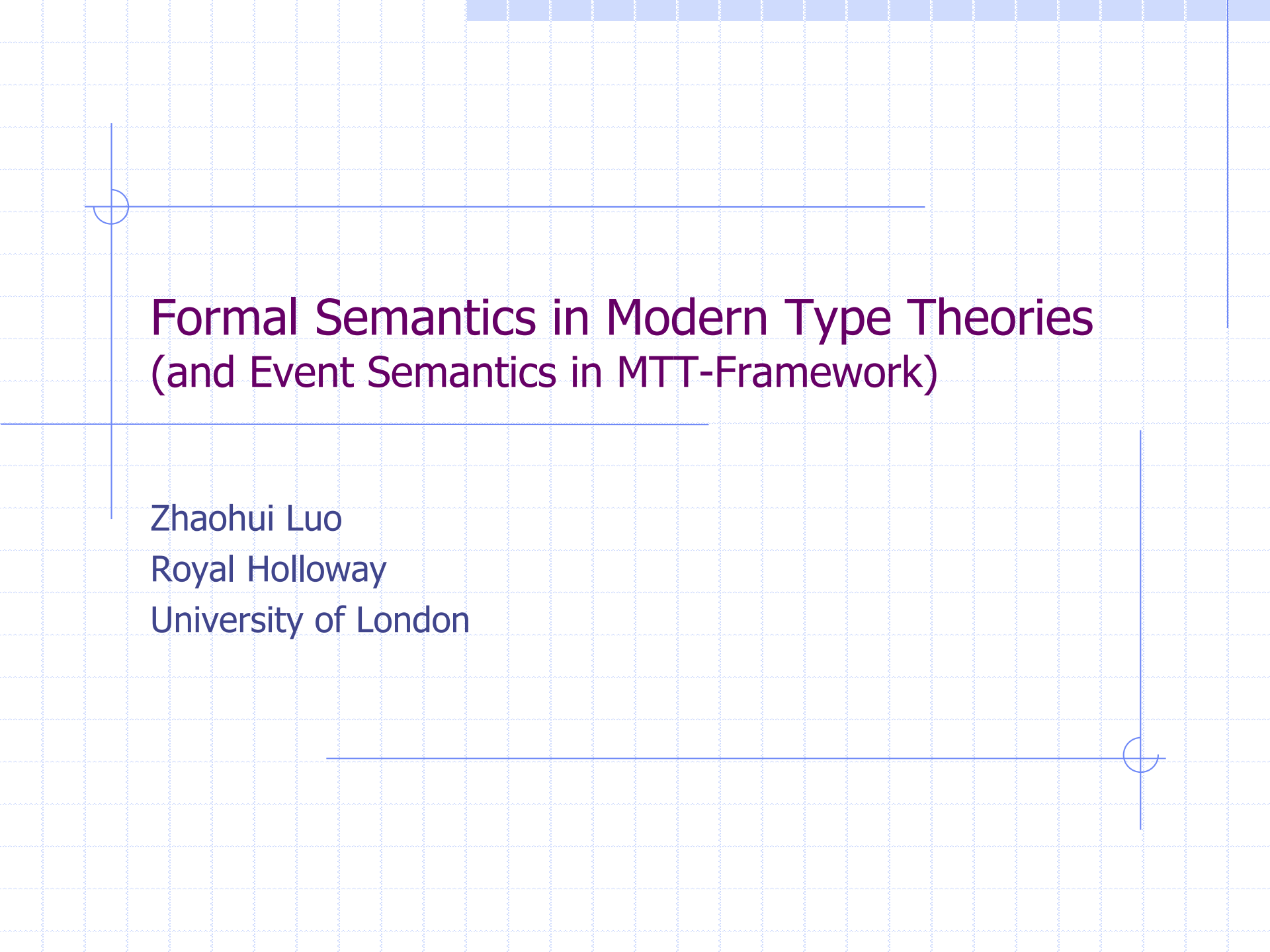# Formal Semantics in Modern Type Theories
(and Event Semantics in MTT-Framework)

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This talk

I. Formal semantics in Modern Type Theories: overview

- ❖ MTT-semantics is both model-theoretic and proof-theoretic
- ❖ HoTT-logic for MTT-semantics in Martin-Löf's TT
  - ❖ paper in Proc. of LACompLing18

II. Event semantics in MTT-framework

- ❖ (Neo-)Davidsonian event semantics and problems
- ❖ Event semantics in MTT-framework
  - ❖ Events in MTT-semantics
  - ❖ Event structure with dependent types

I. Overview of MTT-semantics

❖ Natural Language Semantics – study of meaning (communicate = convey meaning)

❖ Various kinds of theories of meaning

- ❖ Meaning is reference ("referential theory")
  - ❖ Word meanings are things (abstract/concrete) in the world.
  - ❖ c.f., Plato, …
- ❖ Meaning is concept ("internalist theory")
  - ❖ Word meanings are ideas in the mind.
  - ❖ c.f., Aristotle, …, Chomsky.
- ❖ Meaning is use ("use theory")
  - ❖ Word meanings are understood by their uses.
  - ❖ c.f., Wittgenstein, …, Dummett.
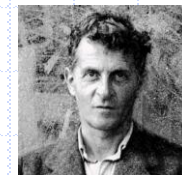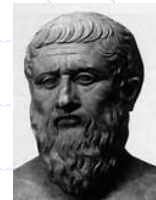
Type-Theoretical Semantics

❖ **Montague Semantics**
  - ❖ R. Montague (1930–1971)
  - ❖ Dominating in linguistic semantics since 1970s
  - ❖ Set-theoretic, using simple type theory as intermediate
  - ❖ Types ("single-sorted"): e, t, e→t, …

❖ **MTT-semantics:** formal semantics in modern type theories
  - ❖ Examples of MTTs:
    - ❖ Martin-Löf's TT: predicative; non-standard FOL
    - ❖ pCIC (Coq) & UTT (Luo 1994): impredicative; HOL
  - ❖ Ranta (1994): formal semantics in Martin-Löf's type theory
  - ❖ Recent development on MTT-semantics
    - ➔ full-scale alternative to Montague semantics

❖ Recent development on rich typing in NL semantics

   ❖ Asher, Bekki, Cooper, Grudzińska, Retoré, …

      ❖ S. Chatzikyriakidis and Z. Luo (eds.) Modern Perspectives in Type Theoretical Sem. Springer, 2017. (Collection on rich typing & …)

   ❖ MTT-semantics is one of these developments.

      ❖ Z. Luo. Formal Semantics in Modern Type Theories with Coercive Subtyping. Linguistics and Philosophy, 35(6). 2012.

      ❖ S. Chatzikyriakidis and Z. Luo. Formal Semantics in Modern Type Theories. Wiley/ISTE. (Monograph on MTT-semantics, to appear)

❖ Advantages of MTT-semantics, including

   ❖ Both model-theoretic & proof-theoretic – offering a new perspective not available before (explicated later today)

MTT-semantics: basic categories

Category	Semantic Type
S	Prop (the type of all propositions)
CNs (book, man, …)	types (each common noun is interpreted as a type)
IV	A→Prop (A is the "meaningful domain" of a verb)
Adj	A→Prop (A is the "meaningful domain" of an adjective)
Adv	∏A:CN.(A→Prop)→(A→Prop) (polymorphic on CNs)

In MTT-semantics, CNs are types rather than predicates:

❖ "man" is interpreted as a type Man : Type.

❖ Man could be a structured type (say, Σ(Human,male))

❖ A man talked.

❖ $\exists$m:Man.talk(m) : Prop, where talk : Human→Prop and Man≤Human (subtyping – crucial for MTT-semantics; see later.)

❖ Rich type structure ("many-sorted", but types have structures):
  ❖ Existing types in MTTs: Table, $\sum$x:Man.handsome(x), …
  ❖ Newly introduced types to MTTs: Phy•Info (representing copredication)
  ❖ Type-theoretic representations for various linguistic features
    (Adj/Adv modifications, coordination, copredication, coercions, events, …)
❖ Selectional restrictions: meaninglessness v.s. falsity
  (#) Tables talk.
  ❖ Montague: $\forall$x:e.table(x)$\supset$talk(x) (well-typed, false in the intended model)
  ❖ MTT-sem: $\forall$x:Table.talk(x)   (ill-typed as talk:Human$\rightarrow$Prop; meaningless)
  Note:
  ❖ Well-typedness corresponds to meaningfulness (c.f., [Asher11] and others)
  ❖ Typing in MTTs is decidable, while truth/falsity of a formula is not.

Modelling Adjective Modification: Case Study
[Chatzikyriakidis & Luo: FG13, JoLLI17]

Classical classification	example	Characterisation of Adj(N)	MTT-semantics
intersective	handsome man	N & Adj	$\sum x$:Man.handsome(x)
subsective	large mouse	N (Adj depends on N)	large : ΠA:CN. A$\rightarrow$Prop large(mouse) : Mouse$\rightarrow$Prop
privative	fake gun	$\neg$N	$G = G_R + G_F$ with $G_R \leq_{inl} G$, $G_F \leq_{inr} G$
non-committal	alleged criminal	nothing implied	$\exists h$:Human. $H_{h,A}(...)$

❖ $H_{h,A}(...)$ expresses, eg, "h alleges ...", for various non-committal adjectives A; it uses the Leibniz equality $=_{Prop}$. [Luo 2018] (*)

❖ cf, work on hyperintensionality (Cresswell, Lappin, Pollard, ...)

Note on Subtyping in MTT-semantics

❖ Simple example

A human talks. Paul is a handsome man.

Does Paul talk?

Semantically, can we type talk(p)?

(talk : Human→Prop & p : Σ(Man,handsome))

Yes, because p : Σ(Man,handsome) ≤ Man ≤ Human.

❖ Subtyping is crucial for MTT-semantics

  ❖ Coercive subtyping [Luo 1999, Luo, Soloviev & Xue 2012] is adequate for MTTs and we use it in MTT-semantics.

  ❖ Note: Traditional subsumptive subtyping is inadequate for MTTs (eg, canonicity fails with subsumption.)
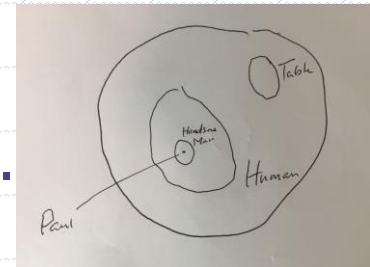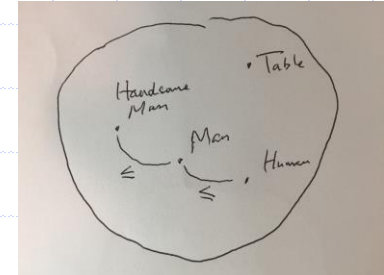
MTT-semantics is both model/proof-theoretic

❖ **Model-theoretic semantics (traditional)**
  ❖ Meaning as denotation (Tarski, …)
  ❖ Montague: NL → (simple TT) → set theory

❖ **Proof-theoretic semantics**
  ❖ Meaning as inferential use (proof/consequence)
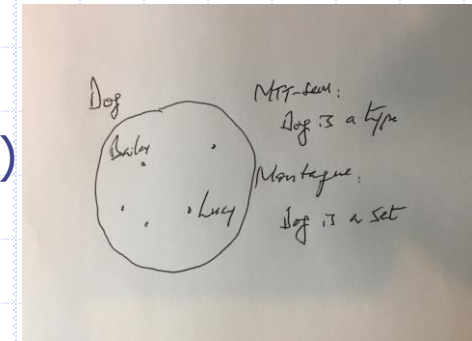 ❖ Gentzen, Prawitz, Martin-Löf (meaning theory)

❖ **MTT-semantics**
  ❖ Both model-theoretic and proof-theoretic – in what sense?
    ❖ Z. Luo. Formal Semantics in Modern Type Theories: Is It Model-theoretic, Proof-theoretic, or Both? Invited talk at LACL14.
  ❖ What does this imply?

❖ **MTT-semantics is model-theoretic**

  ❖ NL → MTT (representational/model-theoretic)
  ❖ MTT as meaning-carrying language
    ❖ <u>types</u> representing collections
    ❖ <u>signatures</u> (eg ,subtyping [Lungu 2018]) representing situations
    ❖ Cf, set theory in Montague semantics

❖ **MTT-semantics is proof-theoretic**

  ❖ MTTs have proof-theoretic meaning theories
    ❖ Judgements can be understood by means of their inferential roles.
    ❖ Use theory of meaning (Wittgenstein, Dummett, Brandom)
    ❖ Proof-theoretic semantics (Gentzen, Prawitz, Martin-Löf, …)
  ❖ Proof technology: reasoning based on MTT-semantics on computers (eg, [Chatzikyriakidis & Luo (JoLLI14)])

Importance for MTT-semantics

❖ Model-theoretic – powerful semantic tools
  ❖ Much richer typing mechanisms for formal semantics
  ❖ Powerful contextual mechanism to model situations
❖ Proof-theoretic – practical reasoning on computers
  ❖ Existing proof technology: proof assistants (Coq, Agda, Lego, …)
  ❖ Applications to NL reasoning
❖ Leading to both of
  ❖ Wide-range modelling as in model-theoretic semantics
  ❖ Effective inference based on proof-theoretic semantics

Remark: new perspective & new possibility not available before!

Advanced features in MTT-semantics: examples

❖ Copredication
- ❖ Linguistic phenomenon studied by many (Pustejovsky, Asher, Cooper, Retoré, …)
- ❖ Dot-types in MTTs: formal proposal [Luo 2009] (*), implementation [Xue & Luo 2012] and copredication with quantification [Chatzikyriakidis & Luo 2018]
- ❖ Linguistic feature difficult, if not impossible, to find satisfactory treatment in a CNs-as-predicates framework. (For a mereological one, see [Gotham16].)

❖ Anaphora analysis/resolution via Σ-types
- ❖ [Sundholm 1986, Ranta 1994] in Martin-Löf's type theory

❖ Linguistic coercions via coercive subtyping [Asher & Luo 2012]

❖ Several recent developments
- ❖ (today) Event semantics in MTT-framework [Luo & Soloviev (WoLLIC17)]
- ❖ Propositional forms of judgemental interpretations [Xue et al (NLCS18)]
- ❖ CNs as setoids [Chatzikyriakidis & Luo (J paper for Oslo meeting 2018)]
- ❖ (today) HoTT-logic for MTT-sem in Martin-Löf's TT (current proceedings)

MTT-semantics in Martin-Löf's TT with H-logic

❖ Martin-Löf's type theory for formal semantics
  ❖ Sundholm, Ranta & many others (all use PaT logic)
❖ PaT logic: propositions as types (Curry-Howard)
  ❖ P is true if, and only if, p : P for some p.
  ❖ But Martin-Löf goes one step further: types = propositions!
  ❖ This is where a problem arises [Luo (LACL 2012)].
❖ Proof irrelevance (*)
  ❖ Example: a handsome man is (m,p) : Σx:Man.handsome(x)
    ❖ Two handsome men are the same iff they are the same man – <u>proof irrelevance</u> (any two proofs of the same proposition are the same.)
  ❖ But in MLTT with PaT logic, this would mean every type collapses! Obviously, that would be absurd.
❖ So, MLTT with PaT logic is actually <u>inadequate</u> for MTT-sem, which has been mainly developed in UTT so far.

MLTT$_h$: Extension of MLTT with H-logic

❖ **H-logic** (in Homotopy Type Theory; HoTT book)

   ❖ A proposition is a type with at most one object.

   ❖ isProp(A) = $\prod$x,y:A.(x=y).

   ❖ Logical operators (examples):

      ❖ P⊃Q = P→Q and ∀x:A.P = $\prod$x:A.P

      ❖ P∨Q = |P+Q| and ∃x:A.P = |Σx:A.P|

   where |A| is <u>propositional truncation</u>, a proper extension.

❖ **MLTT$_h$ = MLTT + h-logic**

   ❖ Proof irrelevance is "built-in" in h-logic (by definition).

   ❖ Claim: MLTT$_h$ is adequate for MTT-semantics.

   ❖ Details in the short paper of LACompLing18 proceedings.
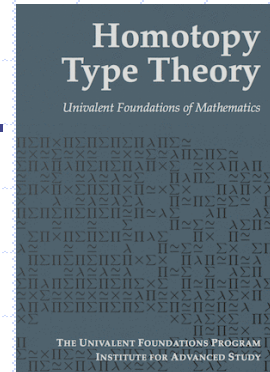
II. Events in MTT-Semantic Framework

❖ Davidson's event semantics [1967]

❖ Original motivation: adverbial modifications (*)

(1) John buttered the toast.

(2) John buttered the toast with the knife in the kitchen.

Does (2) imply (1)? (Cumbersome in MG with meaning postulates.)

❖ Events make it natural without meaning postulates.
In neo-Davidsonian notation with thematic roles (1980s):

(1') $\exists$e:Event. butter(e)

& agent(e)=john & patient(e)=toast

(2') $\exists$e:Event. butter(e) & with(e,knife) & at(e,kitchen)

& agent(e)=john & patient(e)=toast

Obviously, (2') $\Rightarrow$ (1')
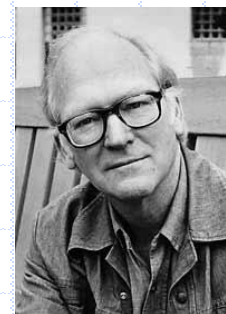
Problems in Event-semantics + Montague

❖ For example, "event quantification problem" (EQP)
❖ Incompatibility between event semantics and MG.

(1) Nobody talked.

Intended neo-Davidsonian event semantics is (2):
(2) ¬∃x:**e.** human(x) & ∃v:Event. talk(v) & agent(v,x)

But the incorrect semantics (3) is also possible – it is well-typed:
(3) ∃v:Event. ¬∃x:**e.** human(x) & talk(v) & agent(v,x)
which moves the event quantifier "∃v:Event" in (2) to the left.

Some proposed solutions to EQP

❖ Many different proposals
  - ❖ Purpose: to force scope of event quantifier to be lower.
  - ❖ Only mention two of them here.
❖ Champollion's quantificational event sem. [2010, 2015]
  - ❖ talk : (Event$\rightarrow$**t**)$\rightarrow$**t** with talk(E) = $\exists$e:Event. e$\in$E & **talk**(e)
  - ❖ Trick: taking a <u>set</u> E of events as argument, but **talk**(e) …
  - ❖ Debatable: intuitive meanings, compositionality & complexity
❖ Winter-Zwarts [2011] & de Groote [2014]
  - ❖ Use Abstract Categorial Grammar (see, eg, [de Groote 01])
  - ❖ ACG structure prevents incorrect interpretation.
❖ Our proposal: dependent event types (solution to EQP & …)

Dependent event types [Luo & Soloviev (WoLLIC17)]

❖ DETs: refining event structure by (dependent) typing

❖ Applications include

❖ A solution to EQP

❖ Selection restrictions in MTT-event semantics

❖ Refined types of events: Event ➔ Evt(…)

❖ Event types dependent on thematic roles agents/patients

❖ For a:Agent and p:Patient, consider DETs

Event, $Evt_A(a)$, $Evt_P(p)$, $Evt_{AP}(a,p)$

❖ Subtyping between DETs:

$$\frac{a : A \quad A \leq B}{a : B}$$

$$Evt_{AP}(a,p) \overset{\leq}{\diagup} \overset{Evt_A(a)}{\underset{}{}} \overset{\leq}{\diagdown} Event$$

$$Evt_{AP}(a,p) \underset{\leq}{\diagdown} \underset{Evt_P(p)}{} \underset{\leq}{\diagup} Event$$
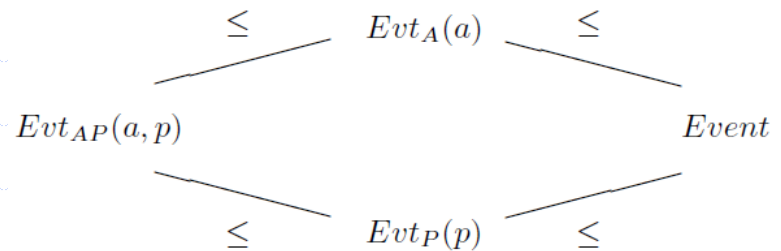
DET-solution to EQP

(1) Nobody talked.

Neo-Davidsonian in Montague's setting (repeated):
(2) $\neg\exists x{:}\mathbf{e}.$ human(x) & $\exists v{:}$Event. talk(v) & agent(v,x)
(3) $\exists v{:}$Event. $\neg\exists x{:}\mathbf{e}.$ human(x) & talk(v) & agent(v,x)
The incorrect (3) is well-typed.

Dependent event types in Montague's setting:
(4) $\neg\exists x{:}\mathbf{e}.$ human(x) & $\exists v{:}Evt_A(x).$ talk(v)
(#) $\exists v{:}Evt_A(x).$ $\neg\exists x{:}\mathbf{e}.$ human(x) & talk(v)
where (#) is ill-typed since the first "x" is outside scope of "$\exists x{:}\mathbf{e}$".

Selectional restrictions

❖ Recall:

(#) Tables talk.

- ❖ Montague: $\forall x{:}\mathbf{e}.talk(x)$ – well-typed but false, as talk : $\mathbf{e}{\rightarrow}\mathbf{t}$
- ❖ MTT-sem: $\forall x{:}Table.talk(x)$ – ill-typed as talk : Human$\rightarrow$Prop

❖ What happens with events?

- ❖ Neo-Davidsonian: talk : Event$\rightarrow\mathbf{t}$ or talk : Event$\rightarrow$Prop
- ❖ Montague: $\forall x{:}\mathbf{e} \ \exists v{:}Event.\ talk(v)$ & agent(v)=x (well-typed)
- ❖ MTT-sem: $\forall x{:}Table \ \exists v{:}Evt_A(x).\ talk(v)$

  (Also well-typed (!) because Table $\leq$ Agent)

So?

❖ Three ways to enforce selectional restriction with events:

    1. Refined typing for verb phrases (like talk)

    2. Refining the typing of thematic roles (like agent)

    3. Refining event types (next slide)

❖ Approach 1 & 2: Instead of the neo-Davidsonian typing talk : Event$\rightarrow$**t**, or agent : Event$\rightarrow$**e**, we consider

    ❖ $talk_h$: Human$\rightarrow$Event$\rightarrow$Prop (Davidson's original proposal) or

    ❖ $talk_d$: $\prod$h:Human. Evt_A(h)$\rightarrow$Prop (dependent typing) or

    ❖ $agent_h$: Event$\rightarrow$Human (with codomain being Human)

        ❖ Tables talk.   (Ill-typed – table x is not a human.)

        ❖ (#) $\forall$x:Table $\exists$v:Event. $talk_h$(x,v) & agent(v)=x   (ill-typed)

        ❖ (#) $\forall$x:Table $\exists$v:Event. talk(v) & $agent_h$(v)=x   (ill-typed)

        ❖ (#) $\forall$x:Table $\exists$v:Evt_A(x). $talk_d$(x,v)   (ill-typed)

❖ Approach 3: refined DETs
  ❖ Let T $\leq_c$ Agent. (example for subtypes of Agent)
    ❖ $Evt_A[T]$: T→Type
    ❖ $Evt_A[T](a) = Evt_A(c(a))$, for any a : T.
❖ Examples
  ❖ Men talk. (OK because Man≤Human)
  ❖ $\forall$x:Man $\exists$v:Evt_A[Human](x). talk(v)
  ❖ Tables talk. (Evt_A[Human](x) ill-typed as x is not a human.)
  ❖ (#) $\forall$x:Table $\exists$v:Evt_A[Human](x). talk(v)
  ❖ John picked up and mastered the book. (b:Book≤ Phy•Info)
  ❖ $\exists$v:Evt_{AP}[Human,Phy•Info](j,b). pick-up(v) & master(v)

Underlying formal systems

❖ Systems extended with dependent event types

   ❖ C_e – Church's simple type theory + DETs
     (with subsumptive subtyping)

   ❖ UTT[E] – the modern type theory UTT + DETs
     (with coercive subtyping as specified in E)

❖ Theorem.

   ❖ C_e (like UTT[E]) have nice meta-theoretic properties
     including, e.g., normalisation and logical consistency.

   ❖ Proof. Faithfully embedding C_e and UTT[E].

(***)

Related (and some future) work on DETs

❖ Original idea
  ❖ Came from my treatment of an example in (Asher & Luo 12)
    ❖ Evt(h) to represent collection of events conducted by h : Human.
  ❖ Further prompted by de Groote's talk at LENLS14 (on EQP etc.)
❖ Other applications of DETs
  ❖ For example, problem with negation in event semantics
    ❖ Krifka's solution [1989]: a <u>mereological</u> negation system
    ❖ Champollion's solution [2015] (as mentioned above)
    ❖ DETs solution: details to be worked out.
❖ DEPs dependent on other parameters
  ❖ Dependency on other thematic roles, say time/location/…:
    Reasonable? Useful?
  ❖ Dependency on other kinds of parameters than thematic roles?

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