AN ANALOGICAL INDUCTIVE SOLUTION TO THE GROUNDING PROBLEM

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Paper 14

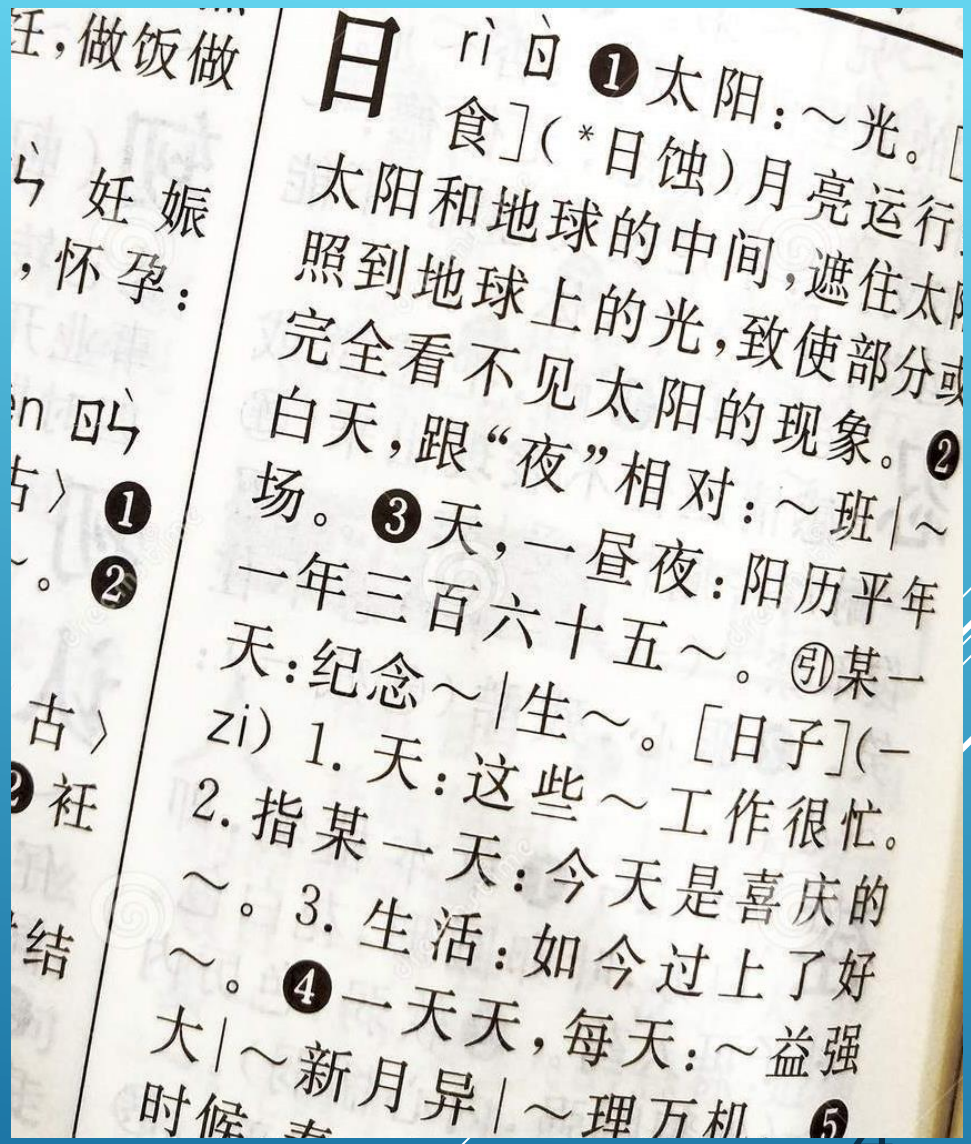
- What is the “symbol grounding problem” ?

Harnad (1990, 1994) Symbol Grounding:

symbols grounded with capacity to interact with real world

- Harnad: try learn Chinese language from Chinese-Chinese dictionary

符号接地问题



Google translate: “symbol grounding problem”
Dictionary: Sun: ~light. Eclipse (solar eclipse) The moon moves between the sun and Earth, blocking the light that hits the Earth….

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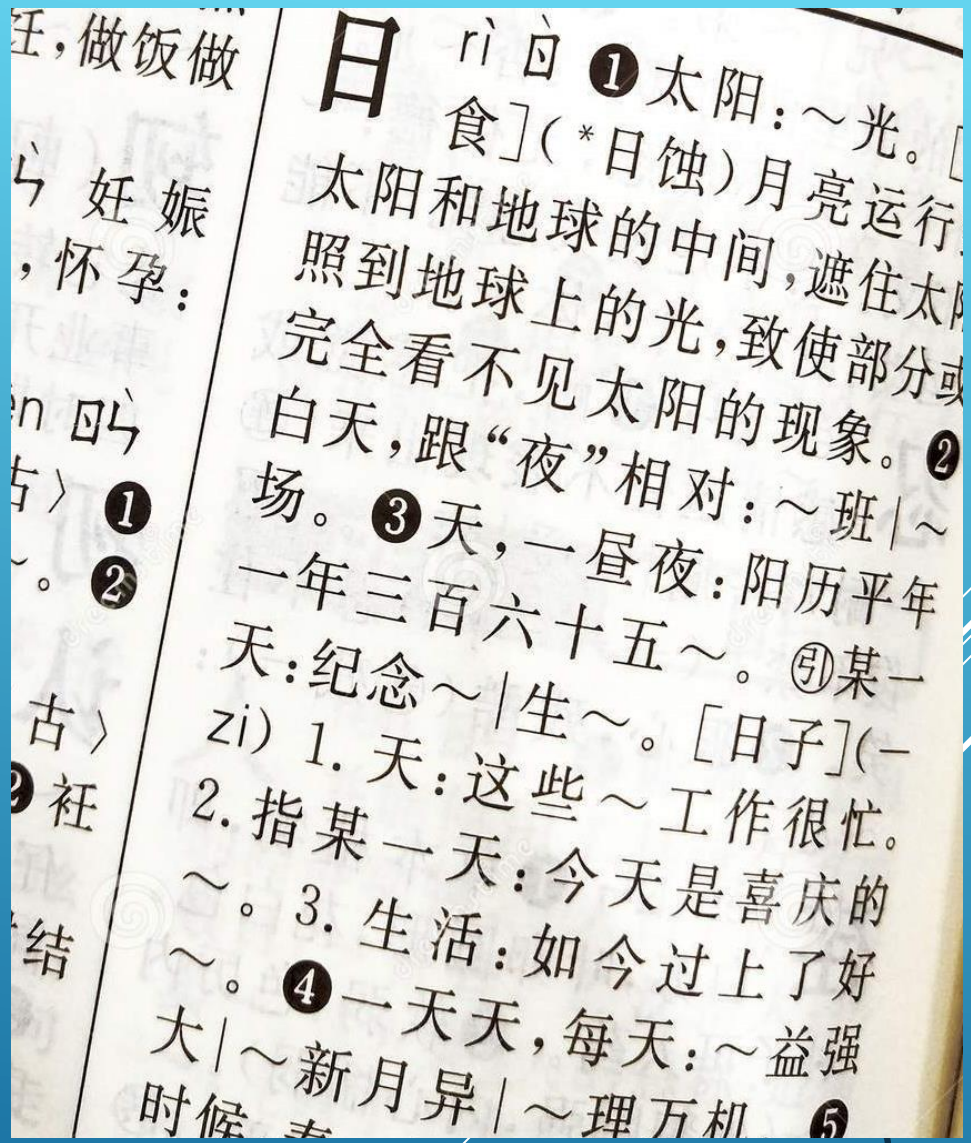
Go from one string of symbols without any meaning attached to the symbols to another string of symbols

符号接地问题



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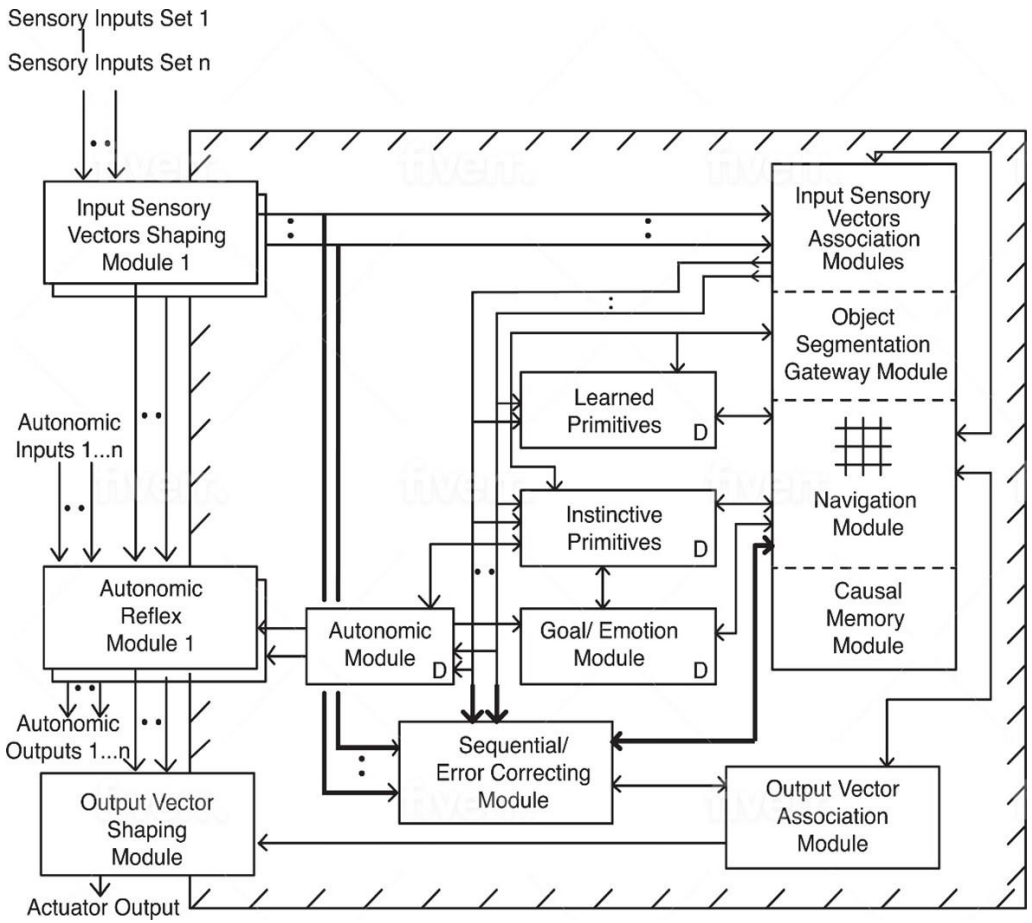
Analogical Inductive Solution to the Grounding Problem via the Causal Cognitive Architecture

What is the Causal Cognitive Architecture?



CAUSAL COGNITIVE ARCHITECTURE

CCA3
CCA4
CCA5

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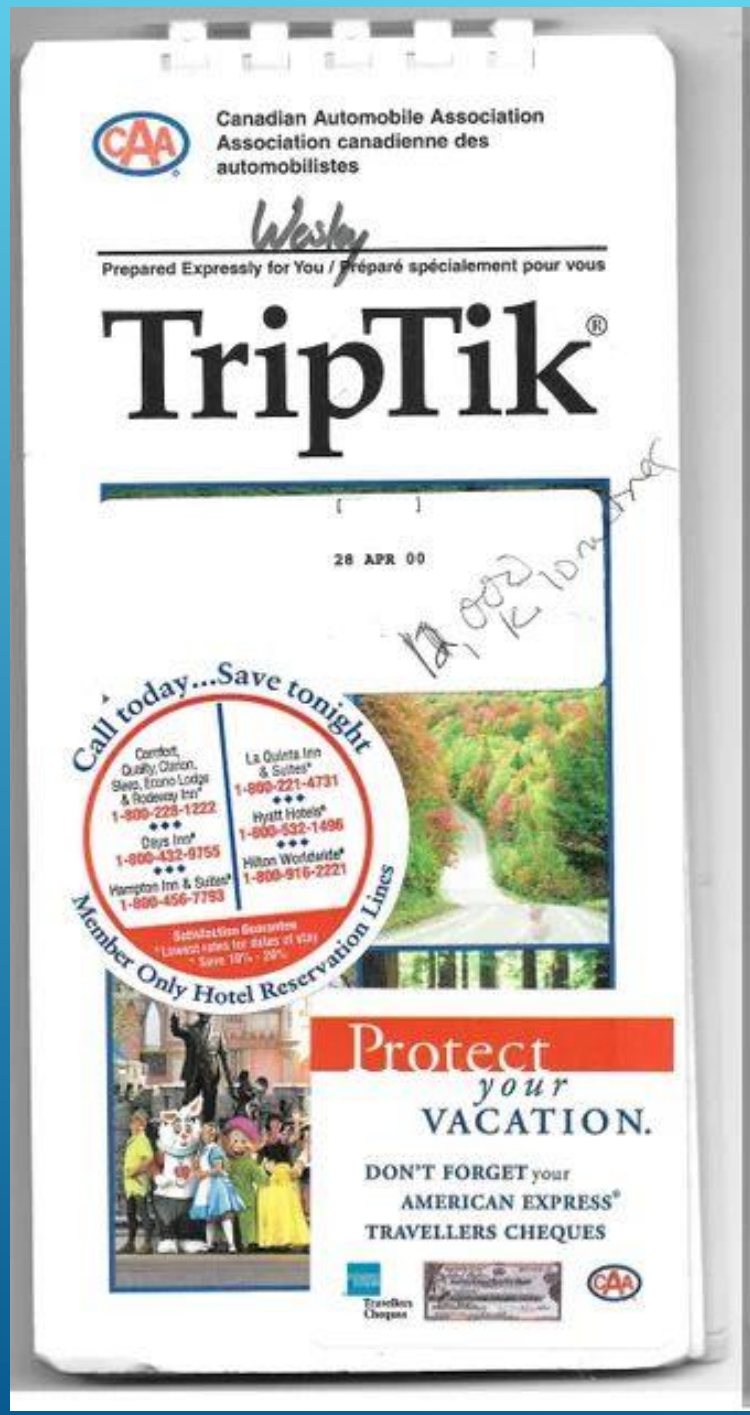
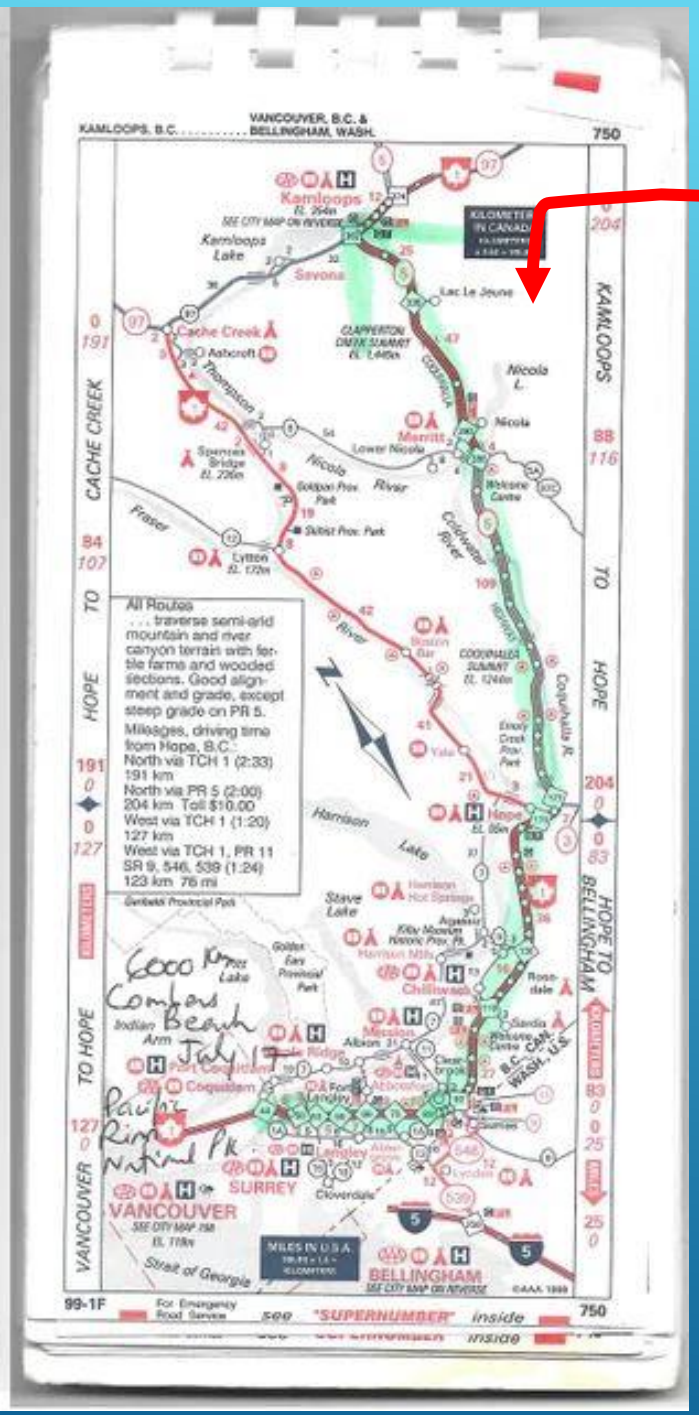




Navigation Map

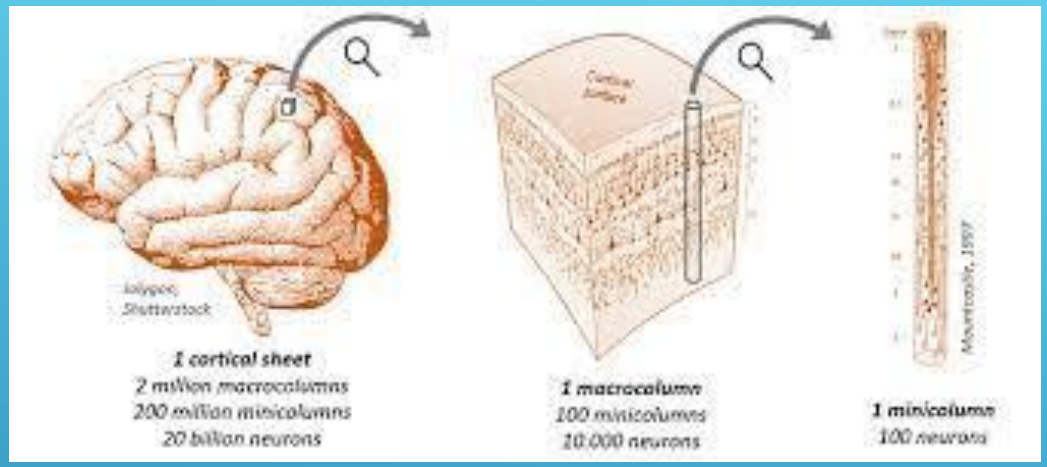
paper version,
2 spatial dimensions

```
self.total_labels = TOTAL_ASSOCIATION_LABELS #default 4
self.gb = np.empty((self.total_maps, 6, 6, 6, self.total_seg
# self.gb = np.empty((1000,6,6,6,16,4), dtype=object) (at ti
# gb[n,x,y,z,s,a]
# 1000 maps each 6×6×6 cube with up to 9 mapped objects -- a
```

Navigation Map

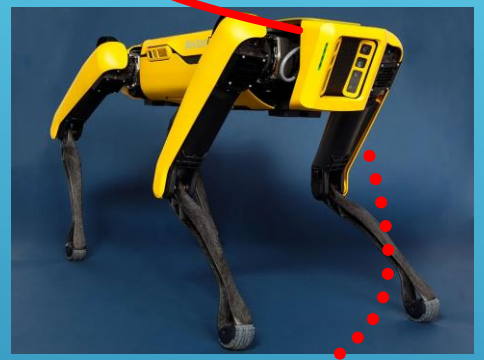
Python version,
3 spatial dimensions +
3 non-spatial dimensions

Think of navigation maps as small maps



- Not one massive associative network
- Rather, billions of small maps
- Neurosymbolic object – works with connectionist principles but can function as a quasi-symbol

CCA5 controlling



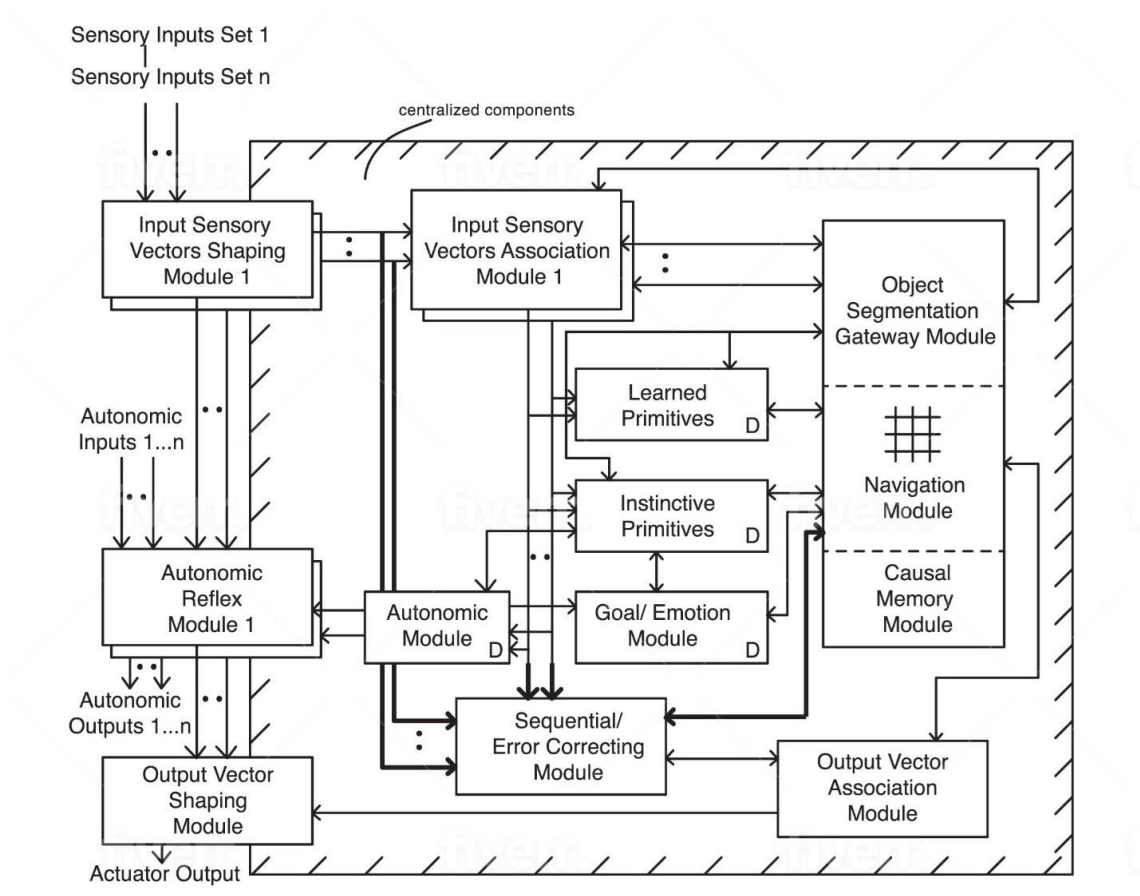
EXTERNAL SENSORY SCENE

air	air	air	air	air
solid33, *link*{1033}	solid08, *link*{1008}	solid08, *link*{1008}	solid08, *link*{1008}	solid33, *link*{1033}
solid33, *link*{1033}	solid08, *link*{1008}	solid08, *link*{1008}	solid08, *link*{1008}	solid33, *link*{1033}
solid33, *link*{1033}	water	solid08, *link*{1008}	solid08, *link*{1008}	solid32, *link*{1032}
solid32, *link*{1032}	water	solid08, *link*{1008}	solid08, *link*{1008}	solid33, *link*{1033}

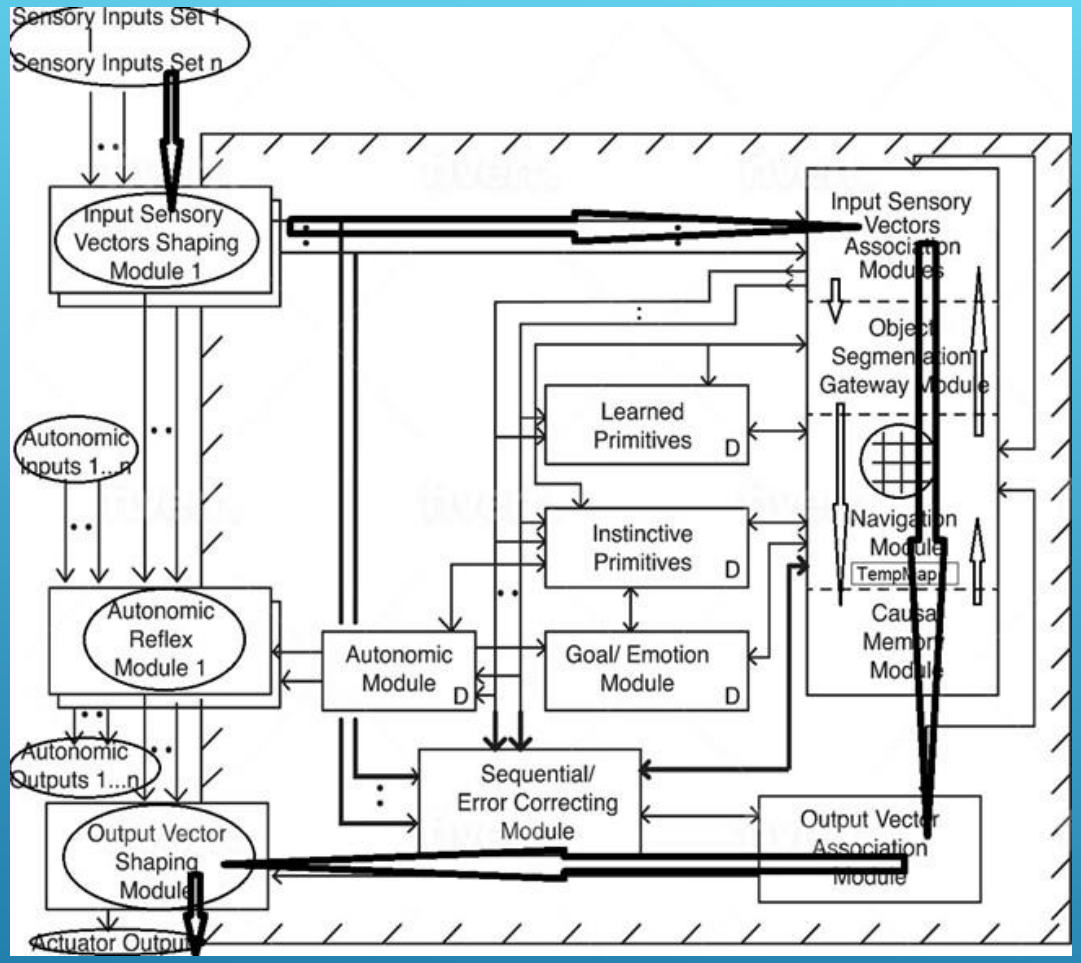
Features, Procedures, Links

PROCESSED "WORKING NAVIGATION MAP"

EVERY MODULE IN THE ARCHITECTURE USES NAVIGATION MAPS



Causal Cognitive Architecture 3



COGNITIVE CYCLE: SENSORY INPUTS IN, PROCESSING, MOTOR OUTPUTS OUT

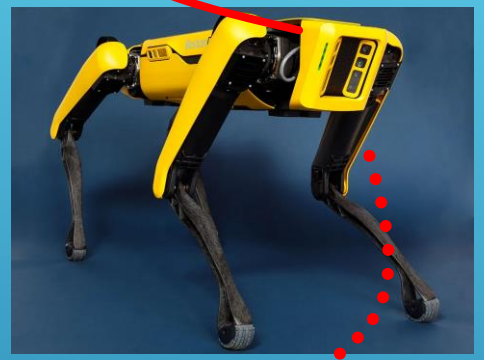
Operations on Navigation Maps

Copy NavMaps…..
Compare NavMaps….
Add NavMaps….
Subtract NavMaps….
Add Vectors….
Match NavMaps…
Feedback NavMaps + Copy NavMaps + Subtract NavMaps….
Feedback NavMaps a slightly different way….

Demonstration Example of Causal Cognitive Architecture

INDUCTIVE FEEDBACK MECHANISM NOT USED

CCA5 controlling



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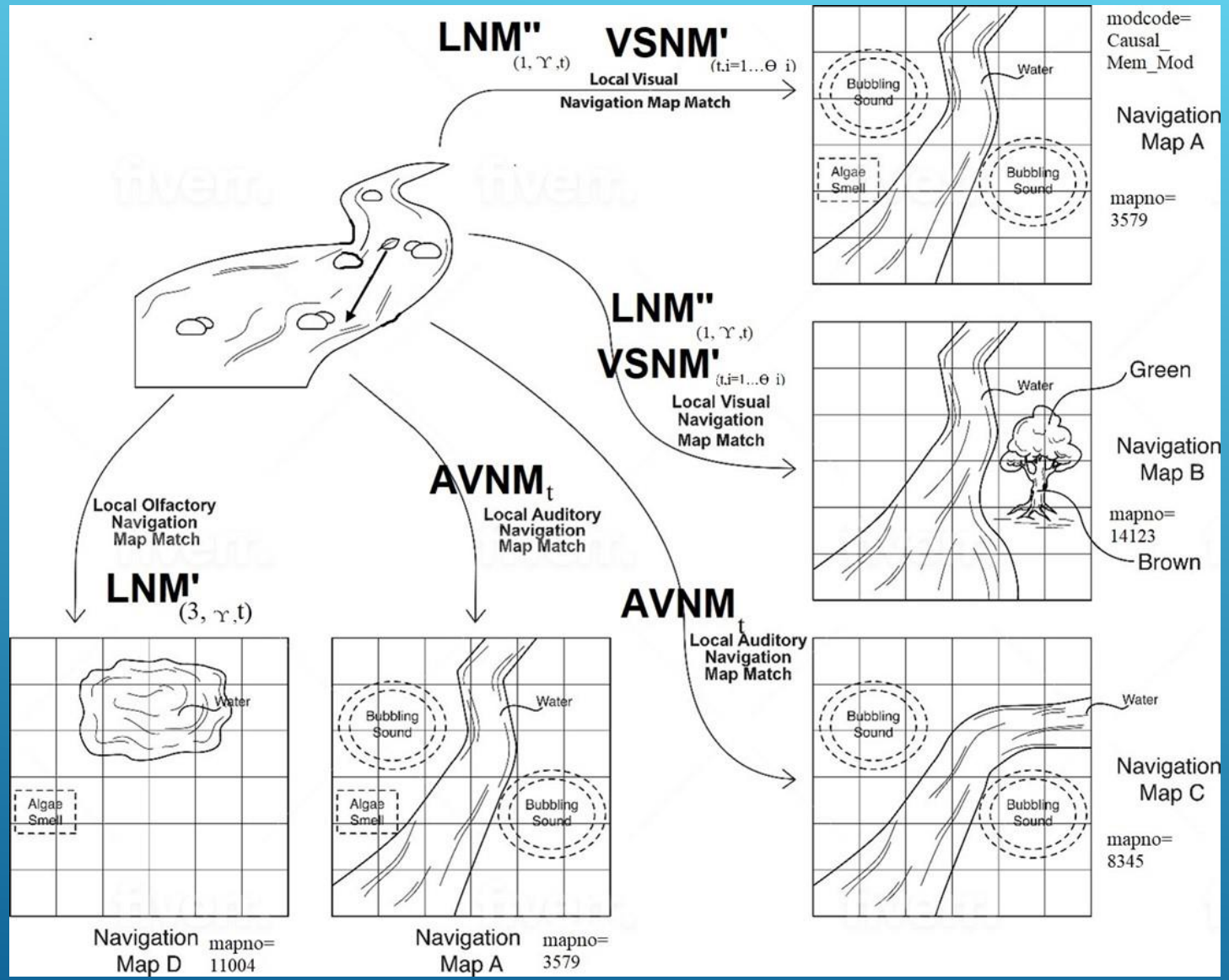

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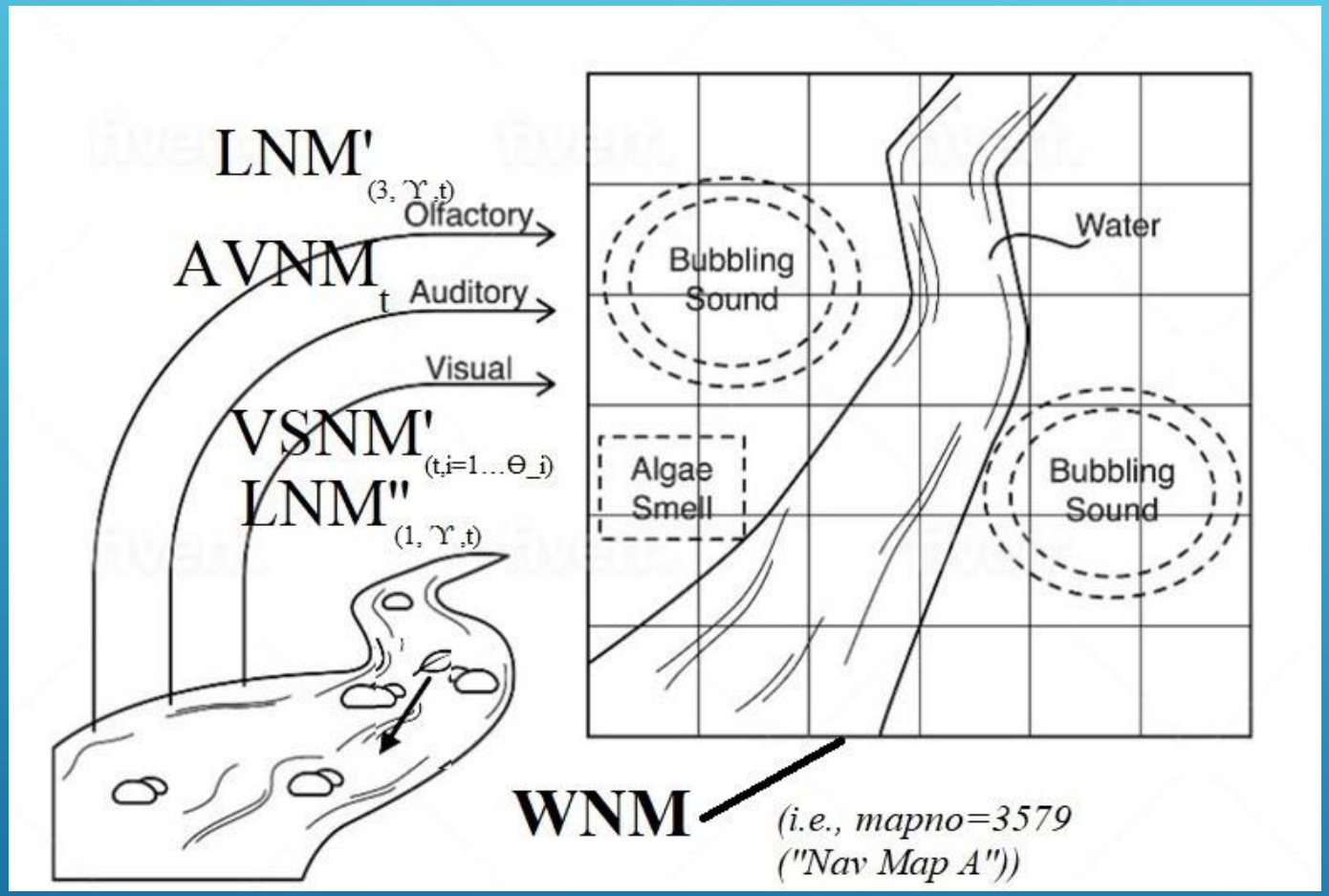
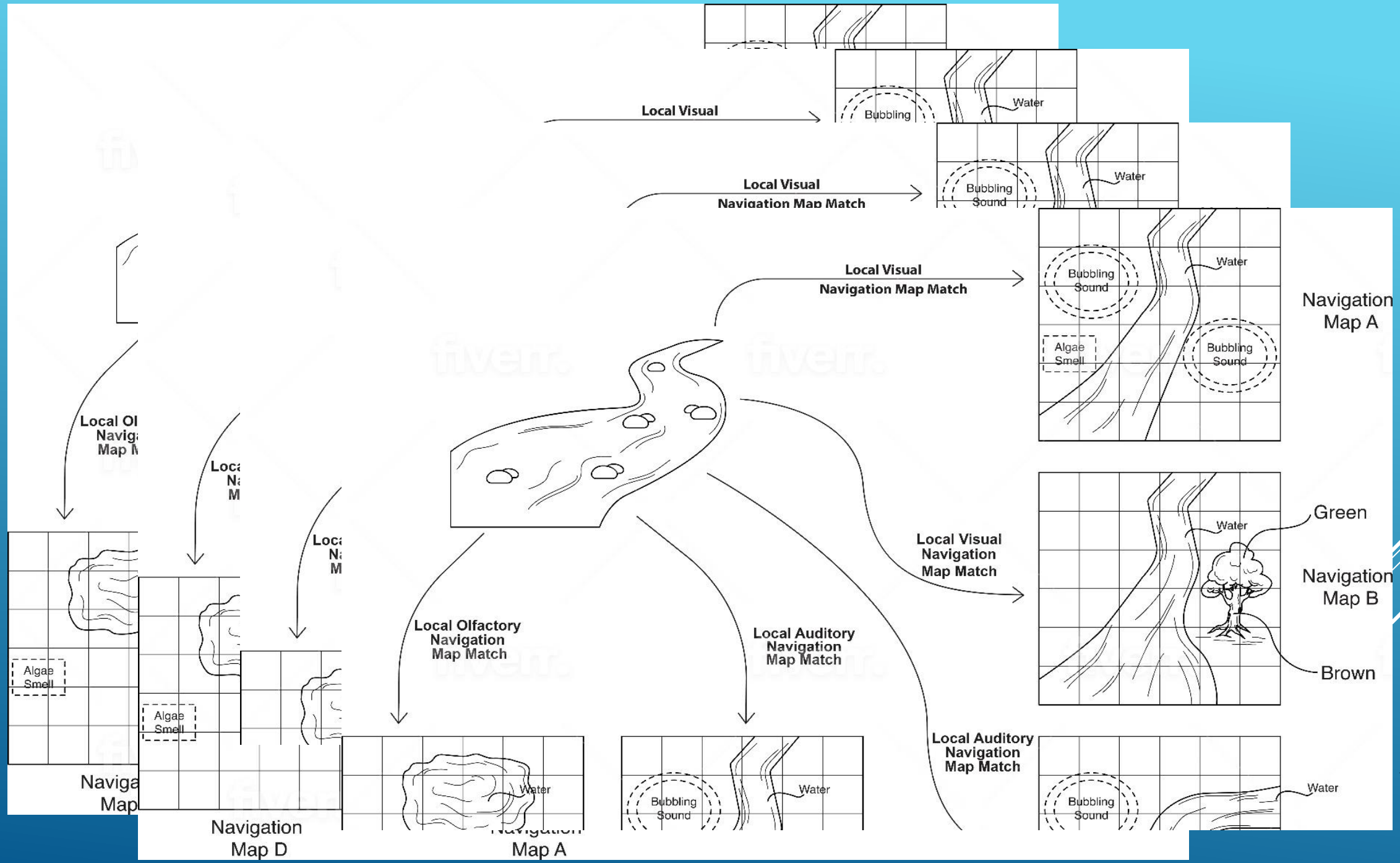
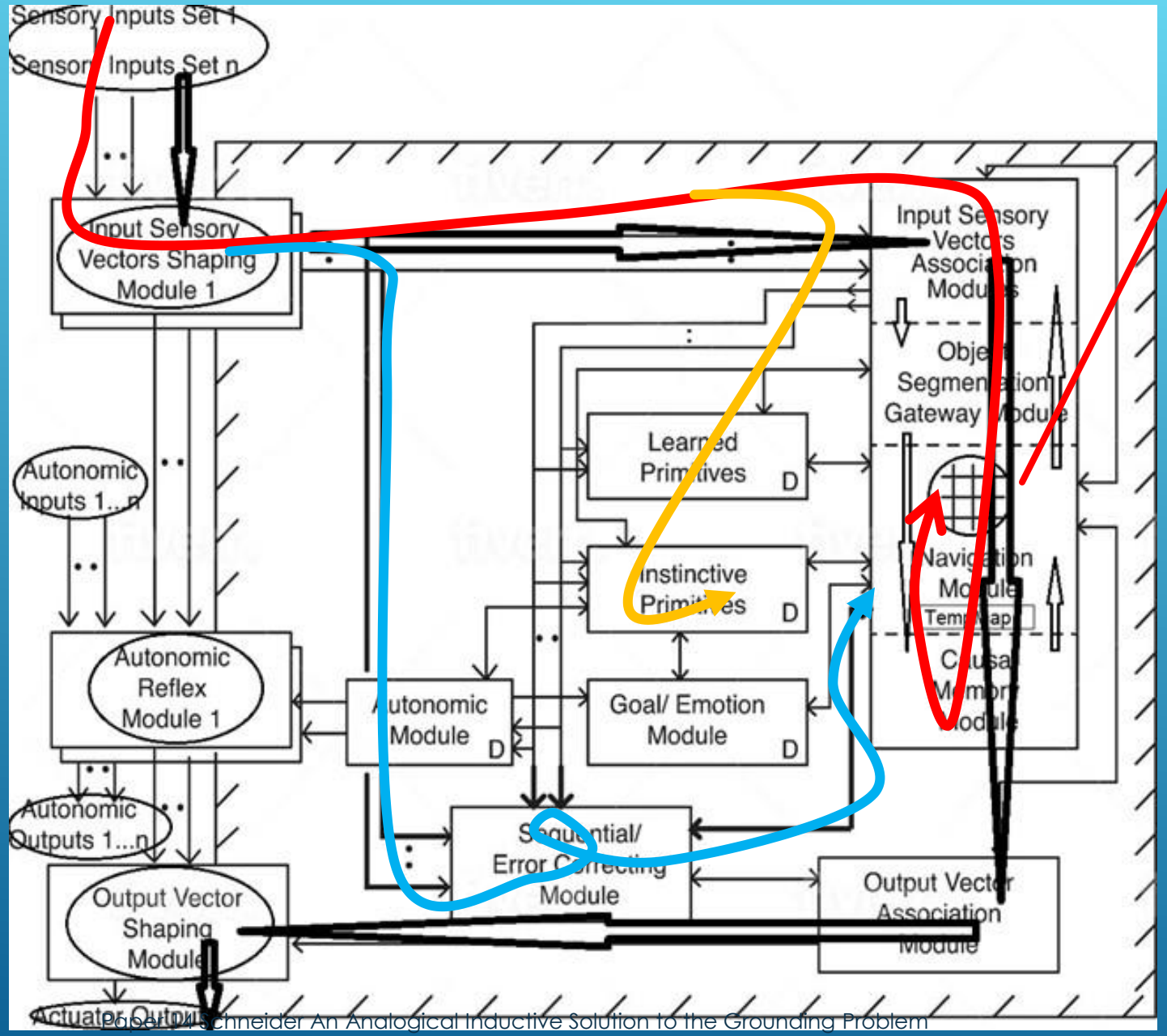
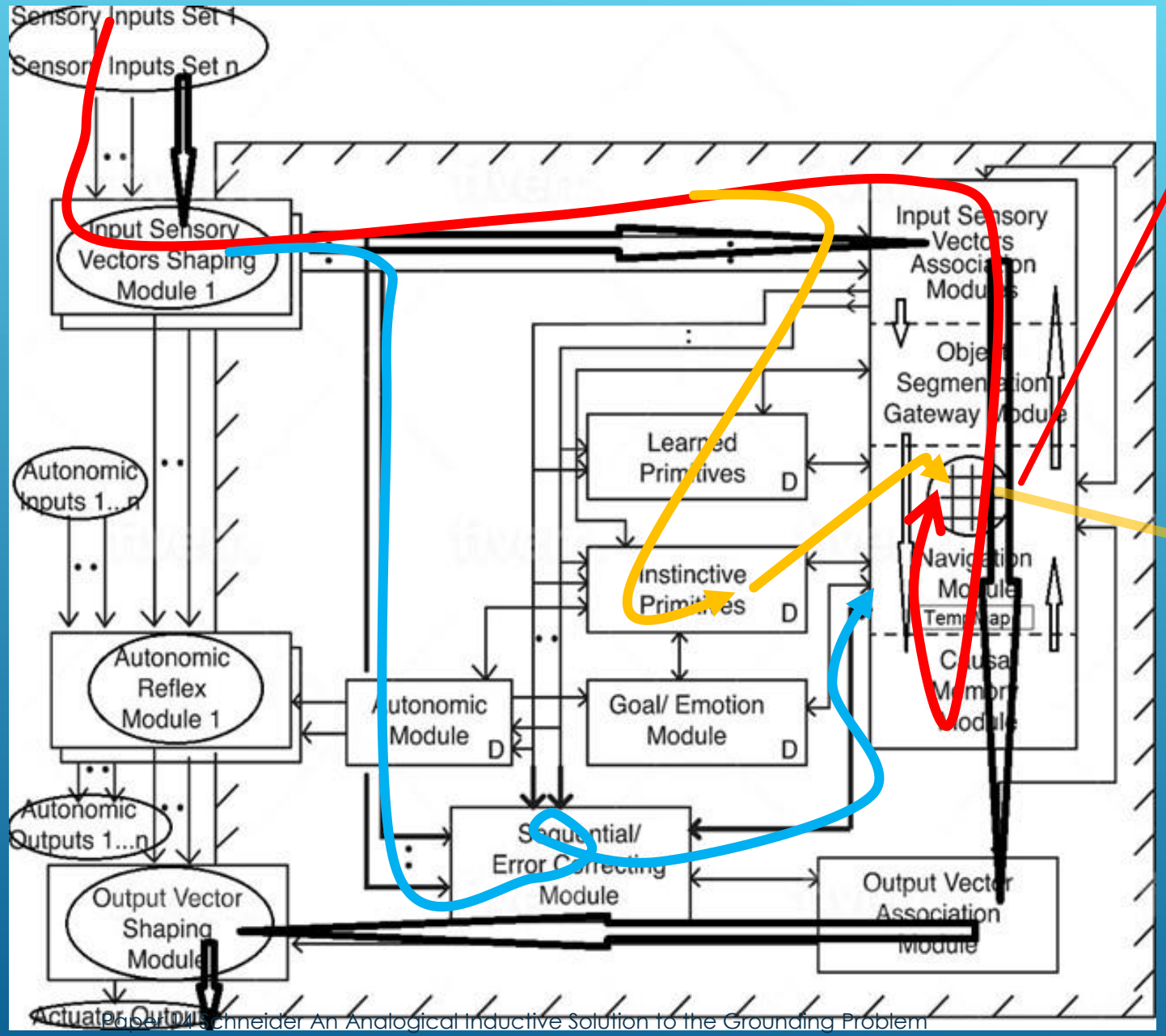

LNM'
(3, ϒ ,t)
Olfactory
AVNM
t
Auditory
Visual
VSNM'
(t,i=1…Θ_i)
LNM"
(1, ϒ ,t)
Bubbling
Sound
Water
Algae
Smell
Bubbling
Sound
WNM
(i.e., mapno=3579
("Nav Map A"))


Local Visual
Bubbling
Water
Local Visual
Navigation Map Match
Bubbling Sound
Water
Local Visual
Navigation Map Match
Bubbling Sound
Water
Algae Smell
Bubbling Sound
Navigation Map A
Local Visual
Navigation Map Match
Water
Green
Navigation Map B
Brown
Local Olfactory Navigation Map Match
Local Auditory Navigation Map Match
Local Auditory Navigation Map Match
Bubbling Sound
Water
Water
Algae Smell
Algae Smell
Navigation Map D
Map A



WNM' (Working Navigation Map)

air	air	air	air	air
solid33, *link*{1033}	solid08, *link*{1008}	solid08, *link*{1008}	solid08, *link*{1008}	solid33, *link*{1033}
solid33, *link*{1033}	solid08, *link*{1008}	solid08, *link*{1008}	solid08, *link*{1008}	solid33, *link*{1033}
solid33, *link*{1033}	water	solid08, *link*{1008}	solid08, *link*{1008}	solid32, *link*{1032}
solid32, *link*{1032}	water	solid08, *link*{1008}	solid08, *link*{1008}	solid33, *link*{1033}



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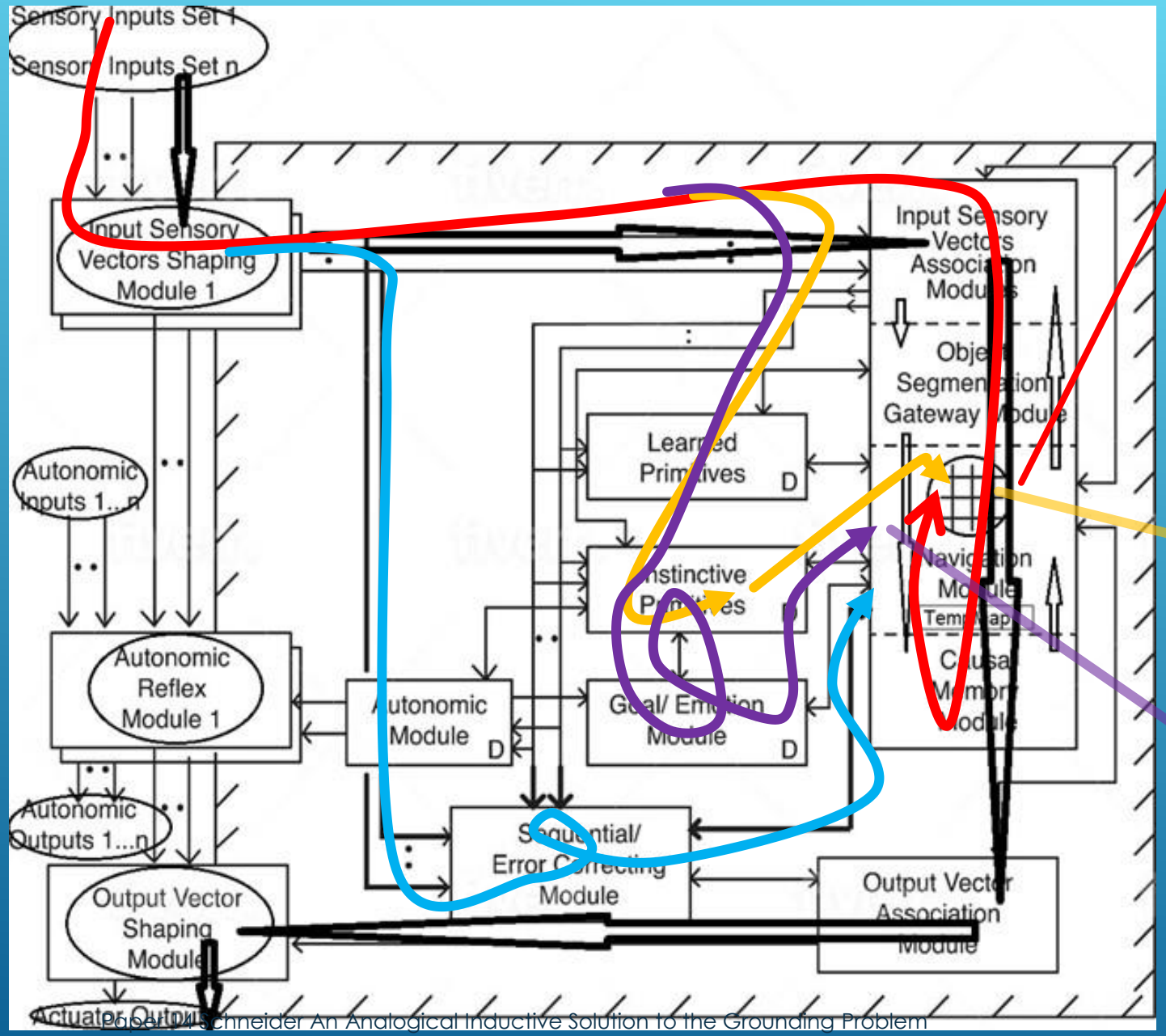
solid33, *link*{1033}	solid08, *link*{1008}	solid08, *link*{1008}	solid08, *link*{1008}	solid33, *link*{1033}
solid33, *link*{1033}	water	solid08, *link*{1008}	solid08, *link*{1008}	solid32, *link*{1032}
solid32, *link*{1032}	water	solid08, *link*{1008}	solid08, *link*{1008}	solid33, *link*{1033}

WPR' (Working Primitive)

solid33, *link*{1033}				



WNM' (Working Navigation Map)

WPR' (Working Primitive)

GOAL – cross the river

Architecture described by equations/pseudocode

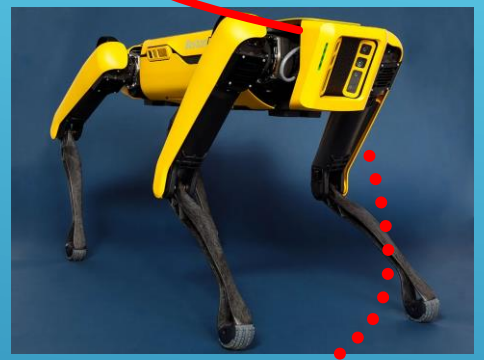
$$\mathbf{action}_t = \text{Navigation_Module.apply_primitive}(\mathbf{WPR}_t, \mathbf{WNM'}_t) \quad (78)$$

Working Primitive

Working Navigation Map

Pseudocode for algorithm which applies the best matching instinctive or learned primitive (WPR) on the navigation map in the Navigation Module (WNM), producing an **action** value then sent to the output stages

CCA5 controlling



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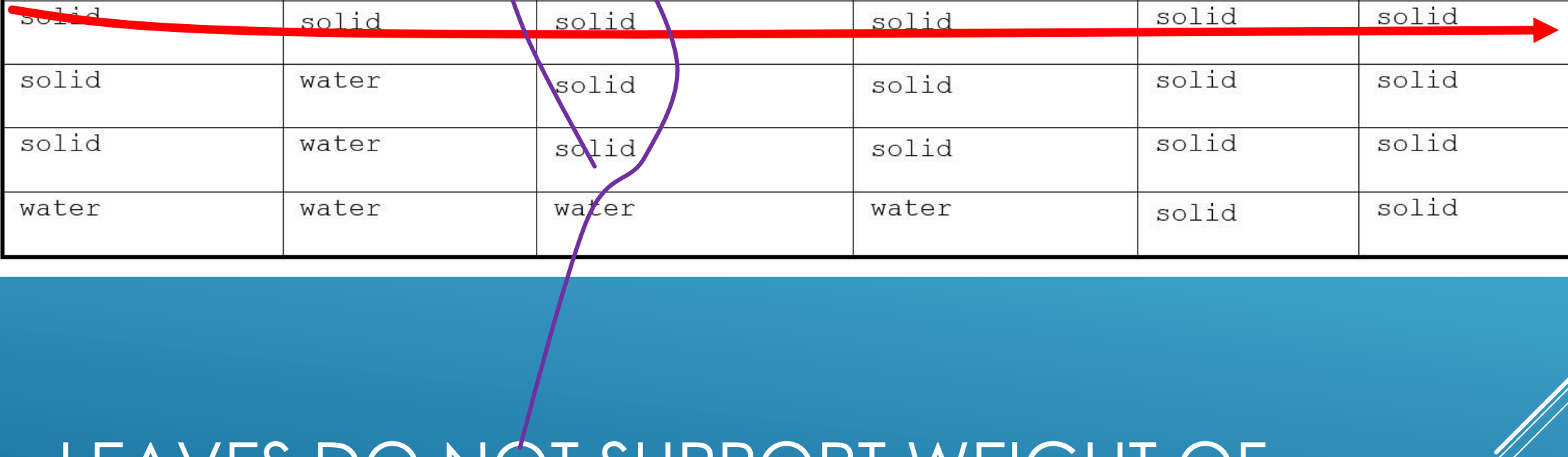
solid33, *link*{1033}	water	solid08, *link*{1008}	solid08, *link*{1008}	solid32, *link*{1032}
solid32, *link*{1032}	water	solid08, *link*{1008}	solid08, *link*{1008}	solid33, *link*{1033}

PART OF INITIAL DATABASE (NOT EXPERIENCED)
SOLID08 (LEAVES) RECOGNIZED
LINK {1008} THIN SHEETS, FROM FACTS

air	air	air	air	air	air
solid	solid	solid	solid	solid	solid
solid	solid	solid	solid	solid	solid
solid	water	solid	solid	solid	solid
solid	water	solid	solid	solid	solid
water	water	water	water	solid	solid

PATH FINDING INSTINCTIVE PRIMITIVE FINDS A PATH ACROSS THE RIVER

air	air	air	air	air	air
solid	solid	solid	solid	solid	solid
solid	solid	solid	solid	solid	solid
solid	water	solid	solid	solid	solid
solid	water	solid	solid	solid	solid
water	water	water	water	solid	solid



LEAVES DO NOT SUPPORT WEIGHT OF ROBOT, IT FALLS INTO RIVER

Causal Cognitive Architecture trying to cross river again

air	air	air	air	air	air
solid	solid	solid	solid	solid	solid
solid	solid	solid	solid	solid	solid
solid	water	solid	solid	solid	solid
solid	water	solid	solid	solid	solid
water	water	water	water	solid	solid

Will not go – negative experience in link, instinctive primitive will not pathfind this route

→ After falling into the water, now is well grounded about leaves floating on the river !!

Symbol grounding via Navigation Map architecture

$$grounded_feature = \forall_{feature}: (feature \in \mathbf{all_LNMs}_{\chi} \text{ AND } feature \in \mathbf{s}(t))$$

OR

$$\forall_{feature}: (feature \in \mathbf{WNM'}_{t} \text{ AND } (action_{t-1} \neq \text{“move*”} \text{ or } \mathbf{WPR}_{t-1} = [\text{“analogical*”}])) \quad (104)$$

$$\forall_{\chi,t}: \mathbf{all_navmaps}_{\chi,t} = grounded_feature \text{ OR}$$

$$\texttt{link}(\mathbf{all_navmaps}_{\chi,t}) \neq [\,] \text{ OR } \mathbf{cellfeatures}_{\chi,t} = [\,] \quad (105)$$

NEW Demonstration Example of Causal Cognitive Architecture

-NEW CCA5 ROBOT – NO MEMORY ABOUT CROSSING THIS RIVER
-FULL CCA5 ARCHITECTURE USED

Symbol grounding via Navigation Map architecture

$$grounded_feature = \forall_{feature}: (feature \in \mathbf{all_LNMs}_{\chi} \text{ AND } feature \in \mathbf{s}(t))$$

OR

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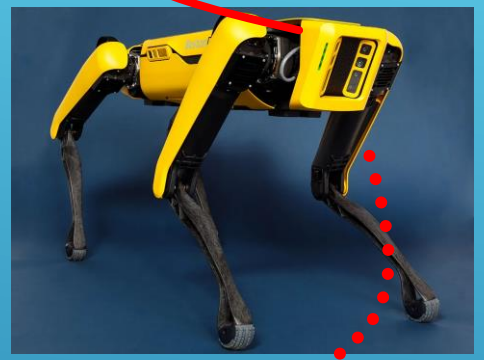
CCA5 controlling



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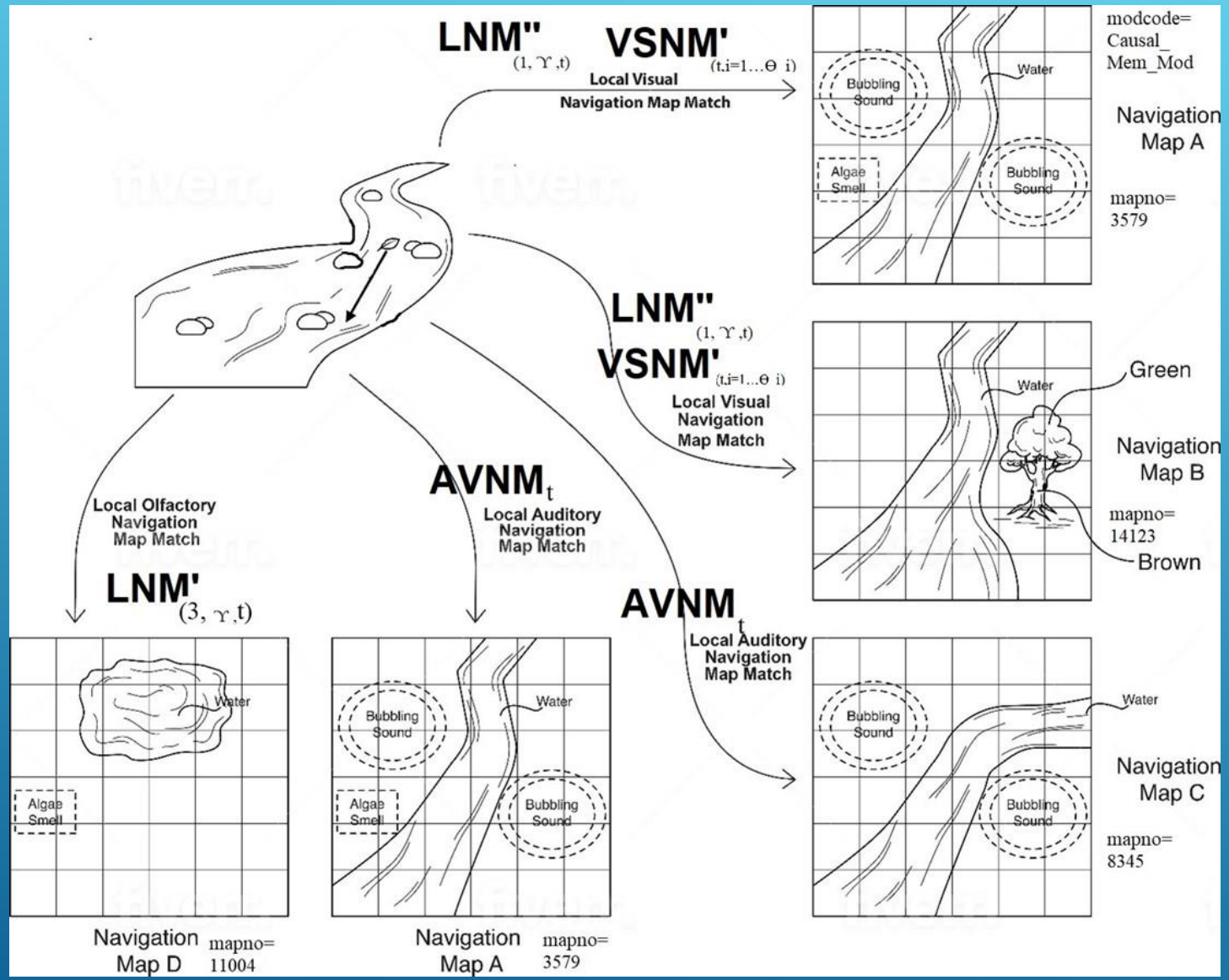
Feedback NavMaps + Copy NavMaps + Subtract NavMaps….
Feedback NavMaps a slightly different way….



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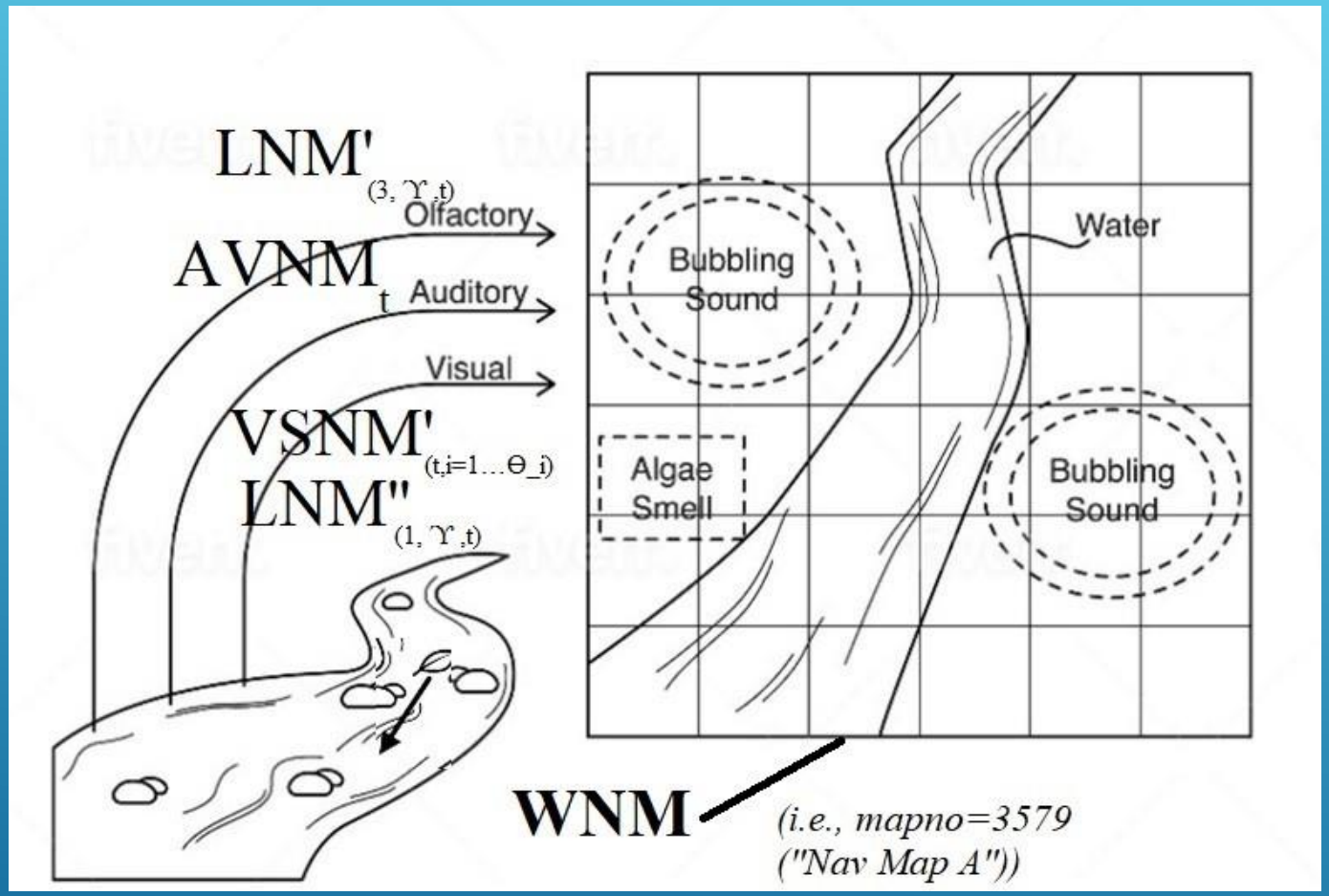
LNM'
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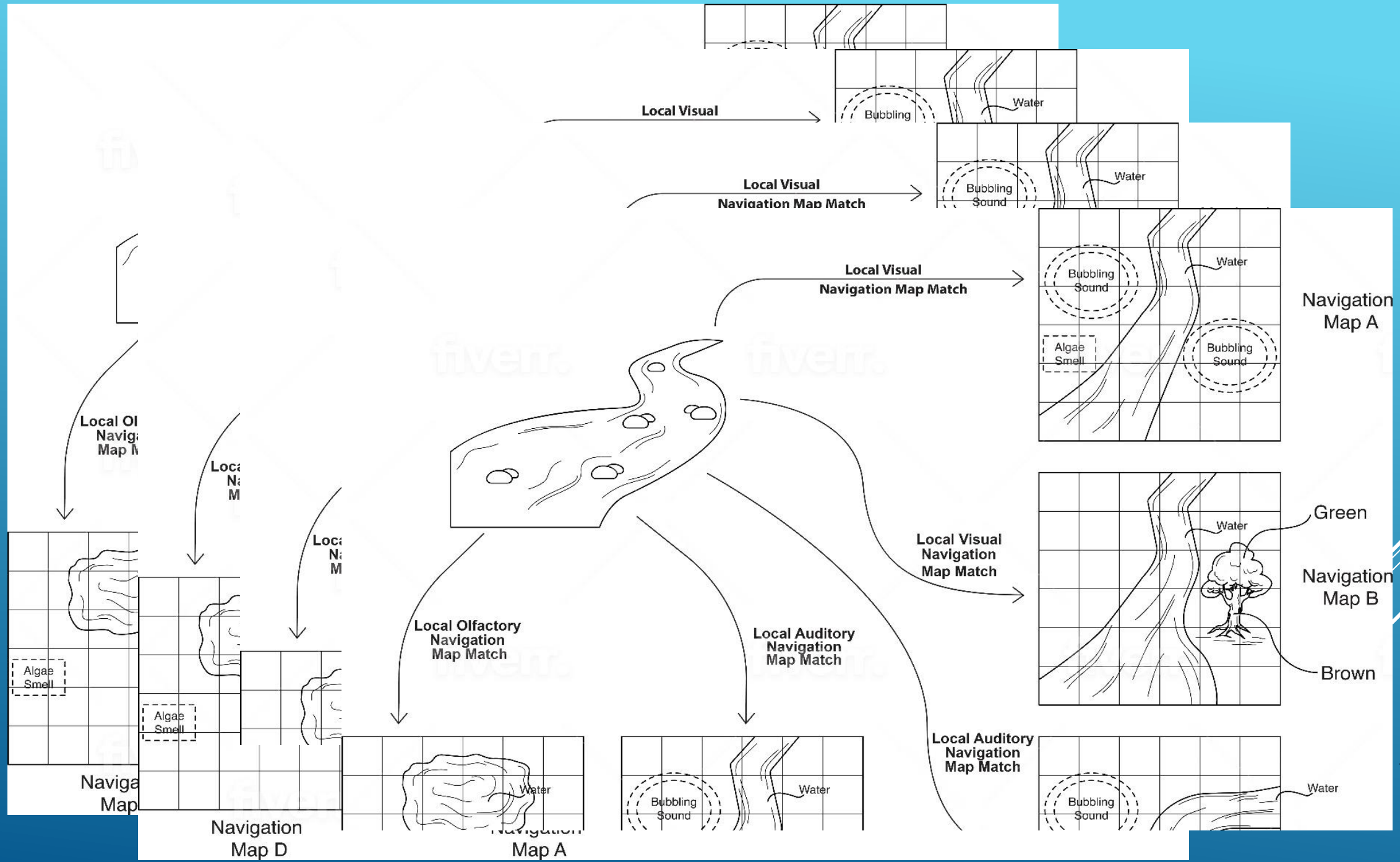
LNM"
(1, ϒ ,t)
Bubbling
Sound
Water
Algae
Smell
Bubbling
Sound
WNM
(i.e., mapno=3579
("Nav Map A"))


Local Visual
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Navigation Map Match
Bubbling Sound
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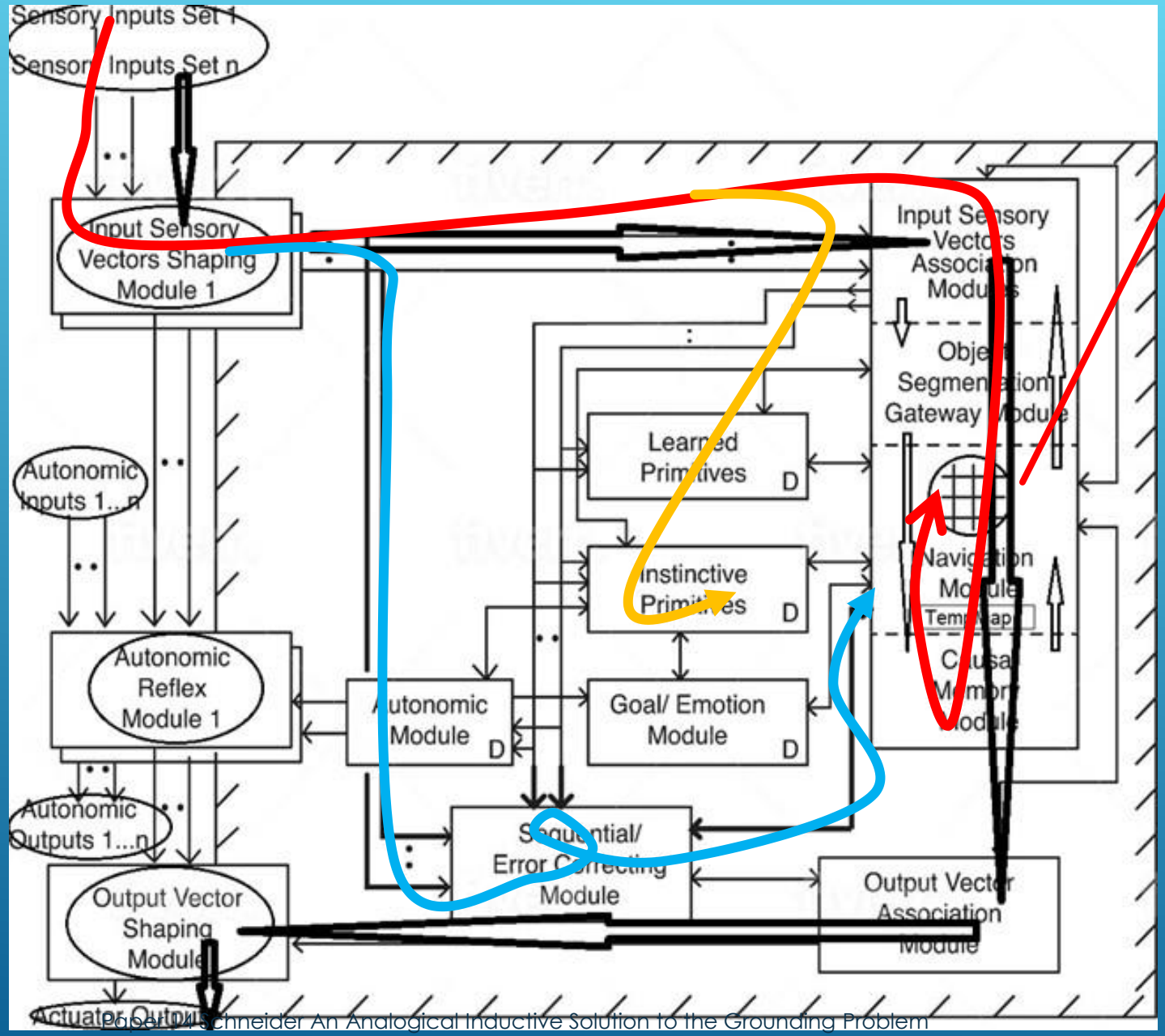
Bubbling Sound
Water
Algae Smell
Bubbling Sound
Navigation Map A
Local Visual
Navigation Map Match
Water
Green
Navigation Map B
Brown
Local Olfactory Navigation Map Match
Local Auditory Navigation Map Match
Local Auditory Navigation Map Match
Algae Smell
Algae Smell
Navigation Map D
Water
Bubbling Sound
Water
Map A
Bubbling Sound
Water



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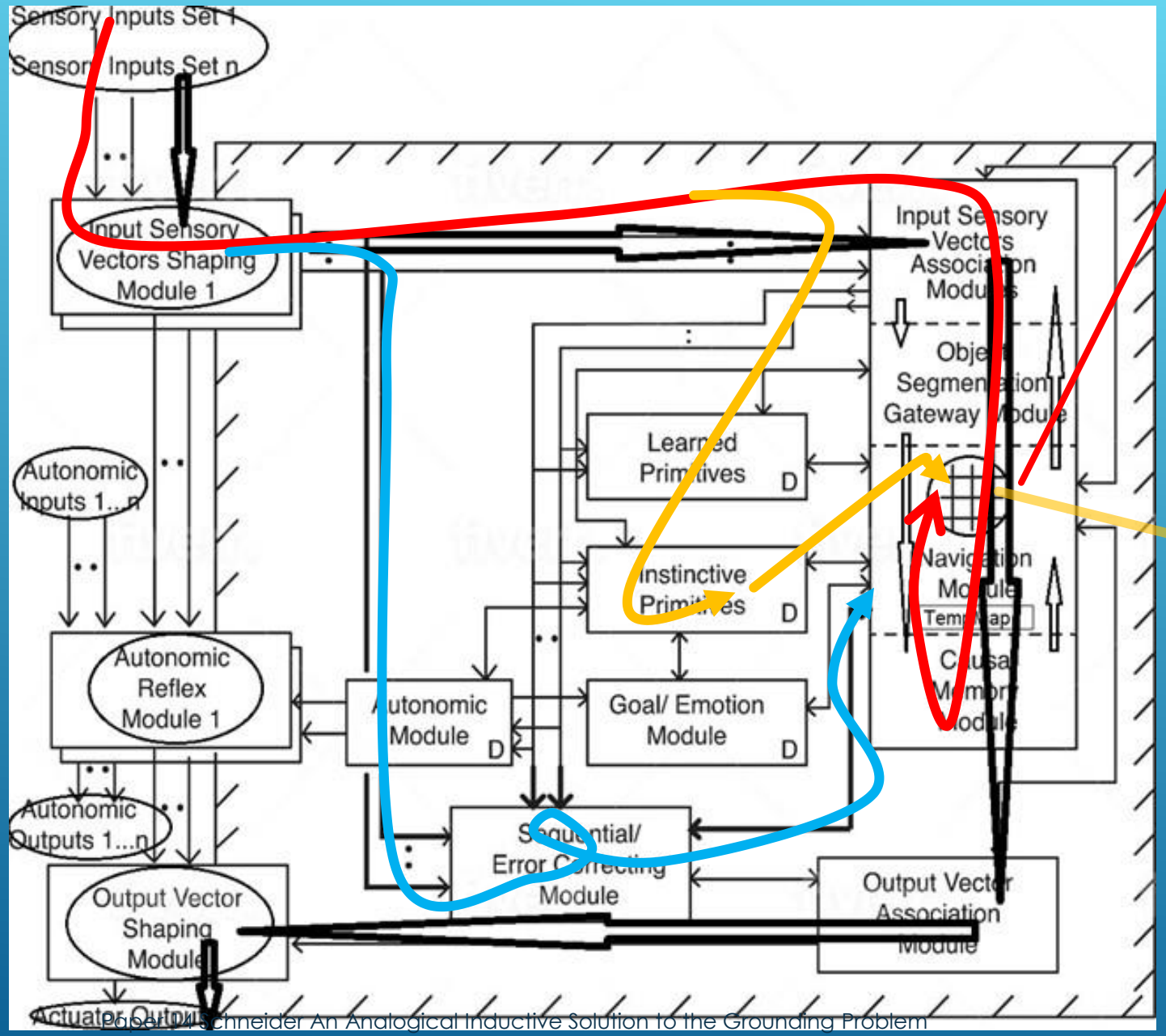

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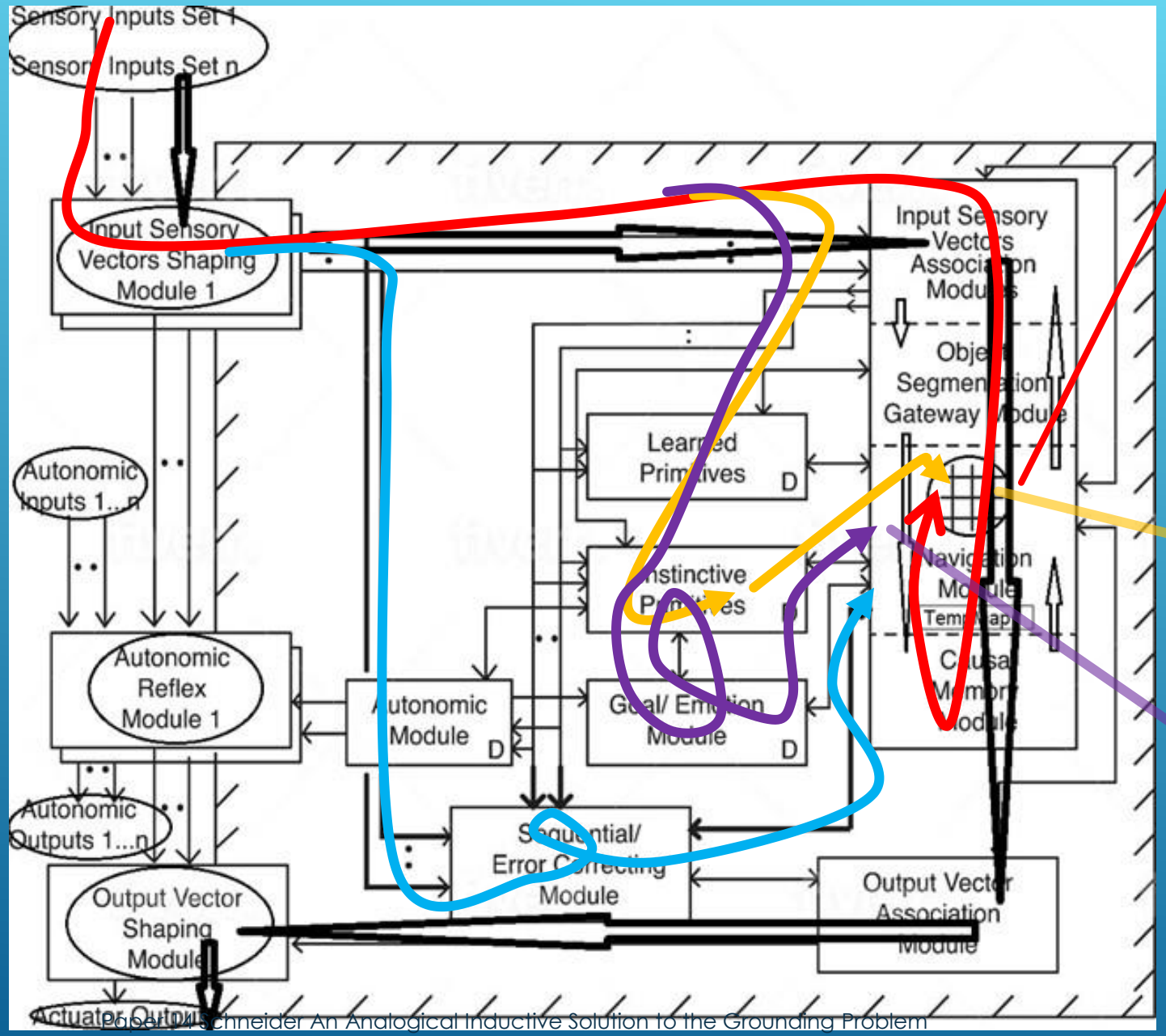
solid33, *link*{1033}	water	solid08, *link*{1008}	solid08, *link*{1008}	solid32, *link*{1032}
solid32, *link*{1032}	water	solid08, *link*{1008}	solid08, *link*{1008}	solid33, *link*{1033}

WPR' (Working Primitive)

solid33, *link*{1033}				



WNM' (Working Navigation Map)

WPR' (Working Primitive)

GOAL – cross the river

Architecture described by equations/pseudocode

$$\mathbf{action}_t = \text{Navigation_Module.apply_primitive}(\mathbf{WPR}_t, \mathbf{WNM'}_t) \quad (78)$$

Working Primitive

Working Navigation Map

Pseudocode for algorithm which applies the best matching instinctive or learned primitive (WPR) on the navigation map in the Navigation Module (WNM), producing an **action** value then sent to the output stages

air	air	air	air	air
solid33, *link*{1033}	solid08, *link*{1008}	solid08, *link*{1008}	solid08, *link*{1008}	solid33, *link*{1033}
solid33, *link*{1033}	solid08, *link*{1008}	solid08, *link*{1008}	solid08, *link*{1008}	solid33, *link*{1033}
solid33, *link*{1033}	water	solid08, *link*{1008}	solid08, *link*{1008}	solid32, *link*{1032}
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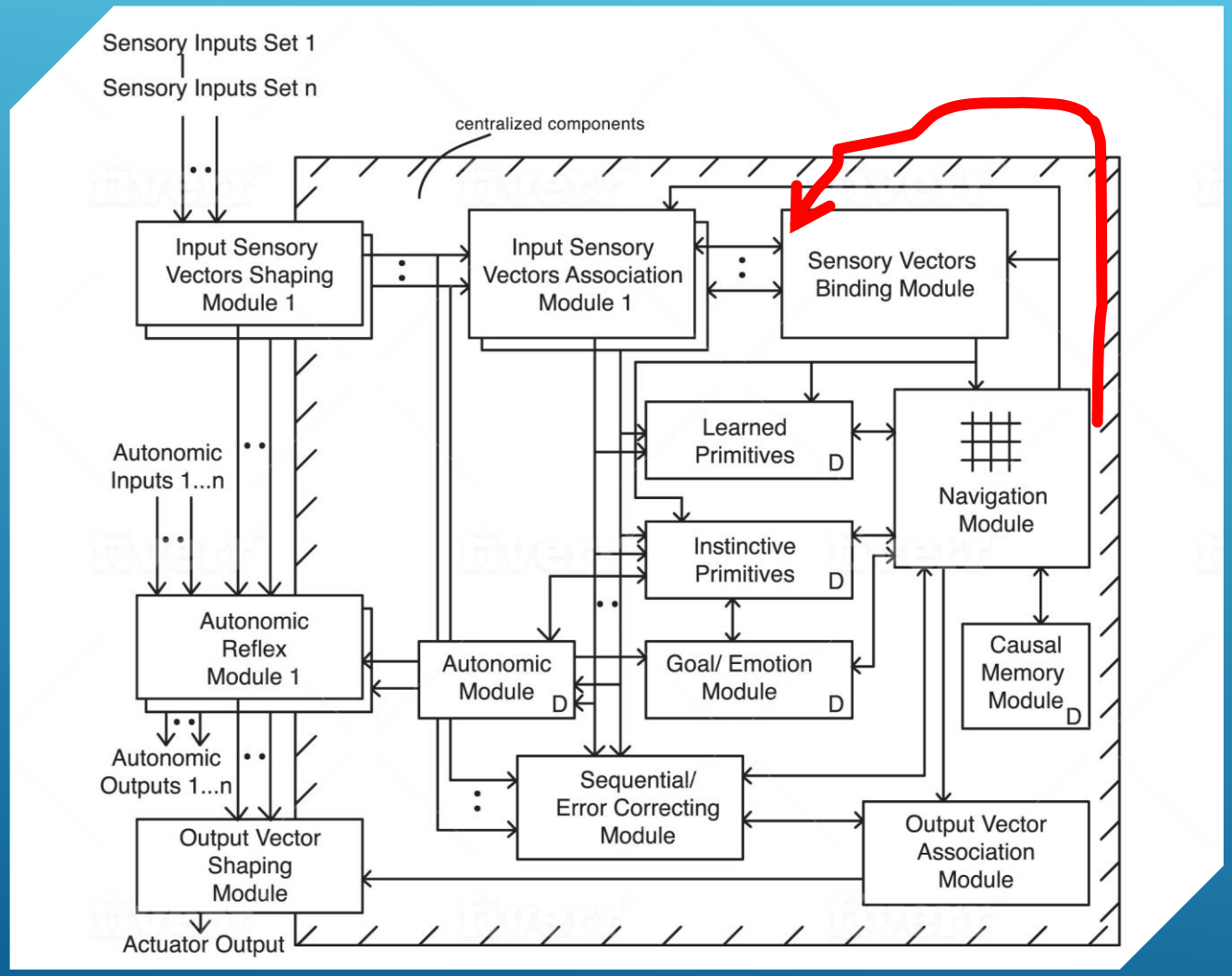
SOLID08 (LEAVES) RECOGNIZED
LINK {1008} THIN SHEETS, FROM FACTS



Feedback of partial results, and re-operate on them

(**action**$_t$ ≠“ move*” and **WPR**$_t$ ≠ [“discard*”] and **WPR**$_t$ ≠ [“feedback*”])
or **WPR**$_t$ = [“analogical*”],
⇒`Navigation_Module.feedback_intermediate`(**WNM’**$_t$) (86)
⇒ **WNM’**$_t$ = `Causal_Memory_Module.match_best_multisensory_navmap`(**WNM’**$_t$)(87)

⇒ **short_term_memory** ∈ R^{mxnxo} (88)
⇒ **short_term_memory** = **WNM’**$_t$ (89)
⇒ **WNM’**$_t$ = `Navigation_Module.next_map1` (**WNM’**$_t$) (90)
⇒ **WNM’**$_t$ = **WNM’**$_t$ – **short_term_memory** (91)
(**action**$_{t-1}$ ≠ “move*” and **WPR**$_{t-1}$ ≠ [“discard*”]) or **WPR**$_{t-1}$ = [“analogical*”],
⇒ **WNM’**$_t$ = `Navigation_Module.retrieve_and_add_intermediates` (92)

($ACTION_T \neq$ "MOVE*" AND $\mathbf{WPR}_T \neq$ ["DISCARD*"]) OR $\mathbf{WPR}_T =$ ["FEEDBACK*"],

⇒`Nav_Mod.feedback_to_assocn_mod(`**WNM'**$_t$-*original*`)` (95) #1 #3

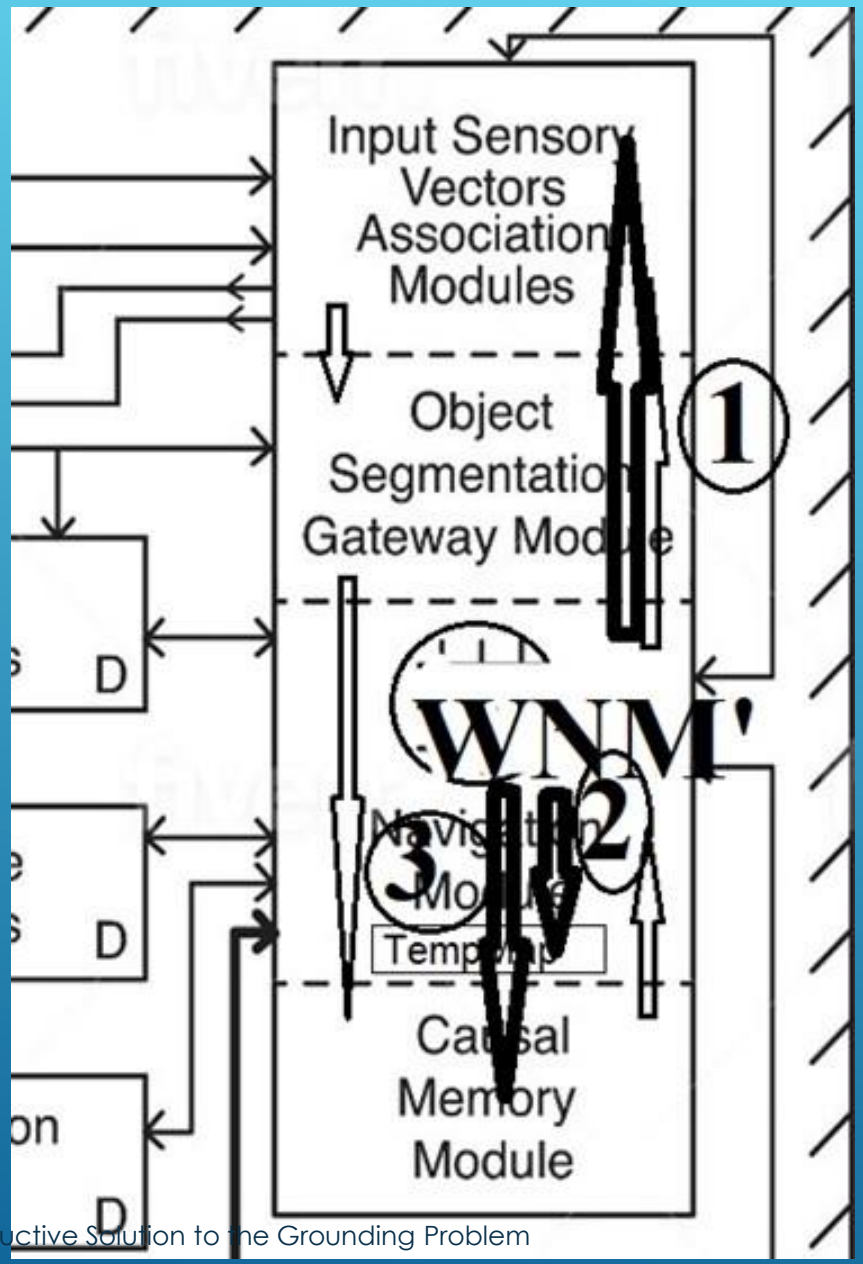
⇒ **WNM'**$_t$-*best_match* = `Causal_Mem_Mod.match_best_map(`**WNM'**$_t$-*original*`)` (96)

⇒ **TempMap**$_t$ = `Nav_Mod.use_linkaddress1_map(`**WNM'**$_t$-*best_match*`)` (97)

⇒ **WNM'**$_t$-*difference* = `Nav_Mod.subtract(`**WNM'**$_t$-*best_match* , **TempMap**$_t$`)` (98)

(($action_{t-1} \neq$ "move*" or $\mathbf{WPR}_{t-1}$ = ["analogical*"]) and $\mathbf{WPR}_{t-1} \neq$ ["discard*"] and $\mathbf{WPR}_{t-1} \neq$ ["feedback*"]),

⇒ **WNM'**$_t$-*analogical* = `Nav_Mod.retrieve_and_add_vector_assocn()` (99)


Input Sensory
Vectors
Association
Modules
Object
Segmentation
Gateway Module
1
WNM'
2
3
Causal
Memory
Module

($ACTION_T \neq$ "MOVE*" AND $\mathbf{WPR}_T \neq$ ["DISCARD*"]) OR $\mathbf{WPR}_T =$ ["FEEDBACK*"],

⇒`Nav_Mod.feedback_to_assocn_mod(`**WNM'**$_t$-*original*`)` (95)

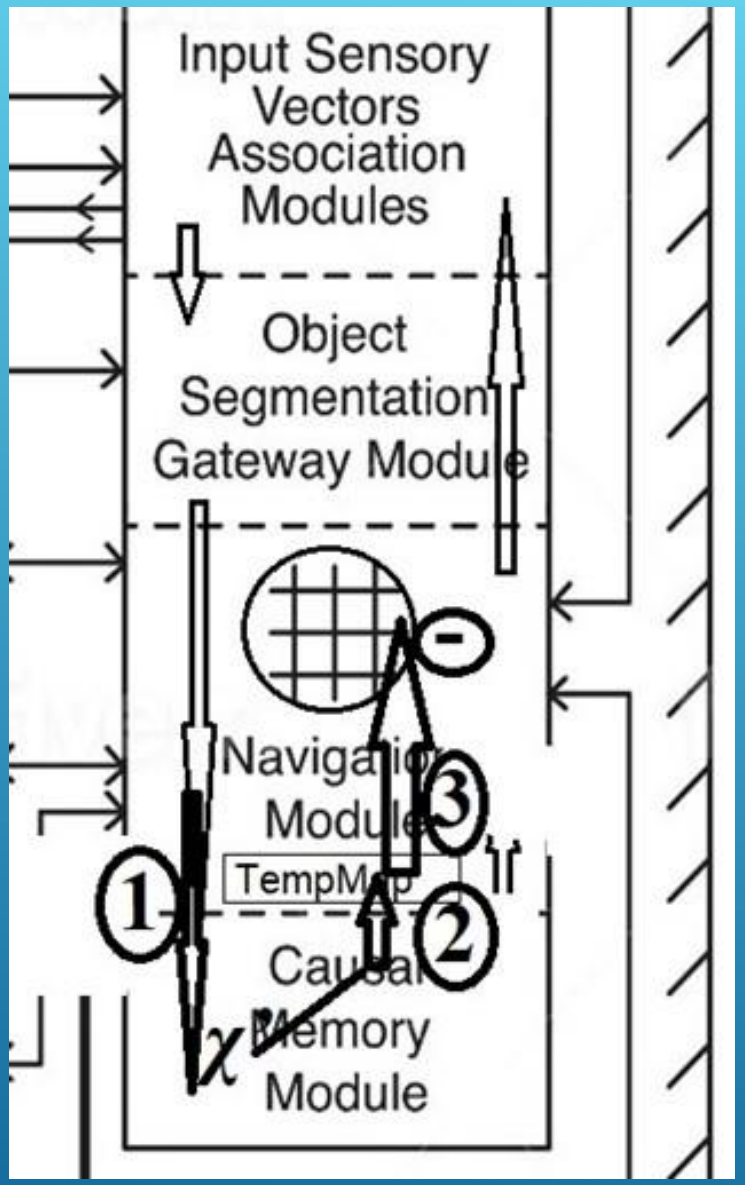
⇒ **WNM'**$_t$-*best_match* = `Causal_Mem_Mod.match_best_map(`**WNM'**$_t$-*original*`)` (96)

⇒ **TempMap**$_t$ = `Nav_Mod.use_linkaddress1_map(`**WNM'**$_t$-*best_match*`)` (97) #1, #2

⇒ **WNM'**$_t$-*difference* = `Nav_Mod.subtract(`**WNM'**$_t$-*best_match* , **TempMap**$_t$`)` (98) #3

(($action_{t-1} \neq$ "move*" or $\mathbf{WPR}_{t-1}$ = ["analogical*"]) and $\mathbf{WPR}_{t-1} \neq$ ["discard*"] and $\mathbf{WPR}_{t-1} \neq$ ["feedback*"]),

⇒ **WNM'**$_t$-*analogical* = `Nav_Mod.retrieve_and_add_vector_assocn()` (99)



Paper 14 Schneider An Analogical Inductive Solution to the Grounding Problem

($ACTION_T \neq$ "MOVE*" AND $\mathbf{WPR}_T \neq$ ["DISCARD*"]) OR $\mathbf{WPR}_T =$ ["FEEDBACK*"],

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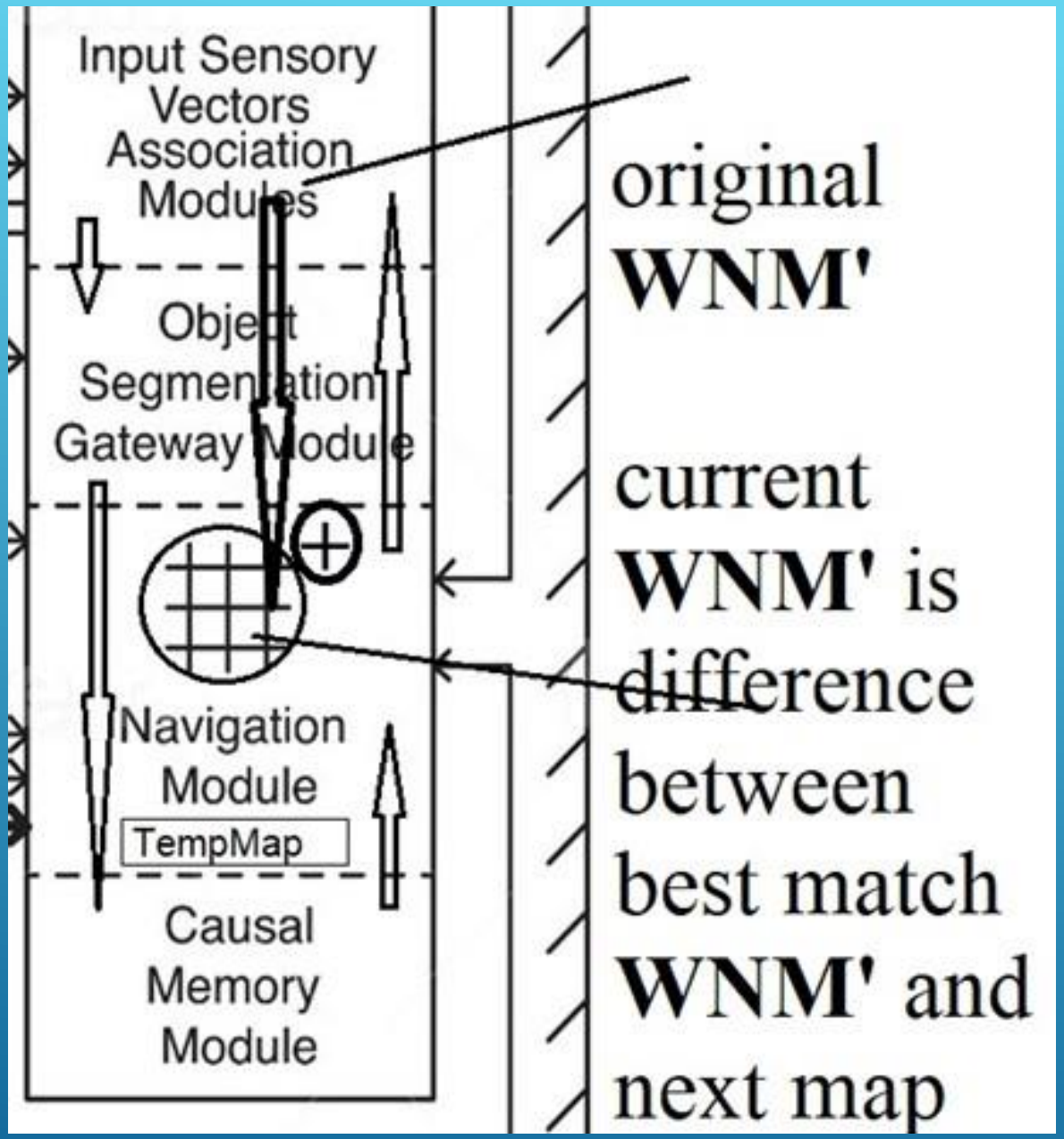
(($action_{t-1} \neq$ "move*" or $\mathbf{WPR}_{t-1}$ = ["analogical*"]) and $\mathbf{WPR}_{t-1} \neq$ ["discard*"] and $\mathbf{WPR}_{t-1} \neq$ ["feedback*"]),

⇒ **WNM'**$_t$-*analogical* = `Nav_Mod.retrieve_and_add_vector_assocn()` (99)



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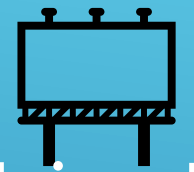
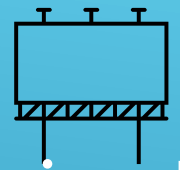
Induction by Analogy Has Occurred



Object **x**



Object **y**

A_1x, A_2x, A_3x…. A_nx

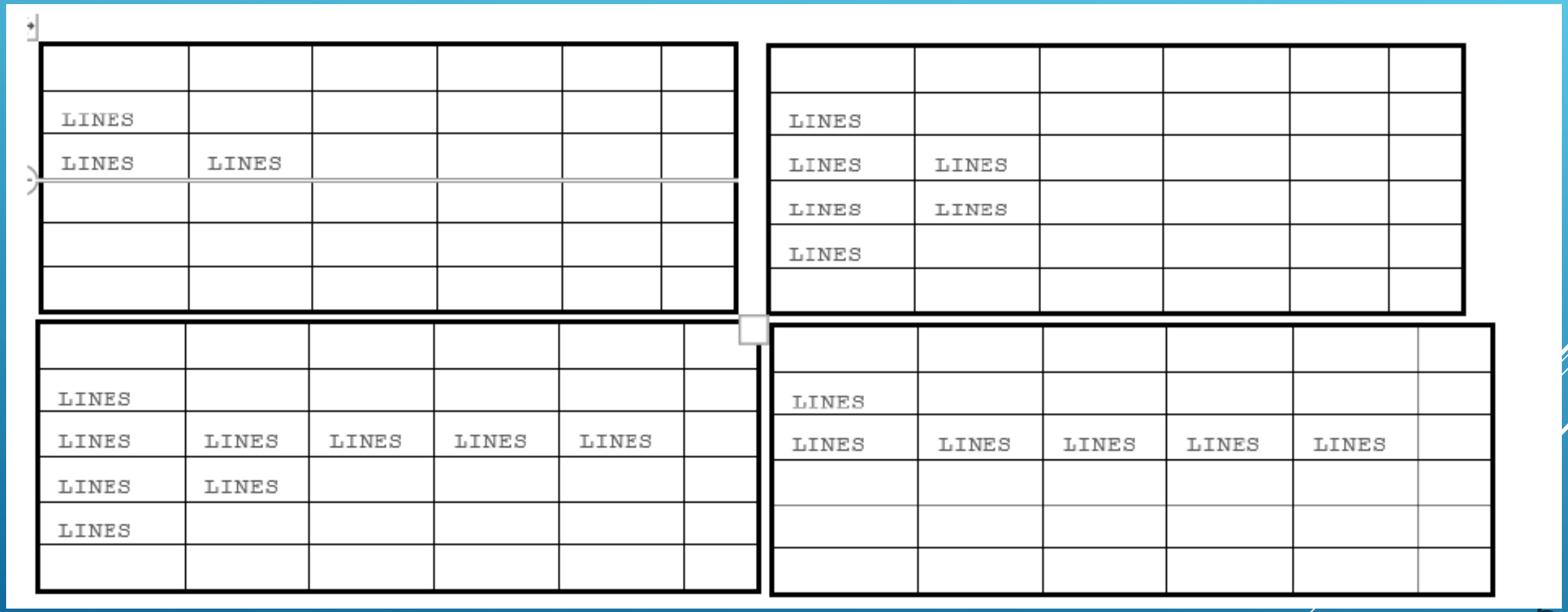
A_1y, A_2y, A_3y….A_ny

By ← Object **y** has property B

∴ Bx

Objects **x** and **y** have properties A_1…A_n in common

Thus, likely that object **x** also has property B



(Figure 2 simplified from Chollet's Abstraction and Reasoning Corpus)

Input sensory data is now in the Working Navigation Map (WNM). What action next?

LINES					
LINES	LINES				

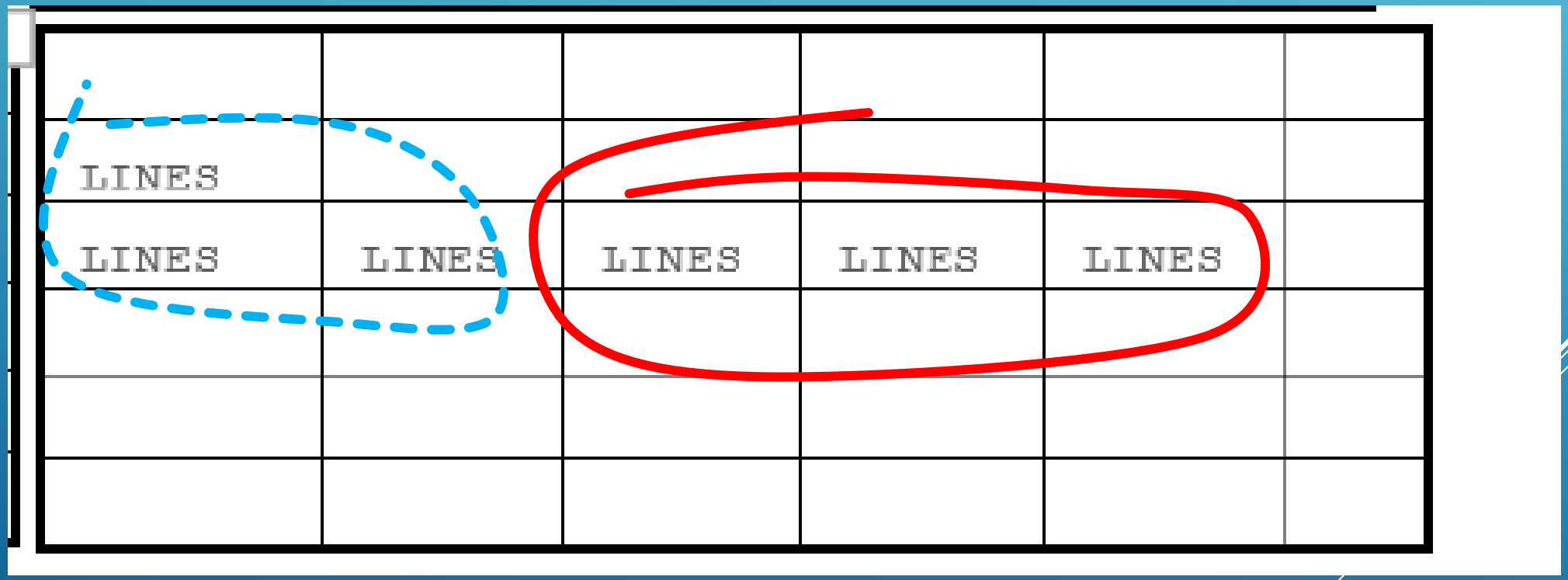
Best matching navigation map from Causal Memory Module now becomes the new Working Navigation Map (WNM) (and feed back the old map)

LINES					
LINES	LINES				
LINES	LINES				
LINES					

Links from that Working Navigation Map go to this Navigation Map – this is what occurred next in the past

LINES					
LINES	LINES	LINES	LINES	LINES	
LINES	LINES				
LINES					

Retrieve the original Working Navigation Map (which occurs automatically in the next cognitive cycle) and apply the difference to it. Results in new Working Navigation Map.



Is solid1008 a solid for pathfinding instinctive primitive?
Link {1008} -- can recognize object in scene as solid{1008} and knows it is thin sheets
No other grounding

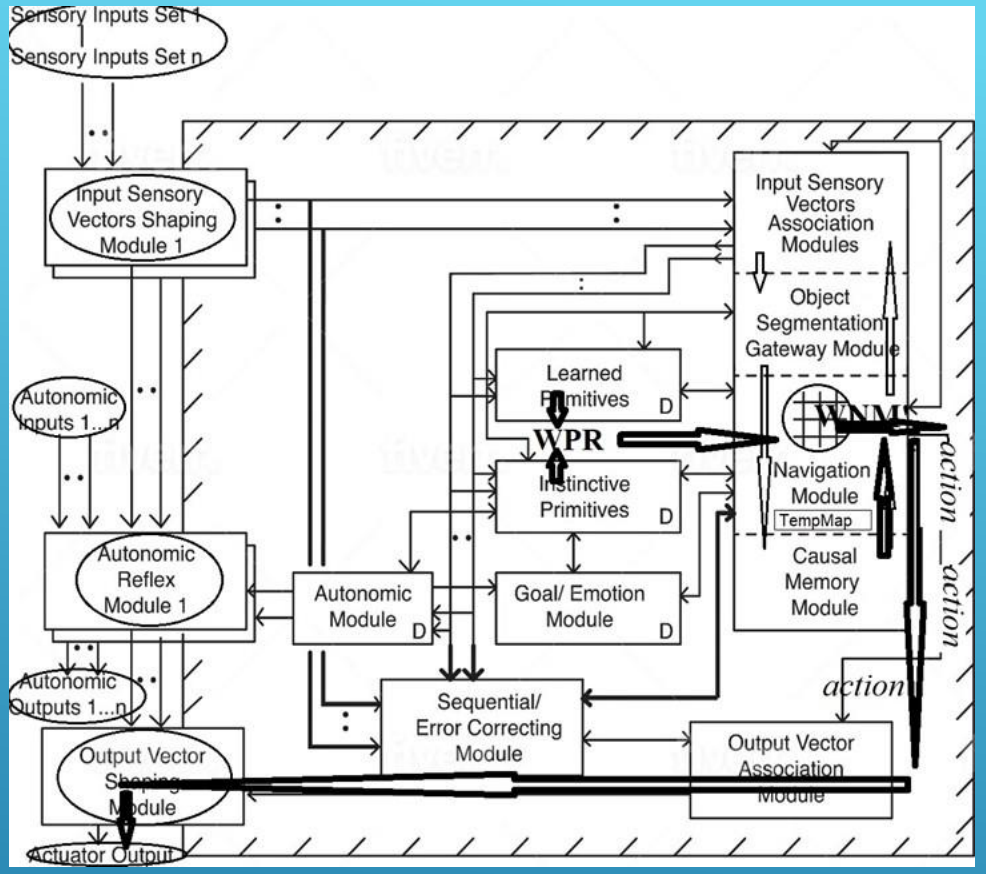
-Matches to NavMap about thin sheets it stepped on deep puddle and got legs wet

-Equation (98) WNM_difference is legs wet
-Equation (99) WNM_analogical becomes solid{1008} and legs wet

-This becomes next WNM' processed by the Navigation Module
-Instinctive primitive running considers solid{1008} as water, not solid, for transformation of NavMap

air	air	air	air
solid	water	water	water
solid	water	water	water
solid	water	water	water
solid	water	water	water
water	water	water	water

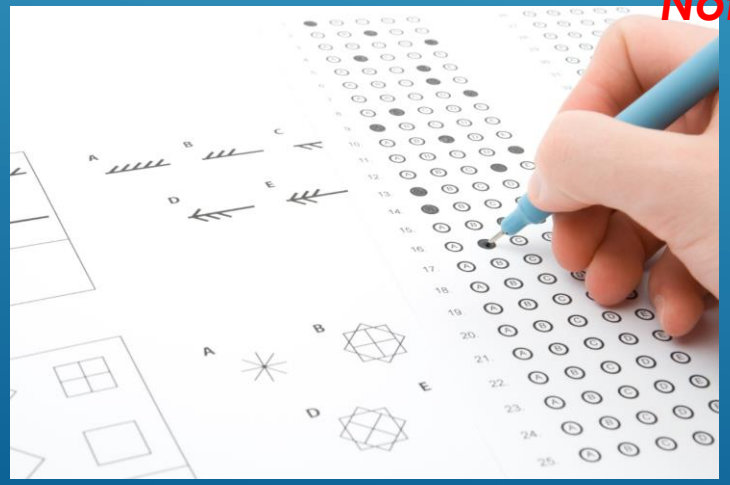
NOT SOLID FOR PATHFINDING PRIMITIVE



PATHFINDING INSTINCTIVE PRIMITIVE RESULTS IN SWITCH DIRECTION, DO NOT CROSS

Paper 14 Schneider An Analogical Inductive Solution to the Grounding Problem

- Analogical inductive abilities are a core mechanism now of the architecture.
- Not a special algorithm it calls.
- A core, ubiquitous mechanism of the architecture.



Not a module for IQ tests

Symbol grounding via Inductive Analogical Feedback Mechanism

grounded_feature = $\forall_{\text{feature}}$: (feature $\in$ ***all_LNMs***$_{\chi}$ AND feature $\in$ ***s***(t))

OR

$\forall_{\text{feature}}$: (feature $\in$ **WNM'**$_t$ AND (*action*$_{t-1} \neq$ "move*" or **WPR**$_{t-1}$ = ["analogical*"])) (104)

$\forall_{\chi,t}$: ***all_navmaps***$_{\chi,t}$ = grounded_feature OR `link`(***all_navmaps***$_{\chi,t}$) $\neq$ [ ] OR ***all_navmaps***$_{\chi,t}$ = [ ] (105)

LANGUAGE & GROUNDING IN THE CCA5 ARCHITECTURE

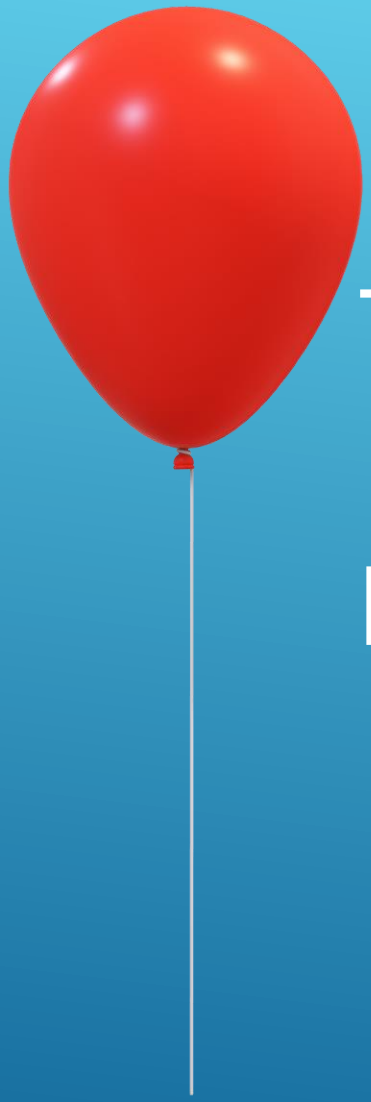
$action_t$= `Nav_Mod.apply_primitive_nav_to_protolang` **(WPR$_t$, WNM'$_t$)** (106)

-simple nouns and verbs to describe a history of Working Navigation Maps which occurred

-same mathematics applies – grounding occurs

AN ANALOGICAL INDUCTIVE SOLUTION TO THE GROUNDING PROBLEM

- Symbol grounding is an engineering issue.
- Symbol grounding results in better problem-solving performance.



Thank you

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