments shall be local / sensitive to knowledge (via forcing)
2. non-determinism must be eliminated (via choice sequences)

$$w \Vdash \mathcal{I}_\alpha$$

THE CREATING SUBJECT

All mathematics is a mental construction performed by an idealized subject, subject to the following observations about knowledge:

All mathematics is a mental construction performed by an idealized subject, **subject to the following observations about knowledge:**

All mathematics is a mental construction performed by an idealized subject, subject to the following observations about knowledge:

1. experiences are never forgotten (monotonicity, functoriality)

All mathematics is a mental construction performed by an idealized subject, **subject to the following observations about knowledge:**

1. experiences are never forgotten (**monotonicity, functoriality**)
2. at a point in time, the subject knows whether or not it has experienced a judgment (**decidability**)

All mathematics is a mental construction performed by an idealized subject, **subject to the following observations about knowledge**:

1. experiences are never forgotten (**monotonicity, functoriality**)
2. at a point in time, the subject knows whether or not it has experienced a judgment (**decidability**)

Corollary

The meaning of a judgment \mathcal{J} must be explained in terms of its forcing condition, $w \Vdash \mathcal{J}$, for any stage/world w .

...

2. at a point in time, the subject knows whether or not it has experienced a judgment (decidability)

...

2. at a point in time, the subject knows whether or not it has experienced a judgment (decidability)

Remark

Contra Dummett, I by no means take the above as requiring that the following shall be true in a constructive metatheory, divorced from time:

$$\forall w. \forall \mathcal{J}. (w \Vdash \mathcal{J}) \vee \neg(w \Vdash \mathcal{J}) \quad (\text{Dummett's infelicity})$$

The above is impossible in a Beth model.

logical consequence \Rightarrow semantic consequence

Brouwer?, Martin-Löf, Sundholm \Rightarrow *Brouwer?, Heyting, Allen, Zeilberger*

logical consequence \Rightarrow **semantic consequence**

Brouwer?, Martin-Löf, Sundholm \Rightarrow *Brouwer?, Heyting, Allen, Zeilberger*

proof conditions \Rightarrow **assertion conditions**

Dummett, Martin-Löf, Sundholm \Rightarrow *Brouwer, Heyting, Van Atten*

logical consequence \Rightarrow **semantic consequence**

Brouwer?, Martin-Löf, Sundholm \Rightarrow *Brouwer?, Heyting, Allen, Zeilberger*

proof conditions \Rightarrow **assertion conditions**

Dummett, Martin-Löf, Sundholm \Rightarrow *Brouwer, Heyting, Van Atten*

global meaning explanation \Rightarrow **local meaning explanation**

Husserl, Dummett, Martin-Löf \Rightarrow *Brouwer, Beth, Kripke,
Grothendieck, Lawvere, Joyal*

assertion acts (judgments) are intensional (local)

assertion acts (judgments) are intensional (local)

$$|_x \mathcal{J}(x)$$

(general judgment)

assertion acts (judgments) are intensional (local)

$|_x \mathcal{I}(x)$

(general judgment)

$\mathcal{I}_2 (\mathcal{I}_1)$

(hypothetical judgment)

assertion acts (judgments) are intensional (local)

$|_x \mathcal{I}(x)$

(general judgment)

$\mathcal{I}_2 (\mathcal{I}_1)$

(hypothetical judgment)

$M \Downarrow N$

(evaluation)

assertion acts (judgments) are intensional (local)

$ _x \mathcal{I}(x)$	(general judgment)
$\mathcal{I}_2 (\mathcal{I}_1)$	(hypothetical judgment)
$M \Downarrow N$	(evaluation)
A type	(typehood)

assertion acts (judgments) are intensional (local)

$ _x \mathcal{I}(x)$	(general judgment)
$\mathcal{I}_2 (\mathcal{I}_1)$	(hypothetical judgment)
$M \Downarrow N$	(evaluation)
$A \text{ type}$	(typehood)
$A \text{ verif}$	(verification)

assertion acts (judgments) are intensional (local)

$ _x \mathcal{I}(x)$	(general judgment)
$\mathcal{I}_2 (\mathcal{I}_1)$	(hypothetical judgment)
$M \Downarrow N$	(evaluation)
$A \text{ type}$	(typehood)
$A \text{ verif}$	(verification)
$A \text{ true}$	(truth)

assertion acts (judgments) are intensional (local)

$ _x \mathcal{I}(x)$	(general judgment)
$\mathcal{I}_2 (\mathcal{I}_1)$	(hypothetical judgment)
$M \Downarrow N$	(evaluation)
$A \text{ type}$	(typehood)
$A \text{ verif}$	(verification)
$A \text{ true}$	(truth)
$M = N \in A$	(membership)

assertion acts (judgments) are intensional (local)

$w \Vdash _x \mathcal{I}(x)$	(general judgment)
$w \Vdash \mathcal{I}_2 (\mathcal{I}_1)$	(hypothetical judgment)
$w \Vdash M \Downarrow N$	(evaluation)
$w \Vdash A \text{ type}$	(typehood)
$w \Vdash A \text{ verif}$	(verification)
$w \Vdash A \text{ true}$	(truth)
$w \Vdash M = N \in A$	(membership)

$w \Vdash |_x \mathcal{I}(x)$

(general judgment)

$w \Vdash \mathcal{I}_2 (\mathcal{I}_1)$

(hypothetical judgment)

$$w \Vdash |_x \mathcal{I}(x) \quad \Longleftrightarrow \quad \dots$$

$$w \Vdash \mathcal{I}_2 (\mathcal{I}_1) \quad \Longleftrightarrow \quad \dots$$

$$w \Vdash |_x \mathcal{I}(x) \iff \forall u \succeq w. \forall x \in \mathcal{D}_u. u \Vdash \mathcal{I}(x)$$

$$w \Vdash \mathcal{I}_2 (\mathcal{I}_1) \iff \forall u \succeq w. u \Vdash \mathcal{I}_1 \Rightarrow u \Vdash \mathcal{I}_2$$

$$\begin{aligned}
w \Vdash |_x \mathcal{I}(x) &\iff \forall u \geq w. \forall x \in \mathcal{D}_u. u \Vdash \mathcal{I}(x) \\
w \Vdash \mathcal{I}_2 (\mathcal{I}_1) &\iff \forall u \geq w. u \Vdash \mathcal{I}_1 \Rightarrow u \Vdash \mathcal{I}_2
\end{aligned}$$

where \mathcal{D}_w is the species of constructions that have been effected by stage w

The meaning of a proposition/type is an intensional (world-indexed) specification of verification acts, i.e. a local meaning explanation for $w \Vdash P \text{ } \textit{verif}$ (and its synthesis).

The meaning of a proposition/type is an intensional (world-indexed) specification of verification acts, i.e. a local meaning explanation for $w \Vdash P \text{ } \textit{verif}$ (and its synthesis).

For a type A , implicit in the explanation of $w \Vdash A \text{ } \textit{verif}$ is a \mathbb{W} -indexed family of PERs $\mathcal{V}[[A]]_w \subseteq \mathcal{D}_w \times \mathcal{D}_w$ whose members **reflect** the computational content (extension) of verification acts.

Truth (**justification**) consists in recognizing the effectiveness of a procedure for **verification**.

Truth (**justification**) consists in recognizing the effectiveness of a procedure for **verification**.

In the model, this corresponds to the inevitability of verification (i.e. a bar, in which verification occurs at all nodes):

$$w \Vdash A \text{ true} \iff \exists \mathfrak{B} \text{ bars } w. \forall u \in \mathfrak{B}. u \Vdash A \text{ verif} \quad (\text{due to Dummett})$$

The analytic judgments of type theory are reflections on mathematical activity.

The analytic judgments of type theory are reflections on mathematical activity.

1. **Canonical membership** reflects **verification**

$$\mathcal{V}[[A]]_w(M, N) \bowtie w \Vdash A \text{ } \textit{verif}$$

The analytic judgments of type theory are reflections on mathematical activity.

1. **Canonical membership** reflects **verification**
2. **Membership** reflects **justification**

$$w \Vdash M = N \in A \not\bowtie w \Vdash A \text{ true}$$

The analytic judgments of type theory are reflections on mathematical activity.

1. **Canonical membership** reflects **verification**
2. **Membership** reflects **justification**
3. **Computation** reflects **the recognition of a bar**

$$w \Vdash M = N \in A \not\bowtie w \Vdash A \text{ true}$$

The analytic judgments of type theory are reflections on mathematical activity.

1. **Canonical membership** reflects **verification**
2. **Membership** reflects **justification**
3. **Computation** reflects **the recognition of a bar**

$$\wedge \left\{ \begin{array}{l} w \Vdash M \Downarrow M' \\ w \Vdash N \Downarrow N' \\ \mathcal{V} \llbracket A \rrbracket_w (M', N') \end{array} \right\} \bowtie \exists \mathcal{B} \text{ bars } w. \forall u \in \mathcal{B}. u \Vdash A \text{ verif}$$

choice sequences (streams of objects) may be propounded over time based on the previous experience of the creating subject.

choice sequences (streams of objects) may be propounded over time based on the previous experience of the creating subject.

Example:

$$\alpha(i) = \begin{cases} 0 & i \Vdash A \text{ true} \\ 1 & \neg(i \Vdash A \text{ true}) \end{cases} \quad (\text{KS})$$

Let $\mathcal{K}_A : \mathbf{FinSet}^{\mathbf{W}^{\text{op}}}$ be the presheaf of constructions of A *true* effected “so far” for each canonical proposition A .

Let $\mathcal{K}_A : \mathbf{FinSet}^{\mathbf{Wop}}$ be the presheaf of constructions of A *true* effected “so far” for each canonical proposition A .

We now can give a precise, but non-deterministic, dynamics to **require**:

Let $\mathcal{K}_A : \mathbf{FinSet}^{\mathbf{Wop}}$ be the presheaf of constructions of A *true* effected “so far” for each canonical proposition A .

We now can give a precise, but non-deterministic, dynamics to **require**:

$$\frac{w \Vdash A \Downarrow A' \quad M \in \mathcal{K}_{A'}(w) \quad w \Vdash [M/x] N \Downarrow N'}{w \Vdash \mathbf{require} \ x : A \ \mathbf{in} \ N \Downarrow N'} \quad (*)$$

We need a way to deterministically choose a representative of $\mathcal{K}_A(w)$. First, let κ_A be the choice sequence of lists given by enumerating $\mathcal{K}_A(w)$ at each stage w , in order of time.

We need a way to deterministically choose a representative of $\mathcal{K}_A(w)$. First, let κ_A be the choice sequence of lists given by enumerating $\mathcal{K}_A(w)$ at each stage w , in order of time.

Idea: reformulate Type Theory relative to a choice sequence of “choosers”.

SPREADS: SETS OF CHOICE SEQUENCES

A spread direction \mathfrak{S} is a restriction on choice sequences which is defined by a condition on their finite approximations (prefixes, neighborhoods), subject to the following laws:

SPREADS: SETS OF CHOICE SEQUENCES

A spread direction \mathfrak{S} is a restriction on choice sequences which is defined by a condition on their finite approximations (prefixes, neighborhoods), subject to the following laws:

1. the empty neighborhood shall be admitted

$$\mathfrak{S}(\langle \rangle)$$

SPREADS: SETS OF CHOICE SEQUENCES

A spread direction \mathfrak{S} is a restriction on choice sequences which is defined by a condition on their finite approximations (prefixes, neighborhoods), subject to the following laws:

1. the empty neighborhood shall be admitted

$$\mathfrak{S}(\langle \rangle)$$

2. if a neighborhood is admitted, so shall all its subneighborhoods

$$|_{\vec{u}, m} \mathfrak{S}(\vec{u}) \left(\mathfrak{S}(\vec{u} \smallfrown m) \right)$$

SPREADS: SETS OF CHOICE SEQUENCES

A spread direction \mathfrak{S} is a restriction on choice sequences which is defined by a condition on their finite approximations (prefixes, neighborhoods), subject to the following laws:

1. the empty neighborhood shall be admitted

$$\mathfrak{S}(\langle \rangle)$$

2. if a neighborhood is admitted, so shall all its subneighborhoods

$$|_{\vec{u}, m} \mathfrak{S}(\vec{u}) \left(\mathfrak{S}(\vec{u} \smallfrown m) \right)$$

3. a neighborhood may always be refined within the spread

$$|_{\vec{u}} \mathfrak{S}(\vec{u} \smallfrown m) \left(\mathfrak{S}(\vec{u}) \right)$$

THE require ORACLE: DYNAMICS

A spread direction for index-choosers:

$$\frac{\overline{\mathfrak{S}(\langle \rangle)}}{\mathfrak{S}(\vec{u})} \quad \frac{\mathfrak{S}(\vec{u}) \quad |_n \rho(n) < n \quad (n \in \mathbb{N}^+)}{\mathfrak{S}(\vec{u} \smallfrown \rho)} \quad (\text{spread law})$$

A spread direction for index-choosers:

$$\frac{\overline{\mathfrak{S}(\langle \rangle)}}{\mathfrak{S}(\vec{u})} \quad \frac{\mathfrak{S}(\vec{u}) \quad |_n \rho(n) < n \quad (n \in \mathbb{N}^+)}{\mathfrak{S}(\vec{u} \smallfrown \rho)} \quad (\text{spread law})$$

Reformulate type theory relative to an arbitrary $\alpha \in \mathfrak{S}$! For instance:

$$\frac{w \Vdash M \Downarrow_\alpha M' \quad w \Vdash N \Downarrow_\alpha N' \quad \mathcal{V} \llbracket A \rrbracket_w^\alpha (M', N')}{w \Vdash M = N \in_\alpha A}$$

A spread direction for index-choosers:

$$\frac{\overline{\mathfrak{S}(\langle \rangle)}}{\mathfrak{S}(\langle \rangle)} \quad \frac{\mathfrak{S}(\vec{u}) \quad |_n \rho(n) < n \quad (n \in \mathbb{N}^+)}{\mathfrak{S}(\vec{u} \smallfrown \rho)} \quad (\text{spread law})$$

Reformulate type theory relative to an arbitrary $\alpha \in \mathfrak{S}$! For instance:

$$\frac{M \Downarrow_\alpha M' \quad N \Downarrow_\alpha N' \quad \mathcal{V} \llbracket A \rrbracket^\alpha (M', N')}{M = N \in_\alpha A}$$

Deterministic choice for \varkappa_A :

$$\frac{w \Vdash A \Downarrow_{\alpha} A' \quad |\varkappa_{A'}(w)| = \ell \quad \text{hd}(\alpha)(\ell) = i \quad \varkappa_{A'}(w)(i) = M}{w \Vdash \varkappa_A \ni_{\alpha} M}$$

Deterministic choice for \varkappa_A :

$$\frac{A \Downarrow_{\alpha} A' \quad |\varkappa_{A'}| = \ell \quad \text{hd}(\alpha)(\ell) = i \quad \varkappa_{A'}(i) = M}{\varkappa_A \ni_{\alpha} M}$$

Deterministic choice for \varkappa_A :

$$\frac{A \Downarrow_{\alpha} A' \quad |\varkappa_{A'}| = \ell \quad \text{hd}(\alpha)(\ell) = i \quad \varkappa_{A'}(i) = M}{\varkappa_A \ni_{\alpha} M}$$

Deterministic dynamics for **require**:

$$\frac{\varkappa_A \ni_{\alpha} M \quad [M/x]N \Downarrow_{\text{tl}(\alpha)} N'}{\mathbf{require} \ x : A \ \mathbf{in} \ N \Downarrow_{\alpha} N'} \quad (\text{for } \alpha \in \mathfrak{S})$$

Theorem

The following rule is valid in our semantics:

$$\frac{A \text{ true}_\alpha \quad x : A \vdash_\alpha N \in B}{\textbf{require } x : A \textbf{ in } N \in_\alpha B} \textit{require}$$

$$\frac{A \text{ true}_{\alpha} \quad x : A \vdash_{\alpha} N \in B}{\textbf{require } x : A \textbf{ in } N \in_{\alpha} B} \textit{require}$$

$$\overline{A \text{ true}_\alpha} \quad \mathcal{D} \qquad \overline{x : A \vdash_\alpha N \in B} \quad \mathcal{E}$$

$$\overline{\mathbf{require} \ x : A \text{ in } N \in_\alpha B} \quad \text{require}$$

$$\frac{}{A \text{ true}_\alpha} \mathcal{D} \qquad \frac{}{x : A \vdash_\alpha N \in B} \mathcal{E}$$

$$\frac{\frac{}{\text{require } x : A \text{ in } N \Downarrow_\alpha N'} \quad \frac{}{\mathcal{V}[[B]]^\alpha(N', N')}}{\text{require } x : A \text{ in } N \in_\alpha B} \text{require}$$

$$\overline{A \text{ true}_\alpha} \quad \mathcal{D} \qquad \overline{x : A \vdash_\alpha N \in B} \quad \mathcal{E}$$

$$\frac{\overline{\mathcal{K}_A \ni_\alpha M} \quad \overline{[M/x]N \Downarrow_\alpha N'}}{\text{require } x : A \text{ in } N \Downarrow_\alpha N'} \quad \frac{}{\mathcal{V} \llbracket B \rrbracket^\alpha (N', N')} \quad \text{require}$$

$$\frac{}{\text{require } x : A \text{ in } N \in_\alpha B}$$

$$\frac{}{A \text{ true}_\alpha} \mathcal{D} \qquad \frac{}{x : A \vdash_\alpha N \in B} \mathcal{E}$$

$$\frac{\frac{\frac{\checkmark}{A \text{ true}_\alpha} \mathcal{D}}{\varkappa_A \ni_\alpha \textcolor{red}{M}} \quad \frac{}{[M/x]N \Downarrow_\alpha \textcolor{red}{N'}}}{\text{require } x : A \text{ in } N \Downarrow_\alpha \textcolor{red}{N'}} \quad \frac{}{\mathcal{V}[[B]]^\alpha(N', N')} \text{require}$$

$$\frac{}{\text{require } x : A \text{ in } N \in_\alpha B}$$

$$\frac{\overline{A \text{ true}_\alpha} \quad \mathcal{D}}{\overline{\frac{|_{y,z} [y/x]N = [z/x]N \in_\alpha B \quad (y = z \in_\alpha A)}{x : A \vdash_\alpha N \in B}} \quad \mathcal{E}} \quad \mathcal{F}$$

$$\frac{\frac{\checkmark}{A \text{ true}_\alpha} \quad \mathcal{D} \quad \frac{\overline{\not\prec_A \ni_\alpha M} \quad \overline{[M/x]N \Downarrow_\alpha N'}}{\overline{\text{require } x : A \text{ in } N \Downarrow_\alpha N'} \quad \overline{\mathcal{V}[[B]]^\alpha(N', N')}}}{\overline{\text{require } x : A \text{ in } N \in_\alpha B} \quad \text{require}} \quad \mathcal{F}$$

$$\frac{\overline{A \text{ true}_\alpha} \quad \mathcal{D}}{\overline{\frac{\overline{|_{y,z} [y/x]N = [z/x]N \in_\alpha B \ (y = z \in_\alpha A)} \quad \mathcal{F}}{x : A \vdash_\alpha N \in B} \quad \mathcal{E}}}$$

$$\frac{\overline{[M/x]N \in_\alpha B \ (M \in_\alpha A)} \quad \checkmark \quad \mathcal{F}(M, M) \quad \overline{M \in_\alpha A}}{\overline{\quad}}$$

$$\frac{\overline{A \text{ true}_\alpha} \quad \checkmark \quad \mathcal{D} \quad \overline{\not\prec_A \ni_\alpha M} \quad \overline{[M/x]N \Downarrow_\alpha N'} \quad \overline{\text{require } x : A \text{ in } N \Downarrow_\alpha N'} \quad \overline{\mathcal{V}[[B]]^\alpha(N', N')} \quad \text{require}}{\overline{\text{require } x : A \text{ in } N \in_\alpha B}}$$

$$\frac{\overline{A \text{ true}_\alpha} \quad \mathcal{D}}{\overline{\frac{|_{y,z} [y/x]N = [z/x]N \in_\alpha B \quad (y = z \in_\alpha A)}{x : A \vdash_\alpha N \in B}} \quad \mathcal{F} \quad \mathcal{E}}$$

$$\frac{\overline{\frac{\checkmark}{[M/x]N \in_\alpha B \quad (M \in_\alpha A)}{\mathcal{F}(M, M)} \quad \frac{\overline{\kappa_A \ni_\alpha M}}{M \in_\alpha A}}{\quad}$$

$$\frac{\overline{\frac{\checkmark}{A \text{ true}_\alpha} \quad \mathcal{D}} \quad \frac{\overline{\kappa_A \ni_\alpha M} \quad \overline{[M/x]N \Downarrow_\alpha N'}}{\text{require } x : A \text{ in } N \Downarrow_\alpha N'} \quad \frac{\overline{\mathcal{V}[[B]]^\alpha(N', N')}}{\text{require } x : A \text{ in } N \in_\alpha B} \quad \text{require}$$

$$\frac{}{A \text{ true}_\alpha} \mathcal{D} \quad \frac{\frac{}{|_{y,z} [y/x]N = [z/x]N \in_\alpha B \ (y = z \in_\alpha A)} \mathcal{F}}{x : A \vdash_\alpha N \in B} \mathcal{E}$$

$$\frac{\frac{}{[M/x]N \in_\alpha B \ (M \in_\alpha A)} \mathcal{F}(M, M)}{\frac{}{[M/x]N \in_\alpha B \ (M \in_\alpha A)} \mathcal{F}(M, M)} \mathcal{D} \quad \frac{\frac{}{A \text{ true}_\alpha} \mathcal{D}}{\frac{}{M \in_\alpha A} \mathcal{D}} \mathcal{D}$$

$$\frac{\frac{}{A \text{ true}_\alpha} \mathcal{D}}{\frac{}{A \text{ true}_\alpha} \mathcal{D}} \mathcal{D} \quad \frac{\frac{}{\not\vdash_A \ni_\alpha M} \mathcal{D} \quad \frac{}{[M/x]N \Downarrow_\alpha N'} \mathcal{D}}{\text{require } x : A \text{ in } N \Downarrow_\alpha N'} \mathcal{D} \quad \frac{}{\mathcal{V}[[B]]^\alpha(N', N')} \mathcal{D}$$

$$\frac{}{\text{require } x : A \text{ in } N \in_\alpha B} \text{require}$$

$$\frac{}{A \text{ true}_\alpha} \mathcal{D} \quad \frac{\overline{|y,z} [y/x]N = [z/x]N \in_\alpha B \ (y = z \in_\alpha A)}{x : A \vdash_\alpha N \in B} \begin{matrix} \mathcal{F} \\ \mathcal{E} \end{matrix}$$

$$\frac{\overline{[M/x]N \in_\alpha B \ (M \in_\alpha A)} \checkmark \mathcal{F}(M,M) \quad \frac{\overline{A \text{ true}_\alpha} \checkmark \mathcal{D} \quad \overline{\not x_A \ni_\alpha \mathbf{M}}}{M \in_\alpha A}}{[M/x]N \in_\alpha B}$$

$$\frac{\overline{A \text{ true}_\alpha} \checkmark \mathcal{D} \quad \overline{\not x_A \ni_\alpha \mathbf{M}} \quad \overline{[M/x]N \Downarrow_\alpha \mathbf{N}'} \quad \overline{\mathcal{V} \llbracket B \rrbracket^\alpha (\mathbf{N}', \mathbf{N}')}}{\text{require } x : A \text{ in } N \Downarrow_\alpha \mathbf{N}'} \text{require}$$

$$\frac{\overline{A \text{ true}_\alpha} \quad \mathcal{D}}{\overline{\frac{\overline{|_{y,z} [y/x]N = [z/x]N \in_\alpha B \ (y = z \in_\alpha A)} \quad \mathcal{F}}{x : A \vdash_\alpha N \in B} \quad \mathcal{E}}}$$

$$\frac{\overline{\frac{\checkmark}{[M/x]N \in_\alpha B \ (M \in_\alpha A)} \quad \mathcal{F}(M, M)} \quad \frac{\overline{\frac{\checkmark}{A \text{ true}_\alpha} \quad \mathcal{D}} \quad \frac{\not\propto_A \ni_\alpha \mathbf{M}}{M \in_\alpha A}}{\overline{[M/x]N \in_\alpha B}}$$

$$\frac{\overline{\frac{\checkmark}{A \text{ true}_\alpha} \quad \mathcal{D}} \quad \frac{\not\propto_A \ni_\alpha \mathbf{M} \quad \overline{[M/x]N \Downarrow_\alpha \mathbf{N}'}}{\overline{\text{require } x : A \text{ in } N \Downarrow_\alpha \mathbf{N}' \quad \mathcal{V}[[B]]^\alpha(\mathbf{N}', \mathbf{N}')}} \quad \text{require}$$

$$\text{require } x : A \text{ in } N \in_\alpha B$$

$$\frac{\overline{A \text{ true}_\alpha} \quad \mathcal{D}}{\overline{\frac{|_{y,z} [y/x]N = [z/x]N \in_\alpha B \ (y = z \in_\alpha A)}{x : A \vdash_\alpha N \in B}} \quad \mathcal{E}} \quad \mathcal{F}$$

$$\frac{\frac{\overline{[M/x]N \in_\alpha B \ (M \in_\alpha A)} \quad \mathcal{F}(M, M)}{\overline{\frac{\overline{[M/x]N \Downarrow_\alpha \mathbf{N}'} \quad \mathcal{G} \quad \overline{\mathcal{V}[[B]]^\alpha(N', N')}}{\mathcal{H}}}} \quad \frac{\frac{\overline{A \text{ true}_\alpha} \quad \mathcal{D}}{\mathcal{K}_A \ni_\alpha \mathbf{M}} \quad \frac{\overline{M \in_\alpha A}}{\mathcal{K}_A \ni_\alpha \mathbf{M}}}{\overline{[M/x]N \in_\alpha B}} \quad \mathcal{H}$$

$$\frac{\frac{\overline{A \text{ true}_\alpha} \quad \mathcal{D}}{\mathcal{K}_A \ni_\alpha \mathbf{M}} \quad \frac{\overline{[M/x]N \Downarrow_\alpha \mathbf{N}'}}{\overline{\text{require } x : A \text{ in } N \Downarrow_\alpha \mathbf{N}'}} \quad \frac{\overline{\mathcal{V}[[B]]^\alpha(N', N')}}{\overline{\text{require } x : A \text{ in } N \in_\alpha B}} \quad \text{require}$$

$$\frac{\overline{A \text{ true}_\alpha} \quad \mathcal{D}}{\overline{\frac{|_{y,z} [y/x]N = [z/x]N \in_\alpha B \ (y = z \in_\alpha A)}{x : A \vdash_\alpha N \in B}} \quad \mathcal{E}} \quad \mathcal{F}$$

$$\frac{\frac{\frac{\checkmark}{[M/x]N \in_\alpha B \ (M \in_\alpha A)} \quad \mathcal{F}(M, M) \quad \frac{\frac{\checkmark}{A \text{ true}_\alpha} \quad \mathcal{D} \quad \frac{\kappa_A \ni_\alpha \mathbf{M}}{M \in_\alpha A}}{\frac{[M/x]N \Downarrow_\alpha \mathbf{N'} \quad \mathcal{G} \quad \mathcal{V}[[B]]^\alpha(N', N') \quad \mathcal{H}}{[M/x]N \in_\alpha B}} \quad \mathcal{E}} \quad \mathcal{F}$$

$$\frac{\frac{\frac{\checkmark}{A \text{ true}_\alpha} \quad \mathcal{D} \quad \frac{\kappa_A \ni_\alpha \mathbf{M}}{\text{require } x : A \text{ in } N \Downarrow_\alpha \mathbf{N'} \quad \mathcal{G}} \quad \frac{\mathcal{V}[[B]]^\alpha(N', N')}{\text{require } x : A \text{ in } N \in_\alpha B} \quad \text{require}}{\text{require } x : A \text{ in } N \in_\alpha B} \quad \text{require}$$

$$\frac{\overline{A \text{ true}_\alpha} \quad \mathcal{D}}{\overline{\frac{|_{y,z} [y/x]N = [z/x]N \in_\alpha B \ (y = z \in_\alpha A)}{x : A \vdash_\alpha N \in B}} \quad \mathcal{E} \quad \mathcal{F}$$

$$\frac{\frac{\overline{[M/x]N \in_\alpha B \ (M \in_\alpha A)} \quad \mathcal{F}(M, M) \quad \frac{\overline{A \text{ true}_\alpha} \quad \mathcal{D} \quad \frac{\checkmark}{\kappa_A \ni_\alpha \mathbf{M}}}{M \in_\alpha A}}{\frac{\overline{[M/x]N \Downarrow_\alpha \mathbf{N}'} \quad \mathcal{G} \quad \overline{\mathcal{V}[[B]]^\alpha(N', N')} \quad \mathcal{H}}{[M/x]N \in_\alpha B} \quad \mathcal{H}$$

$$\frac{\frac{\overline{A \text{ true}_\alpha} \quad \mathcal{D} \quad \frac{\checkmark}{\kappa_A \ni_\alpha \mathbf{M}} \quad \frac{\overline{[M/x]N \Downarrow_\alpha \mathbf{N}'} \quad \mathcal{G}}{\text{require } x : A \text{ in } N \Downarrow_\alpha \mathbf{N}'} \quad \frac{\overline{\mathcal{V}[[B]]^\alpha(N', N')} \quad \mathcal{H}}{\text{require } x : A \text{ in } N \in_\alpha B} \quad \text{require}$$

$$\frac{\overline{A \text{ true}_\alpha} \quad \mathcal{D}}{\overline{\frac{|_{y,z} [y/x]N = [z/x]N \in_\alpha B \ (y = z \in_\alpha A)}{x : A \vdash_\alpha N \in B}} \quad \mathcal{E} \quad \mathcal{F}$$

$$\frac{\frac{\overline{[M/x]N \in_\alpha B \ (M \in_\alpha A)} \quad \mathcal{F}(M, M)}{\overline{[M/x]N \Downarrow_\alpha \mathbf{N}'}} \quad \mathcal{G} \quad \frac{\frac{\overline{A \text{ true}_\alpha} \quad \mathcal{D}}{\mathbf{x}_A \ni_\alpha \mathbf{M}} \quad \mathcal{F}(M, M)}{\overline{M \in_\alpha A}} \quad \mathcal{H}$$

$$\frac{\overline{[M/x]N \Downarrow_\alpha \mathbf{N}'}}{\overline{[M/x]N \in_\alpha B}} \quad \mathcal{H}$$

$$\frac{\frac{\overline{A \text{ true}_\alpha} \quad \mathcal{D}}{\mathbf{x}_A \ni_\alpha \mathbf{M}} \quad \frac{\overline{[M/x]N \Downarrow_\alpha \mathbf{N}'}} \quad \mathcal{G}}{\text{require } x : A \text{ in } N \Downarrow_\alpha \mathbf{N}'} \quad \frac{\overline{\mathcal{V}[[B]]^\alpha(N', N')}}{\text{require}} \quad \mathcal{H}$$

$$\frac{\text{require } x : A \text{ in } N \Downarrow_\alpha \mathbf{N}'}{\text{require } x : A \text{ in } N \in_\alpha B} \quad \text{require}$$

□

QUESTIONS?