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# The Universal Theory Model of Concepts and the Dissolution of the Puzzle of Concept Acquisition

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## Abstract

I present a Universal Theory Model of Concepts (UTMC) that helps dissolve a well-known Puzzle of Concept Acquisition: how can a person ever acquire a “new” concept? The key state variables of the UTMC are illustrated in an microgenesis experiment where adult subjects attempt to learn the meaning of 3 new verbs in a “Causal Blocksworld” computer application. The puzzle is dissolved by recognizing the 2 viewpoints that one can take on the UTMC.

## The Microgenesis of New Concepts

In this paper I help dissolve a long-standing dispute between the nativist Jerry Fodor and the developmentalist concerning a fundamental Puzzle of Concept Acquisition: (Fodor 1975, Laurence and Margolis 2002)

*How can a person acquire a genuinely new concept?*

I dissolve the puzzle by describing an experiment concerning the microgenesis of a set of “new” concepts that adults acquire in a single experimental setting. To make sense of the microgenesis (or lack thereof), a new model of concepts is required. I call it the *Universal Theory Model of Concepts* (UTMC). I believe this model is latent in the dispute, and that it is possible to lay the dispute to rest by showing that the source of the dispute is due to the choice of viewpoint enabled in this model.

In this experiment, subjects try to discover the 3 *laws* that govern the behavior of 29 blocks within a computer application called “Causal Blocksworld”. Ten adult subjects participated in this experiment. Unknown to the subjects at the beginning of the experiment, there are four kinds of blocks: As, Bs, Cs and Ds. All four kinds of blocks are perceptually indistinguishable except an alphabetic label; for each of the 4 kinds, a block is the kind of block it is because of what it can activate, and what can activate it. Three laws govern block activation:

- **lawab:** When an block of kind A touches a block of kind B, the B block lights up
- **lawc:** When a block of kind C block touches another block of kind C, the one with a lower “power”  $\alpha$  will light up, where each C block’s power  $\alpha$  is unchangeable.
- **lawd:** When a block of kind D touches another block of kind D, one of them will light up (or not), consistently, across different activations.

29 blocks are introduced to the subject in a staging area in 5 phases (9 in phase 1 and then 5 for each phase thereafter). Subjects engage in free-form play with the objects to discover the above laws, and end up organizing the blocks spatially into clusters, shown in Figure 1(a) for 3 kinds of subjects.

Moreover, subjects are also given cues to the meaning of 3 new verbs – *gorp*, *pilk*, and *seb* in a Word Cue area (see Figure 1(a)) for a subset (one-third) of the blocks:

- **lawab:** When an A block labeled  $x$  activates a B block labeled  $y$ , subjects are shown “ $x$  is gorp $ing$   $y$ ”
- **lawc:** When a C block labeled  $x$  activates a C block labeled  $y$ , subjects are shown “ $x$  is pilk $ing$   $y$ ”
- **lawd:** When a D block labeled  $x$  activates a D block labeled  $y$ , subjects are shown “ $x$  is seb $ing$   $y$ ”

In each of the 5 phases, subjects are asked questions to test whether they have learned the meaning of the 3 verbs. I tested them with two methods: getting their plain text definitions of the 3 verbs and giving them a forced-choice naming condition test for each of the 3 verbs. Plain text definitions were requested in the following way. At the end of phase 1 and at the end of phase 5, subjects are asked 1 question of each of the 3 verbs within the application: “What do you think (*gorp/pilk/seb*) means?” and type in plain text responses. After phase 1, subjects uniformly give responses that do not indicate knowledge of more than one kind, saying e.g. “... it means an object lights up another object” or more often “no idea”. But after phase 5, *some* subjects, but not all, differentiate between the 4 kinds of blocks:

- “gorp means to light up one of the group OUYVI”
- “seb means for one of the object group in RFIDR-PEM to light up another of the same group.”

Naming conditions were tested in the following way. After every phase, subjects are required to touch one block (labeled  $x$ ) to another (labeled  $y$ ), where one of the blocks lights up. No Word Cue is given. Instead, subjects answer a naming condition question, by choosing which of 6 descriptions best describe what happened:

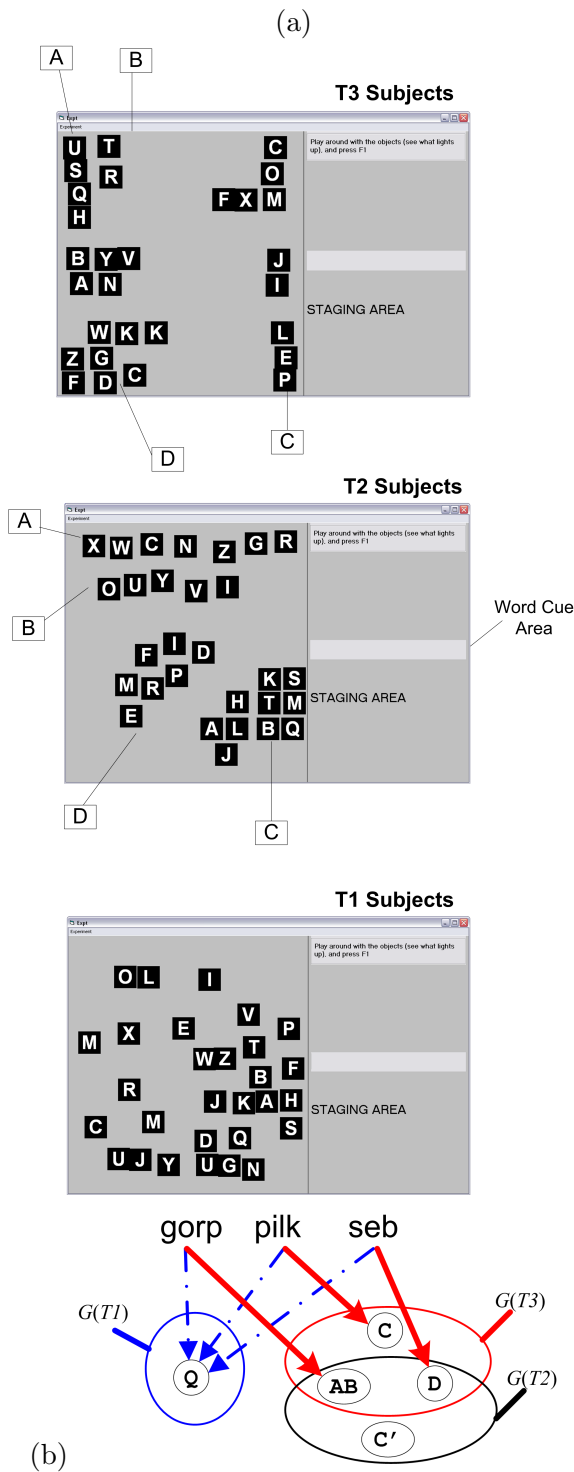


Figure 1: (a) Subjects try to learn the laws and word meanings in a “Causal Blocksworld” computer application by dragging and dropping blocks onto each other. Cues to the meaning of 3 verbs (*gorp*, *pilk* and *seb*) are given in a Word Cue Area (middle). Shown is how T3 Subjects, T2 Subjects and T1 Subjects clustered the blocks; the clusters for the kinds A, B, C and D (boxed) are clear for T3 Subjects and T2 Subjects; (b) When  $T^* = T1$ , all 3 verbs can only be mapped to a single concept in  $G(T1) = \{Q\}$  (dashed arrows); When  $T^* = T3$ , *gorp*, *pilk* and *seb* can be mapped to 3 new concepts AB, C and D in  $G(T3)$  (solid arrows). Also shown is  $G(T2)$ , which overlaps with  $G(T3)$  in concepts AB and D.

- (1)  $x$  gorped  $y$
- (2)  $x$  pilked  $y$
- (3)  $x$  sebbed  $y$
- (4)  $y$  gorped  $x$
- (5)  $y$  pilked  $x$
- (6)  $y$  sebbed  $x$

The combination of the 2 measurements give a coarse view into the concept underlying each verb.

Subjects arrive at three qualitatively different kinds of states (Figure 1a), which I clustered into “T3 subjects” (only 1 subject), “T2 subjects” (2 subjects) and “T1 subjects” (7 subjects) based on the snapshot of their Causal Blocksworld clustering at the end of the experiment:

- The one *T3 Subject* discovered the full structure, organizing the blocks into 4 kinds. Blocks of kind C were organized in a vertical line such that each block would activate all the blocks below it. This subject scored perfectly in the last 2 phases and described *pilk* with “...having a stronger block in one group light up a block in the same group which is weaker than it.”
- *T2 Subjects* discovered that there were 4 kinds, but did not discover that the C blocks had an internal attribute  $\alpha$ . This is also evident by their description of *pilk* being just like *seb* at the end of phase 5. Responses to the naming condition question in the last 2 phases of the experiment were well above chance, however.
- *T1 Subjects* did not discover that there were several kinds of blocks. At the end of the experiment, for each of the 3 verbs their descriptions were similar, e.g. “...it means a block is causing another block to light up”, and their performance on the naming condition questions in the last 2 phases were near chance.

The 3 kinds of subjects internalized a different theory  $T^*$  of how the blocks work – the system of kinds, attributes, relations and laws. Since most subjects (7 of 10) were T1 subjects, I had each undergo an intervention intended for them to undergo “conceptual change”: The intervention was the experiment of Tenenbaum and Niyogi (2003), where 18 blocks (9 of kind A and 9 of kind B) are introduced in 3s; subjects are required to make predictions about when blocks light each up, before and after a critical observation that is sufficient to determine a block’s kind. All 7 subjects, by the end of this intervention, learn that there are two kinds of blocks, A and Bs. I then asked all 7 subjects to repeat the original experiment. The intervention worked: All 7 subjects organized the blocks like Figure 1(b) and their performance on the naming condition questions in the last two phases was well above chance. Thus 7 “T1 subjects” became “T2 subjects”.

In what follows, I will show how the Puzzle of Concept Acquisition can be understood by illustrating  $T^*$  and the lexicon for each of the 3 kinds of subjects using the UTMTC.

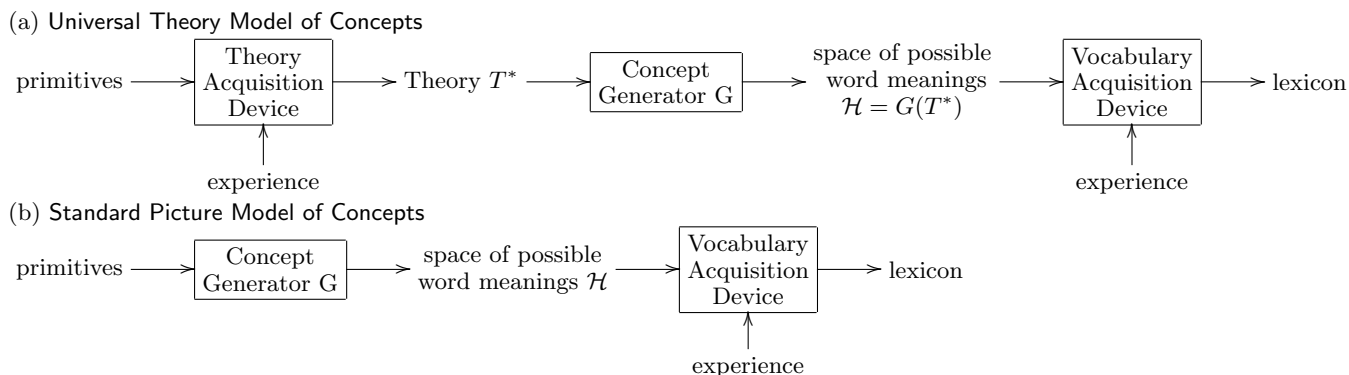


Figure 2: (a) The Universal Theory Model of Concepts: from one viewpoint, a learner can get a “new” concept in  $\mathcal{H}$  with a change in TAD state  $T^*$ ; (b) The Standard Picture Model of Concepts: a learner can never get a “new” concept in  $\mathcal{H}$ .

## The Universal Theory Model of Concepts

This microgenesis study simulates in 30 to 60 minutes essential aspects of *theory change* that takes years in child development (c.f. Carey 1985, Keil 1989) and mirrors similar efforts to induce conceptual change in science education (c.f. Chi et al 1994). Subjects in Causal Blocksworld can be understood to change state from theory  $T1$  to  $T2$  or  $T3$ :

- $T1$ : there is just 1 kind of block, with 1 law  $\text{law}_q$  governing that kind - every block can potentially activate any block
- $T2$ : there are 4 kinds of blocks, with 3 laws:  $\text{law}_{ab}$  (As activate Bs),  $\text{law}_{c'}$  (Cs activate each other) and  $\text{law}_d$  (Ds activate each other)
- $T3$ : there are 4 kinds of blocks, with 3 laws:  $\text{law}_{ab}$  (same as in  $T2$ ),  $\text{law}_c$  (Cs will activate Cs with lower  $\alpha$ ),  $\text{law}_d$  (same as in  $T2$ )

Critically, there is a mapping from a theory ( $T1$  or  $T2$  or  $T3$ ) to a set of lexicalizable concepts that form possible hypotheses for the meanings of the novel verbs *gorp*, *pilk* and *seb*. With  $T1$ ,  $\text{law}_q$  cannot differentiate between the 3 verbs. With the 3 laws in  $T2$  and  $T3$ , however, new concepts become accessible that were not available with  $T1$ .

A *Universal Theory Model of Concepts*, diagrammed in Figure 2(a), shows the minimal model that captures the above phenomena:

- A *Theory Acquisition Device* (TAD) outputs a state  $T^*$  that describes a learner’s naive theory (e.g.  $T1$  or  $T2$ );
- A *Concept Generator*  $G$  maps  $T^*$  to a set of lexicalizable concepts  $G(T^*)$ . The simplest model for  $G$  is one where each law generates one verb concept. Since  $T1$  has only 1 law while  $T2$  has 3,  $G(T1) = \{Q\}$  contains only 1 possible verb concept while  $G(T2) = \{AB, C', D\}$  contains 3.

- A *Vocabulary Acquisition Device* (VAD) uses  $G(T^*)$  to learn a lexicon. Figure 1(d) shows the changing mapping of the 3 verbs for subjects who move from  $T1$  to  $T2$  or  $T3$ . Critically, in the UTMC, subjects cannot learn to distinguish the 3 verbs until  $T^* = T2$  or  $T^* = T3$ , when 3 “new” concepts emerge in  $G(T^*)$ .

$T^*$  generates the possible internal states the learner’s mind may have of a set of observable and unobservable variables in various domains; it is an explicit representation that attempts to explain the law-like regularities of kinds, attributes, relations, part-whole structures, and laws hypothetical and in the world. The TAD has an initial state  $T^*(t = 0)$ , and a set of possible states it may assume. The theory of the initial state of TAD, I will call Universal Theory (UT), analogous to Universal Grammar (Chomsky 1981). Universal Theory constrains the set of possible states that the TAD can be in.

The Puzzle of Concept Acquisition can be dissolved by understanding that there are two viewpoints we can take:

- *Viewpoint 1: Nativist.* The hypothesis space of possible word meanings is exhausted by the union of  $G(T_i)$  for all possible  $T_i$  that may be output by the TAD. This position completely abstracts away the state of the TAD, to reach the conclusion that the set of lexicalizable concepts *cannot* change.
- *Viewpoint 2: Developmentalist.* The hypothesis space of possible word meanings is exhausted by  $G(T^*)$  for just the current state  $T^*$ . The position does not abstract away the TAD state so as to reach the conclusion that the set of lexicalizable concepts *can* change.

Viewpoint 1 is appropriate when concerned about the set of concepts reachable by the *species*; Viewpoint 2 is appropriate when concerned about the set of concepts reachable by the *individual* at specific moment in time.

The Universal Theory Model of Concepts should be compared the Standard Picture Model of Concepts, shown in Figure 2(b). The Standard Picture of the set of hypothesizable word meanings  $\mathcal{H}$  is that they are spanned by a fixed set of primitives. This Standard Picture model underlies much work in lexical semantics (Jackendoff 1983, Pinker 1989) and much work in computational models of vocabulary acquisition (c.f. Siskind 1996, Niyogi 2002, Regier, in press). Once the set of primitives are known, the consequences are grim, as Fodor (1975) points out: the hypothesis space of possible word meanings is fully determined, and it is a *logical impossibility* for  $\mathcal{H}$  to change, thus the Puzzle. Rather than assume  $\mathcal{H}$  is spanned by a *fixed* set of primitives, in the UTMC, a *changable* TAD state  $T^*$  generates a *changable* hypothesis space of possible word meanings  $\mathcal{H} = G(T^*)$  (c.f. Niyogi 2002). The primitives in the UTMC concern *theories* and *not* the lexicon.

### A Candidate Illustration of UT

The key state variables ( $T^*$  and  $G(T^*)$ ) can be fully illustrated in the simplest UT needed to model the 3 kinds of Causal Blocksworld subjects. Quantitative and qualitative relationships between kinds, parts, attributes, relations, and laws that interrelate them appear necessary in any metalanguage for theories. These sets of theoretical entities can be conceived as analogous to a grammar; a grammar models a set of sentences while a theory models a set of observations. Taking the well known context-free grammar's sets of grammatical categories as a model, we could hope to model these sets in the same way:

- a set  $\mathcal{S}$  of  $n_S$  spaces  $S_1, \dots, S_{n_S}$  – we give a few examples below
- a set  $\mathcal{K}$  of  $n_K$  kinds  $K_1, \dots, K_{n_K}$
- a set  $\mathcal{A}$  of  $n_A$  attributes, each element a map  $k \xrightarrow{a} s$  from an element  $k$  in  $\mathcal{K}$  to an element  $s$  in  $\mathcal{S}$
- a set  $\mathcal{R}$  of  $n_R$  relations, each element a map  $k_i \times k_j \xrightarrow{r} s$  from two elements  $k_i, k_j$  in  $\mathcal{K}$  to an element  $s$  in  $\mathcal{S}$
- a set  $\mathcal{L}$  of  $n_L$  laws (described below)
- a set  $\mathcal{O}$  of  $n_O$  kind relations, each element a map  $k_i \rightarrow k_j$  representing an inclusion relation from  $k_i$  in  $\mathcal{K}$  to  $k_j$  in  $\mathcal{K}$
- a set  $\mathcal{P}$  of  $n_P$  part relations (not pursued here)

This is just one possibility and not intended to be a comprehensive model of UT. The specific elements of  $\mathcal{S}$  may include a handful of general purpose spaces, such as **boolean** (2 points), **r** (an infinite set of ordered continuous points), and **r0** (same but one point is minimum). In addition, we may consider that any two elements  $x$  and  $y$  of  $\mathcal{S}$  may have their

*cross product*  $x \times y$  also in  $\mathcal{S}$ , thus making  $\mathcal{S}$  infinite. The set of elements in  $\mathcal{S}$  form the possible ranges for attributes  $\mathcal{A}$  and relations  $\mathcal{R}$ .

I illustrate a set of TAD states modeling the T1 Subjects, T2 Subjects and T3 Subjects TAD state  $T^*$ . We first start with purely “sensory” theory T0:

$\mathcal{K}_0$	=	{BLOCK}	<b>Theory T0</b>
$\mathcal{A}_0$	=	{BLOCK $\xrightarrow{\text{lit}}$ boolean, BLOCK $\xrightarrow{\text{position}}$ $r \times r$ }	
$\mathcal{R}_0$	=	{BLOCK $\times$ BLOCK $\xrightarrow{\text{contact}}$ boolean}	
$\mathcal{L}_0$	=	{}, $\mathcal{O}_0 = \{\}$	

The above is a technical way of encoding that there is one kind **BLOCK**. *Every* individual of that kind has a **lit** attribute (mapped to **true** or **false**), and a **position** attribute (mapped to a point in 2-d space). Moreover, for *every* two blocks, there is a **contact**( $x, y$ ) relation (also mapped to **true** or **false**). However, T0 has no model of how the blocks interact with one another.

T1 Subjects have a slightly richer TAD state. This state includes an arbitrary **activates** relation between any two blocks, governing whether one block will activate another:

$\mathcal{K}_1$	=	$\mathcal{K}_0$	<b>Theory T1</b>
$\mathcal{A}_1$	=	$\mathcal{A}_0$	
$\mathcal{R}_1$	=	$\mathcal{R}_0 \cup \{\text{BLOCK} \times \text{BLOCK} \xrightarrow{\text{activates}}$ boolean}	
$\mathcal{L}_1$	=	$\mathcal{L}_0 \cup \{\text{lawq}\}$ , $\mathcal{O}_1 = \mathcal{O}_0$	

A law **lawq** in  $\mathcal{L}$  specifies that if **activates**( $x_2, x_1$ ) is true between two blocks, then when all enabling conditions in  $\gamma = \{\text{contact}(x_2, x_1)\}$  are true, then **lit**( $x_1$ ) is mapped to **true** (**B<sub>1</sub>**). This is schematized in (a), following the general format of (b):

(a) Specific law <b>lawq</b>	(b) General format
<b>activates</b> ( $x_2 : \text{BLOCK}, x_1 : \text{BLOCK}$ )	<b>causeattr</b> ( $x_j : k_j, \dots$ )
$\downarrow_{\text{B}_1, \gamma = \{\text{contact}(x_1, x_2)\}}$	$\downarrow_{\text{possiblepath}, \gamma}$
<b>lit</b> ( $x_i : \text{BLOCK}$ )	<b>effectattr</b> ( $x_i : k_i, \dots$ )

where there is some **causeattr** attribute (or relation) that is a *potential* “force” for the **effectattr** attribute (or relation) to be driven to the path **possiblepath** – if there is only one force acting, then the **effectattr** will be driven along the specified path. This model is derived from Talmy (1988)’s force dynamic models, but related ideas are found in diSessa (1993). We assume there is a generative model to map elements of  $\mathcal{S}$  into a set of natural **possiblepath** – for **boolean**, simple possible paths are exhausted in part by **B<sub>+</sub>** (onset), **B<sub>-</sub>** (offset), **B<sub>1</sub>** (on), and **B<sub>0</sub>** (off); for **r** there is at least **M<sub>+</sub>** (positive), **M<sub>0</sub>** (no change), **M<sub>-</sub>** (negative); for **r0**, the previous list would be extended to include paths that has the “special point” 0 – e.g **M<sub>-0</sub>** (down to 0), **M<sub>0+</sub>** (up from 0), and so on. By “natural” we mean a possible element of  $T^*$ . Much qualitative reasoning work explores this (Forbus 1984), although UT requires a full delimitation on the set of possible causal laws.



Critically, these word-concept mappings cannot be made unless the learner has  $T2$  or  $T3$ . Until the TAD changes state to  $T2$ , the elements  $AB$  and  $C'$  are not available for the VAD. Until the TAD changes state to  $T3$ , the element  $C$  is not available to the VAD. A teacher who says “ $X$  is pilking  $Z$ ” may have *pilk* mapped to  $C$  in its VAD but the learner’s VAD at  $T2$  or  $T1$  would only have the concept  $Q$  or  $C'$ . A UT model of concepts renders the incommensurability between their concepts of *pilk* fully transparent.

### TAD Mechanisms

The UT model of concepts factorizes the subjects learning problem into *two* coupled induction problems: (1) TAD: Acquire a theory  $T^*$  using the UT theory primitives; (2) VAD: Acquire a lexicon using  $G(T^*)$ . Many proposals for TAD mechanisms are available – ranging from connectionist models and Bayesian causal networks (Rogers and McClelland 2004, Tenenbaum and Niyogi 2003) to analogical encoding and abduction of plausible hypotheses in scientific discovery and vocabulary cues themselves (Gentner 2004; Klahr and Simon 1999). Failures to parse a surface observation using  $T^*$  may be cause for revision, to name another. Subject variability indicates that a model of theory acquisition that mechanically computes  $T^*$  (or  $p(T^*|...)$ ) given data of a particular form is not a plausible account of the TAD.

In these experiments, subject’s conscious abduction processes appear to be primary drivers of theory acquisition. I informally asked the 7  $T1$  subjects to “think aloud” on their second run. Hypotheses verbalized included the alphabetic ordering of the blocks, how they overlapped, which block was being dragged, and the position of the area on the screen. Two subjects used social analogies in their descriptions of how the blocks worked: “ $X$  likes  $Y$ ”, “ $JU$  and  $L$  fight with  $MQ$  and  $J$ ”. What causes these abductive inferences and analogies? There is no comprehensive answer to these questions, nor should any simple comprehensive model of TAD mechanisms be expected.

### The Dissolution of the Puzzle

Good puzzles in cognitive science reveal deep-rooted theoretical problems. The Puzzle of Concept Acquisition reveals that the Standard Picture Model of Concepts cannot explain concept acquisition. The Universal Theory of Concepts *can* explain concept acquisition. It can dissolve the Puzzle because two distinct viewpoints can be taken on the set of lexicalizable concepts:

- Viewpoint 1 *abstracts away* the TAD state, yielding a *species-wide* conclusion that concept acquisition is an impossibility; a subject whose TAD state is stuck in  $T1$  still “has” access to concepts in  $G(T2), G(T3), \dots$  because it is *possible* for the TAD to change state to  $T2, T3, \dots$

- Viewpoint 2 *recognizes* the TAD state, and yields the conclusion that concept acquisition is in fact a possibility through a TAD state change; a person whose TAD state is in  $T1$  “has” *only* the concepts  $G(T1)$ , and no others.

Questions concerning species-wide universals (what is a possible TAD state  $T^*$ ? what is a possible element of  $G(T^*)$ ?) appear to require Viewpoint 1, while questions concerning temporal processes and trajectories of theory acquisition and vocabulary acquisition require Viewpoint 2. Understanding dispute is facilitated with the Universal Theory Model of Concepts, the key state variables of which are concretely explicated here in Causal Blocksworld. Fodor (1975), who says “there literally isn’t such a thing as the notion of learning a conceptual system richer than the one that one already has” would appear to be taking viewpoint 1, while the developmentalist such as Carey (1991) who says “ $T1$  and the descendent  $T2$  are incommensurable insofar as the beliefs of one cannot be formulated over the concepts over the other” would appear to be taking viewpoint 2. Once the Universal Theory Model of Concepts is taken into account, the gap between the two viewpoints can be reconciled as merely a choice of perspective.

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