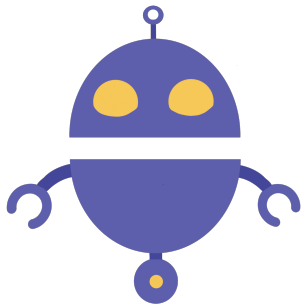
On the syntax and semantics of voice assistants in autonomous vehicles

Warrick Macmillan

6^{th} May 2022



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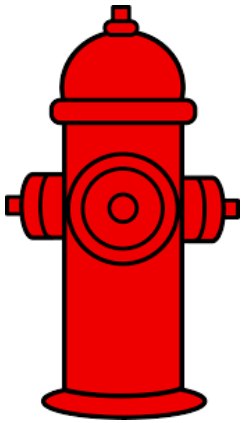

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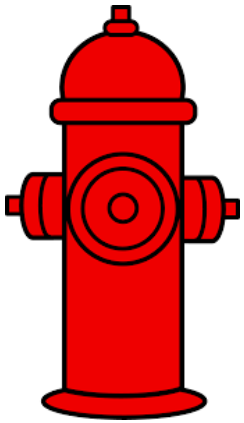

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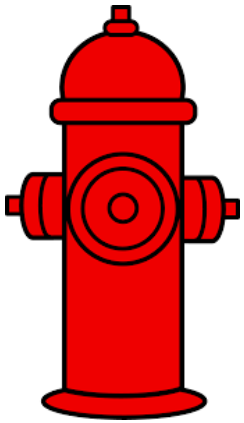

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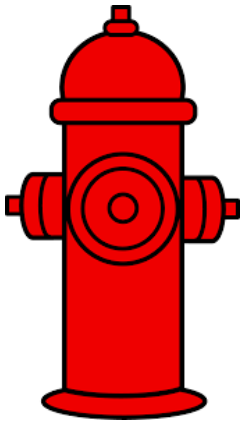

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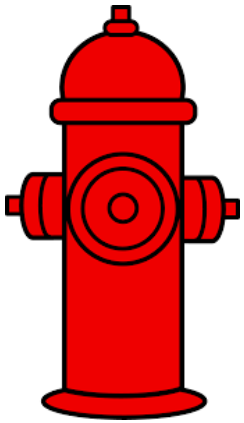

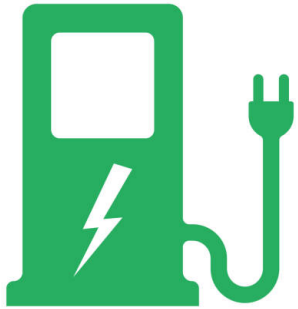

Ambiguities

"Go into the other lane"

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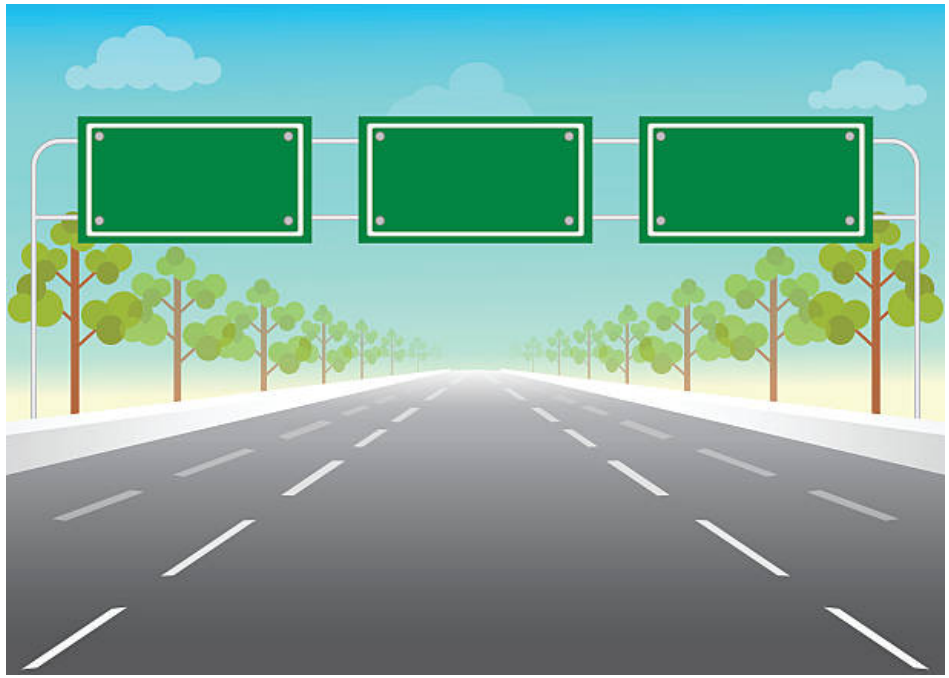

Ambiguities (cont.)

"Drive to the person with the dog"

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Simplified Autonomous Vehicle

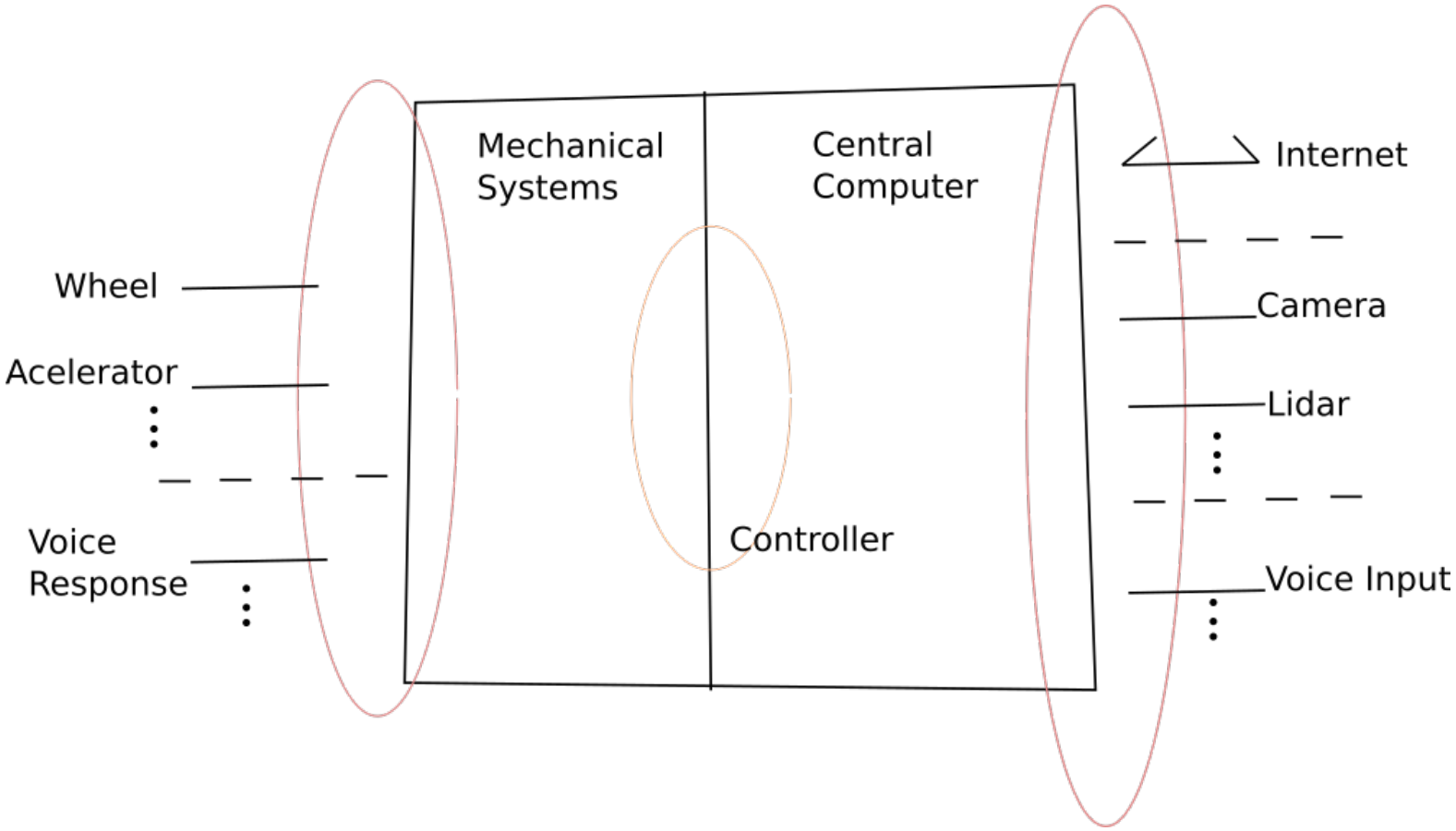

Figure: Self-driving car

Path

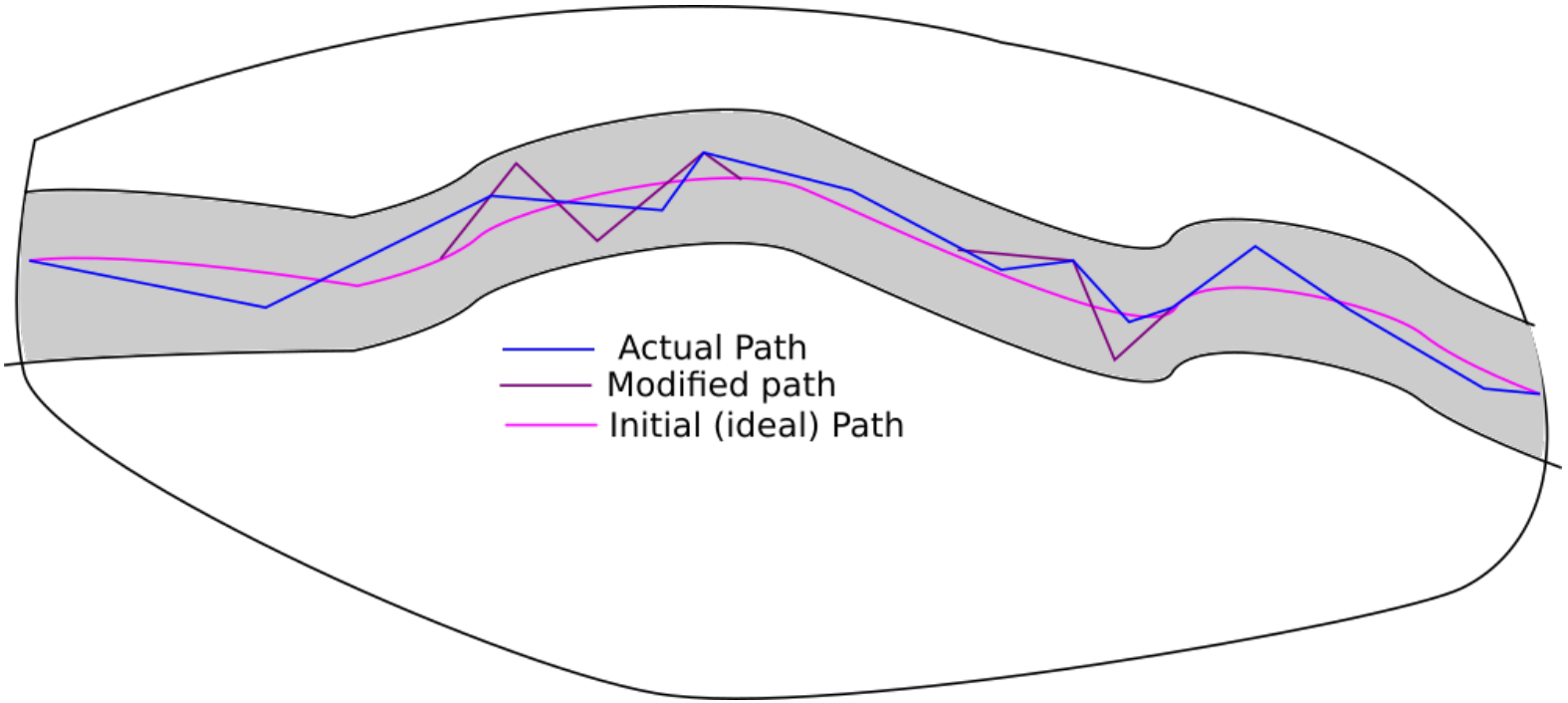

Figure: Initial, modified, and actual paths/routes

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$\forall u \in$ Utt. $\exists r \in$ Routes such that $\forall r' \in$ Routes. $d(u, r) \leq d(u, r')$

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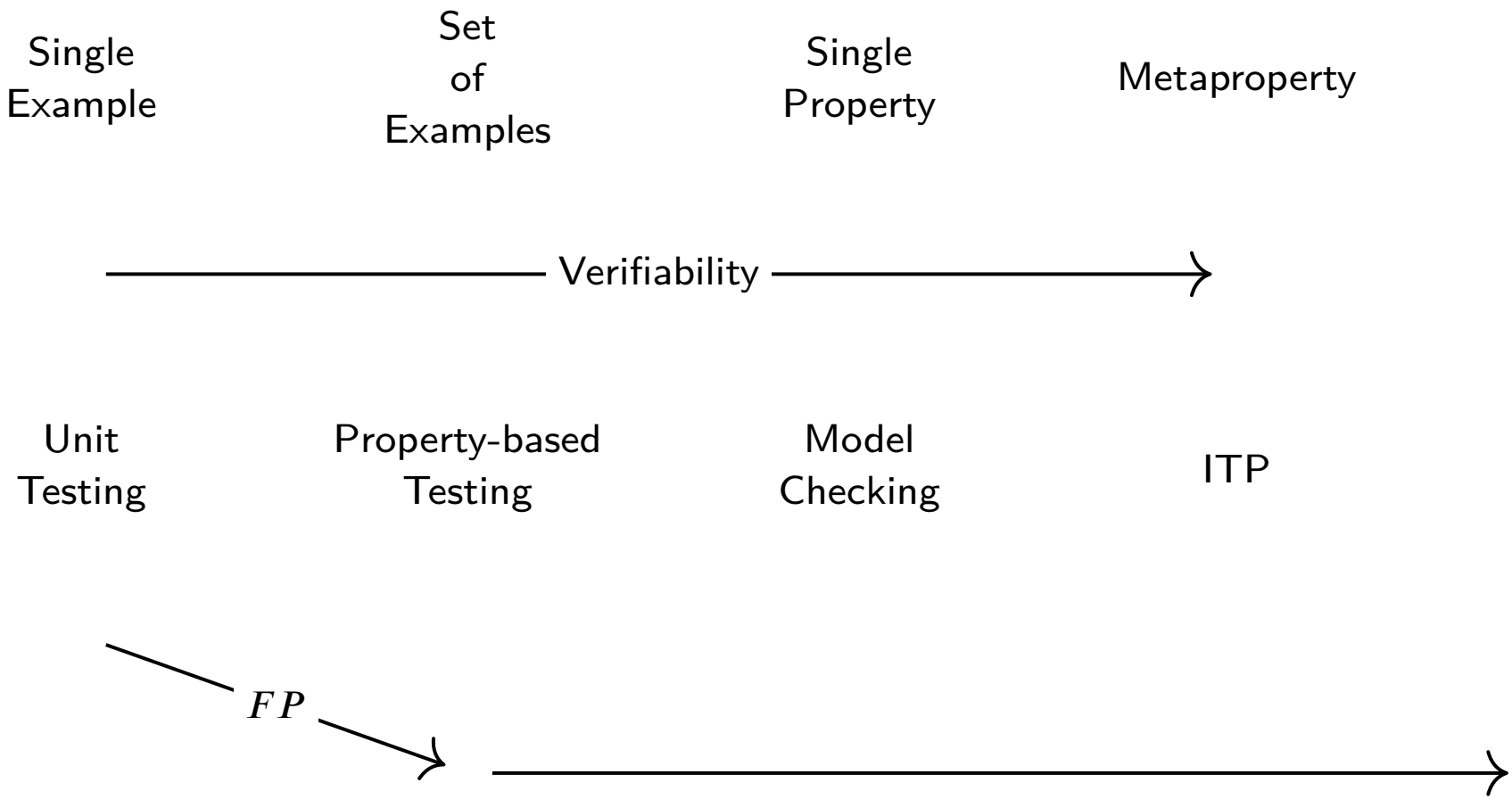
- physical objects in the case of paths in Euclidean space

Verification Spectrum



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- Ensure maps between big-components are functorial with respect to small-component composition
- Verification of system is can similarly be broken into sub-verifications

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1. Functional Programming Languages : GF (Grammatical Framework), Haskell, Agda
2. Natural Language Processing : Semantic Parsing, Controlled Natural Languages
3. Tools : Grammars and logical implementations for motion planning and verification

Ideal Pipeline

$$
\begin{aligned}
\text{Utterance} &\xrightarrow{Speech\ Recognizer} \text{String} \\
&\xrightarrow{Canonicalization_{LLM}} \text{String} \\
&\xrightarrow{Parsing_{GF}} \text{Abstract Syntax Tree (NL)} \\
&\xrightarrow{[\![-]\!]_{Haskell}} \text{Abstract Syntax Tree (LTL)} \\
&\xrightarrow{\vDash_{Agda}} \text{Verifiable Path}
\end{aligned}
\tag{1}
$$

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- Separation of abstract (semantic and syntactic) and concrete (syntactic and morphological) considerations

Abstract Syntax

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- Named functions, declared *fun*, of arbitrary arities over them

Concrete Syntax

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Main Idea

By adding record types and natural number types to concrete categories we gain expressiveness

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([(["Go"],5527),(["be"],5300),(["turn"],4154),(["Turn"],4154)],["VB"])
([(["left"],228),(["came"],59),(["made"],47),(["started"],44)],["VBD"])
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([(["left"],1733),(["parked"],616),(["painted"],307),(["fenced"],263)],["VBN"])
([(["are"],3554),(["'re"],1185),(["reach"],1100),(["get"],770)],["VBP"])
([(["is"],4919),(["has"],795),(["'s"],471),(["ends"],93)],["VBZ"])
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```

n-grams : the 9-gram "so you are moving with the flow of traffic" occurs 311

Ontological Categories

```
cat
  PosCommand    ; -- go to the store
  Place         ; -- the store
  Time          ; -- in 5 minutes
  Action        ; -- drive
  Way           ; -- to
  How           ; -- quickly
  Where         ; -- left
  AdvPh         ; -- to the store
  UndetObj      ; -- store
  Determ        ; -- the
  Object        ; -- the store
  Number        ; -- a
  Conjunct      ; -- and
  Condition     ; -- there is a museum
  Descript      ; -- big
```

GF Functions

```
fun
  -- Explicit Temporality
  DoTil      : Action -> Time -> PosCommand ; go in one minute

  -- Modified action
  ModAction : Action -> AdvPh -> Action ; -- go to the store

  -- Adverbial Phrases
  MkAdvPh      : Way   -> Object -> AdvPh ; -- to the store

  -- Noun Phrases
  WhichObject : Determ -> UndetObj -> Object ; -- the red dog

  -- Modified Noun
  ModObj : Descript -> UndetObj -> UndetObj ; -- black dog
```

Base Ingredients

These represent the tree leaves to be grounded!

```
fun
  Quickly : How      ;
  Left    : Where    ;
  To      : Way      ;
  After   : Way      ;
  Store   : UndetObj ;
  Traffic : UndetObj ;
  London  : Place    ;
  Drive   : Action   ;
  Turn    : Action   ;
  Big     : Descript ;
  A       : Determ   ;
```

go to the store, turn left and stop at the woman with the dog. go to the bridge. finish.

```
p " go to the store , turn left  and stop at the woman with the dog . go to the bridge . Finish ." | tt
* ConsCommands
    * OneCommand
        * CompoundCommand
            * And
              ConsPosCommand
                * SimpleCom
                    * ModAction
                        * Go
                          MkAdvPh
                            * To
                              WhichObject
                                * The
                                  Store
                  BasePosCommand
                    * SimpleCom
                        * ModAction
                            * Turn
                              WherePhrase
                                * Left
                      SimpleCom
                        * ModAction
                            Stop
                            MkAdvPh
                                * At
                                  WhichObject
                                    * The
                                      PhraseModObj
                                        * Woman
                                          MkAdjPh
                                            * With
                                              WhichObject
                                                * The
                                                  Dog
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            * OneCommand
                * Finish
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ModAction
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          * The
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Need a temporal until operator, U, to construct a semantically justifiable interpretation

Haskell LTL

go to the store, turn left and stop at the woman with the dog. go to the bridge. finish.

```
F (Meet
    (Atom "the_store")
    (F (Meet
        (Atom "turn_left")
        (F (Meet
            (Atom "the_woman_with_the_dog")
            (F (Meet
                (Atom "the_bridge")
                (G (Atom "FINISHED")))))))))
```

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semantics :: GListCommands -> Phi
semantics x =
  let (GListCommands ((GOneCommand y) : _)) = normalizeList x
  in case y of
      q@(GSimpleCom a) -> astToAtom q
      (GCompoundCommand GAnd (GListPosCommand xs)) -> listCommand2LTL xs
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normalizeList ::  GListCommands -> GListCommands
  where
    normalizeNestedLists :: GListCommands -> GListPosCommand
      where
        normalizeListPosCommand :: GListPosCommand -> GListPosCommand
          where
            unSentence :: [GCommands] -> [GPosCommand]
            flattenSublist :: GPosCommand -> [GPosCommand]
            where
              getListPosCommands :: GListPosCommand -> [GPosCommand]
```

Temporal Logic

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- Many related temporal logics : CTL, MTL, STL, PrSTL, ...
- Grounding of atomic propositions is central

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To ensure that every location l_i eventually follows its predecessor l_{i-1}, we target the following a class of formulas of the form $F\ (l_1 \wedge F\ (l_2 \wedge ...F\ l_n))$

```
data ϕ : Set where
  atom   : Atom → ϕ
  ⊥ T    : ϕ
  ¬_     : ϕ → ϕ
  _∨_ _∧_ _⇒_ : ϕ → ϕ → ϕ
  X F G : ϕ → ϕ
  _U_ _W_ _R_ : ϕ → ϕ → ϕ
```

$$F\ (l_1 \wedge F\ (l_2 \wedge \ldots F\ l_n))$$

```
visit : List Atom → ϕ
visit [] = ⊤
visit (l :: ls) = (F (atom l)) ∧ visit ls

sequentialVisit : List Atom → ϕ
sequentialVisit [] = ⊤
sequentialVisit (l :: ls) = F (atom l ∧ sequentialVisit ls)

predecessorPrecedesSuccessor : List Atom → ϕ
predecessorPrecedesSuccessor [] = ⊤
predecessorPrecedesSuccessor (l :: []) = ⊤
predecessorPrecedesSuccessor (l :: l' :: ls) =
  ((¬ atom l') U atom l) ∧ predecessorPrecedesSuccessor (l' :: ls)

orderedVisit : List Atom → ϕ
orderedVisit ls = sequentialVisit ls ∧ predecessorPrecedesSuccessor ls
```

```
record M (Atom : Set) : Set1 where
  field
    State : Set
    _↪_ : rel State
    relSteps : relAlwaysSteps _↪_
    L : State → Atom → Set
    -- L'' : Decidable L'
```

```
alwaysSteps : (s : ℕ → State) → Set
alwaysSteps s = ∀ i → s i ↪ s (suc i)

record Path : Set where
  field
    infSeq : ℕ → State
    isTransitional : alwaysSteps infSeq

open Path

headPath : Path → State
headPath p = p .infSeq 0

tailPath : Path → Path
tailPath p .infSeq x = p .infSeq (suc x)
tailPath p .isTransitional i = p .isTransitional (suc i)

-- path-i == drop
path-i : ℕ → Path → Path
path-i n = nTimes n tailPath
```

mutual

```
future : Path → ϕ → Set
future π ψ = Σ[ i ∈ N ] (path-i i π) ⊨ ψ

global : Path → ϕ → Set
global π ψ = ∀ i → (path-i i π) ⊨ ψ

justUpTil : N → Path → ϕ → Set
justUpTil i π ψ = ∀ (j : N) → j <' i → (path-i j π) ⊨ ψ

upTil : N → Path → ϕ → Set
upTil i π ψ = ∀ (j : N) → j ≤' i → (path-i j π) ⊨ ψ

justUntil : Path → ϕ → ϕ → Set
justUntil π ψ ψ = Σ[ i ∈ N ] (path-i i π) ⊨ ψ × justUpTil i π ψ

until : Path → ϕ → ϕ → Set
until π ψ ψ = Σ[ i ∈ N ] (path-i i π) ⊨ ψ × upTil i π ψ
```

```
_⊨_ : Path → ϕ → Set
π ⊨ ⊥       = ⊥'
π ⊨ ⊤       = ⊤'
π ⊨ atom p  = L (headPath π ) p
π ⊨ (¬ ψ)   = ¬' (π ⊨ ψ)
π ⊨ (ψ ∨ ψ ) = (π ⊨ ψ) ⊎ (π ⊨ ψ )
π ⊨ (ψ ∧ ψ ) = (π ⊨ ψ) × (π ⊨ ψ )
π ⊨ (ψ ⇒ ψ ) = (π ⊨ ψ) → (π ⊨ ψ )
π ⊨ X ψ     = tailPath π ⊨ ψ
π ⊨ F ψ     = future π ψ
π ⊨ G ψ     = global π ψ
π ⊨ (ψ U ψ ) = justUntil π ψ ψ
π ⊨ (ψ W ψ ) = justUntil π ψ ψ  ⊎ global π ψ
π ⊨ (ψ R ψ ) = until π ψ  ψ ⊎ global π ψ

_,,_⊨_ : (M : M Atom) → (s : M .M.State) → ϕ → Set
M ,, s ⊨ ϕ = ∀ (π : Path) → headPath π ≡ s → π ⊨ ϕ
```

```
ex-1 : M ,, s0 ⊨ (atom p ∧ atom q)
ex-1 π π0=s0 rewrite π0=s0 = s0p , s0q

ex-2 : M ,, s0 ⊨ (¬ (atom r))
ex-2 π π0=s0 x with headPath π
ex-2 π refl () | .s0

ex-3 : M ,, s0 ⊨ ⊤
ex-3 π init = tt

ex-4 : M ,, s0 ⊨ X (atom r)
ex-4 π π0=s0
  with headPath π | (π .infSeq 1) | (π .isTransitional 0)
ex-4 π refl | .s0 | s1 | x = s1r
ex-4 π refl | .s0 | s2 | x = s2r
```

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- Verifiability and validity

Future

- Expand parser itself

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- Ground semantics to Touchdown location map
- Better data set?

Where does ML come in?

Language Models

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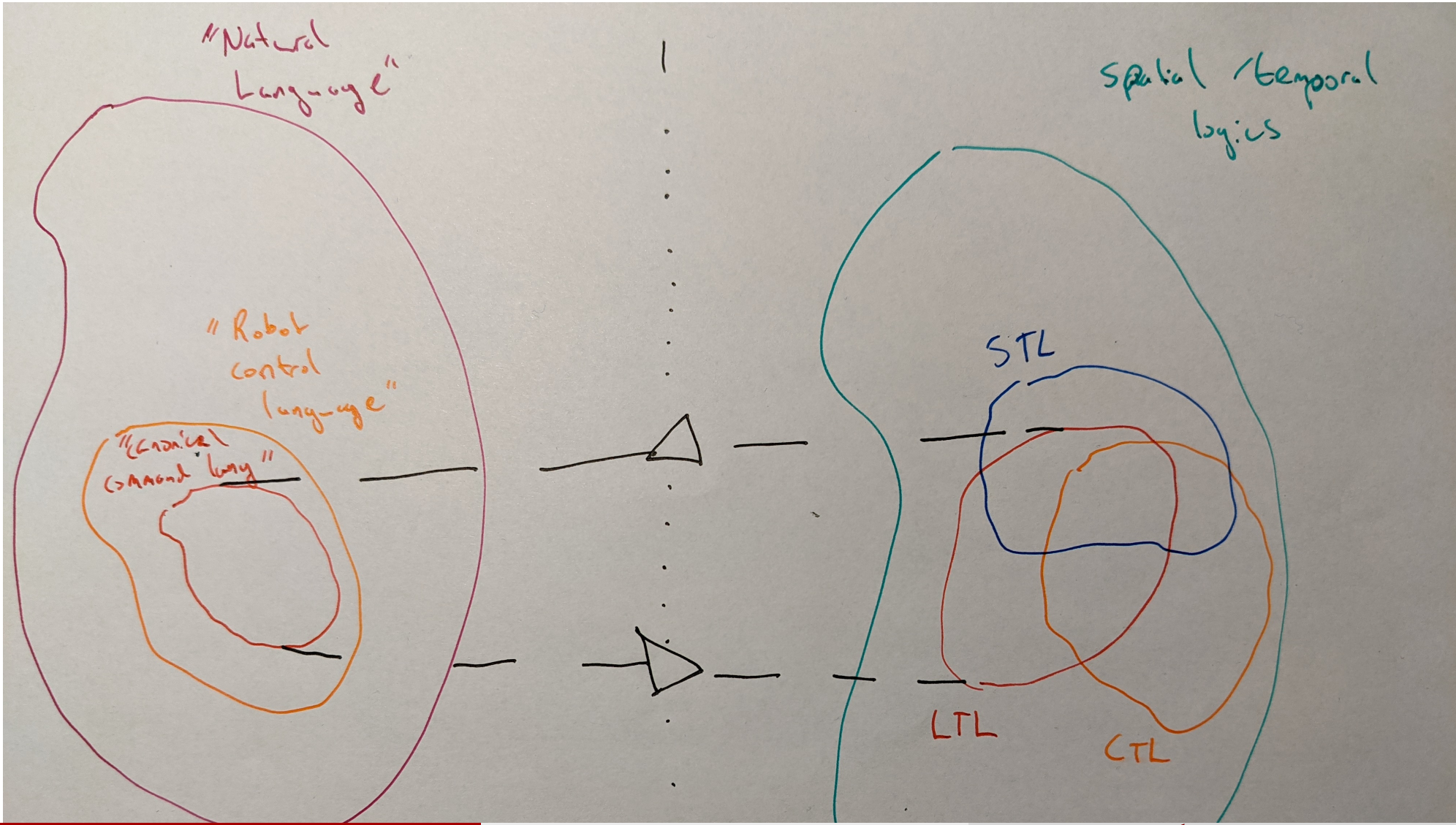
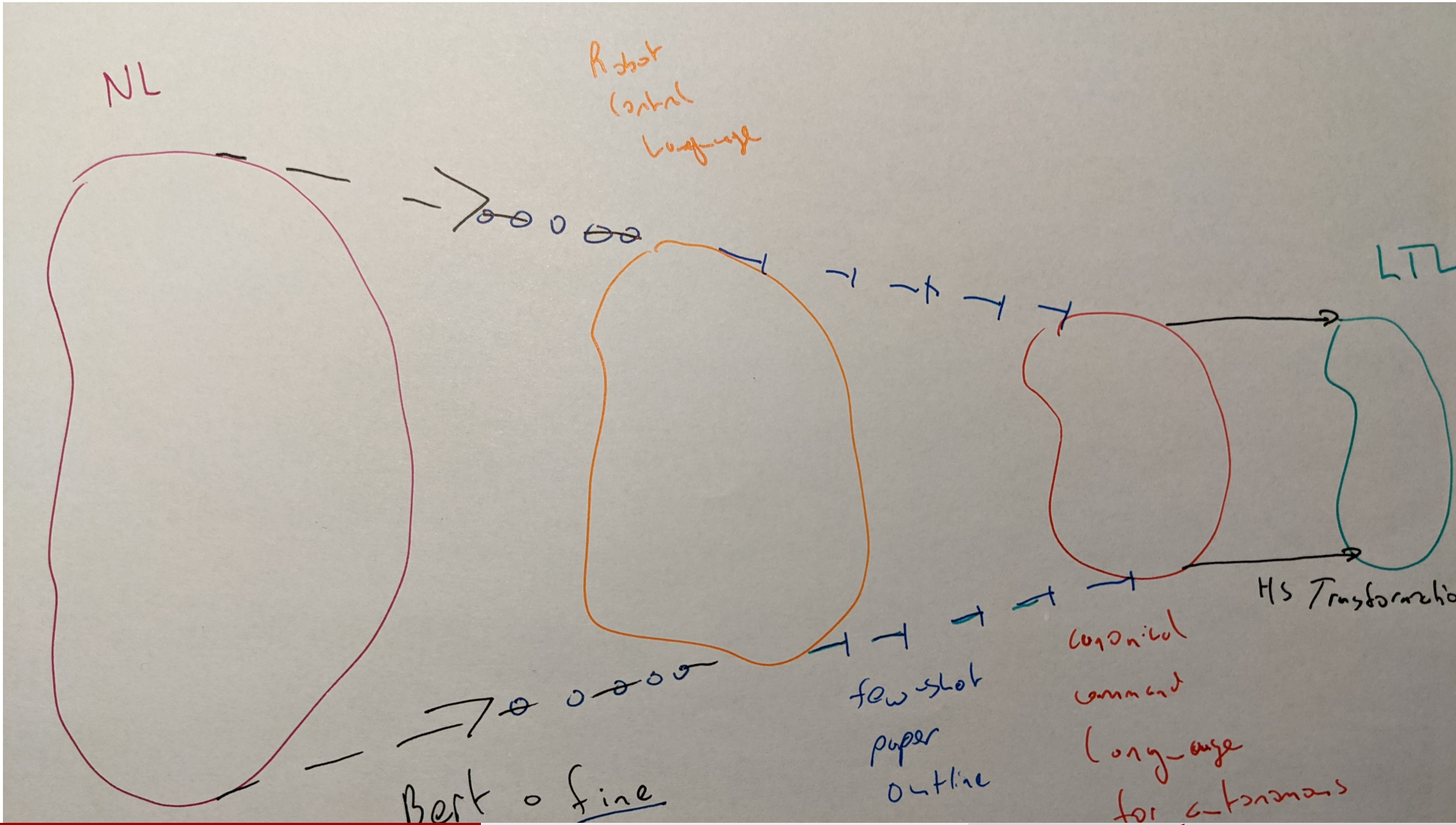
Light-bulb

Integrate their technique and code with our parser and dataset

Language Spaces



Language Transformations



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