SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

LEVEL I

(12)

(14) 1. REPORT NUMBER: HPP-80-9

2. GOVT ACCESSION NO.: AD-A096 510

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle): (6) RLL-1: A Representation Language Language

5. TYPE OF REPORT & PERIOD COVERED: (9) Technical Rept.

6. PERFORMING ORG. REPORT NUMBER: ---

7. AUTHOR(s): (10) Russell Greiner

8. CONTRACT OR GRANT NUMBER(s): (15) N00014-80-C-0609

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
Computer Science Department
Stanford University
Stanford, California 94305

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: --- (11)

11. CONTROLLING OFFICE NAME AND ADDRESS:
Mathematical & Information Sciences Div.
Office of Naval Research, 800 No. Quincy Street, Arlington, Va. 22217

12. REPORT DATE: October 1980

13. NUMBER OF PAGES: 43

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): (12) 43 ---

15. SECURITY CLASS. (of this report): ---

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE: ---

16. DISTRIBUTION STATEMENT (of this Report)

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

---

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Representation, Knowledge, Language, Self-Description, Self Modification, Expert Systems

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

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Stanford Heuristic Programming Project
HPP-80-9 (Working Paper)

October 1980

RLL-1:
A Representation Language Language

by

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Expanded version of the paper published in the
Proceedings of the First National Conference
of the
American Association of Artificial Intelligence
(Stanford University, August 1980)

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APPENDICES

Included in the Supplement:

RLL-1:
A Representation Language Language

The field of AI is strewn with knowledge representation languages. The language designer typically designs that language with one particular application domain in mind; as subsequent types of applications are tried, what had originally been useful features are found to be undesirable limitations, and the language is overhauled or scrapped. One remedy to this bleak cycle might be to construct a representation language whose domain is the field of representational languages itself. Toward this end, we designed and implemented RLL-1[1], a frame-based Representation Languange Language. The components of representation languages in general (such as slots and inheritance mechanisms) and of RLL-1 itself, in particular, are encoded declaratively as frames. By modifying these frames, the user can change the semantics of RLL-1's components, and significantly alter the overall character of the RLL-1 environment.

1. MOTIVATION

Often a large Artificial Intelligence project begins by designing and implementing a high-level language in which to easily and precisely specify the nuances of the task. The language designer typically builds his Representation Language around the one particular highlighted application (such as molecular biology for Units [*Stefik*], or natural language understanding for KRL [*Bobrow & Winograd*] and OWL [*Szolovits, et al.*]). For this reason, his language is often inadequate for any subsequent applications, except those which can be cast in a form similar in structure to the initial task. What had originally been useful *features* are subsequently found to be undesirable *limitations*. Consider Units' explicit copying of inherited facts or KRL's sophisticated but slow matcher.

Building a new language seems cleaner than modifying the antiquated one, so the designer scraps his "extensible, general" language after its one use. The size of the February 1980 SIGART shows how many similar yet incompatible representation schemes have followed this evolutionary path.

One remedy to this bleak cycle might be to construct a representation language whose domain is the field of representation languages itself, a system which could then be tailored to suit many specific applications. Toward this end, we (Professor Douglas Lenat and I) have designed and implemented RLL-1, an object-centered[2] Representation Languange Language.[3]

2. INTRODUCTION

A representation language language (rll) must explicitly represent the components of representation languages in general and of itself in particular. This technique of self-encoding gives the rll its flexibility and adaptability: consider the versatility inherent in the programming language LISP, which also encodes all of its constructs (i.e. programs) within its own formalisms (i.e. as S-expressions). Like all representation languages, the rll should provide an easy, natural interface to users. As such, its primitive building blocks are necessarily larger, more abstract, and more complex than the primitives of programming languages.[4]

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[1] This should be pronounced "RLL negative one" -- as we feel this implementation does not qualify as a *real* representation language language, yet. Section 6 provides the definitions necessary to realize RLL-1's *shortcomings*.

[2] This "*object-centering*" does not represent a loss in generality. We will soon see that each part of the full system, including procedural information, is reified as a unit.

[3] As a representation language language should itself be a completely self-descriptive representation language, there is no need for an RLLL.

[4] Technically, an rll is a Representation Language, that is, a "Language *about* Representation". It attempts to describe representation, in the same way a VLSI Language is designed to deal with VLSI components. To avoid confusion with earlier languages, notably KRL and FRL, which have already coined "RL" to mean "Language *for* Representation", we gave RLL-1 its second "L".

Building blocks of a representation language include such things as control regimes (ExhaustiveBackwardChaining, Agendae), methods of associating procedures with relevant knowledge (Footnotes, Demons), fundamental access functions (Put/Get, Assert/Match), automatic inference mechanisms (InheritFromEvery2ndGeneration, InheritButPermitExceptions), and even specifications of the intended semantics and epistemology of the components (ConsistencyConstraint, EmpiricalHeuristic).

The purpose of an rll is to help manage these complexities, by providing (1) an organized library of such representation language components, and (2) tools for manipulating, modifying, and combining them. Rather than produce a new representation language as the "output" of a session with the rll, it is rather the the rll system itself, reflected in the environment the user sees, which changes gradually in accord with his commands.

Rather than design his representation language from scratch, the AI researcher should be able to use an rll as the "starter" for almost any AI task -- including natural language understanding, ICAI (Intelligent Computer Aided Instruction), designing expert system, or theorem proving. The researcher's first step will be to load in his rll, and set its "parameters" to values appropriate for his domain and application. The rll will then take over, composing the desired new language from these specifications. If ever the researcher wishes to alter this language, he need only issue the appropriate command to the rll system, (using the same format he used, for example, to enter new data) and the language he sees will be modified.

This paper serves several functions, and is intended for several audiences. The first class of readers include those AI researchers who are looking for such a starter system, and are intrigued with this notion of a versatile, self-descriptive system. They should regard this document as an RLL-1 Primer, which describes the advantages and power of an rll, followed by a how-to manual describing this RLL-1 system.

A second (not necessarily distinct) group of readers are researchers interested in the epistemological and representational issues associated with designing and using a self-embedded system. This memo, therefore, includes sections which define what we mean by the term, Representation Language Language, and which show the ways our implementation, RLL-1, handles several potentially difficult problems.

We report here on the current state of both our ideas regarding rlls in general, and our RLL-1 implementation, in particular. The beginning portion, sections 1 through 4, motivates the idea of a rll, illustrating this description with examples taken from the RLL-1 language. Section 3 suggests the facilities an rll must provide, by showing what the RLL-1 user initially sees, and the ways this environment can be modified. Section 4 steps through a long example, indicative of the types of things RLL-1 can do.

This leads up to Section 5, in which a high level description of RLL-1 itself is presented. Section 6 then shows how RLL-1 fit into the class of rlls in general, by specifying a set of criteria which any rll must satisfy. These rlls are then compared with other systems, of various natures, in Section 7.

The appendices provide many of the details intentionally omitted from earlier sections. Appendices A, B and C each elaborate some earlier section of this document: A expands the example presented in Section 4, B sketches a few more examples which use RLL-1, including a coarse outline of a full application, while C demonstrates a point made in Section 5.3. Appendix D states a few of the implementation level principles we followed in designing RLL-1.

Appendices E, F and G comprise a companion paper, [*Greiner*]. These supply the details necessary to actually use this RLL-1 system. Appendix E lists many of the "core" units resident in the initial system. Appendix F describes the RLL-1 environment -- including the top level functions along with other information a novice can use when working with RLL-1. A sample dialogue is presented in Appendix G, to show in detail how to communicate with this current system.

3. OVERVIEW of RLLs
or HOW IS A REPRESENTATION LANGUAGE LIKE AN ORGAN?

When the user starts RLL-1, he finds himself in a LISP environment which contains functions which closely resemble those resident in the Units package [*Stefik*][5]. There is one major difference: whereas the facilities Units offered were essentially unalterable, RLL-1's features are designed for easy modification. If this user desires a new type of inheritance mechanism, he need only create a new Inheritance-type of unit, and initialize it with the desired set of properties. At this point, that new mode of inheritance will automatically be enabled, and usable. This can be done using the same editor and accessing functions used for entering and codifying his domain knowledge (say, VLSI design); only here the information pertains to the actual Knowledge Base system itself, as opposed to chips and diffusion layers.

The Units package has Get and Put as its fundamental storage and retrieval functions; RLL-1 also begins in that state. But there is nothing sacred about even these two "primitives". "Get" and "Put" are themselves encoded as (modifiable) units; if they are altered, the nature of accessing a slot's value will change correspondingly. In short, by issuing a small number of commands the user can radically alter the character of the RLL-1 environment, and thereby mold it to his personal preferences and to the specific needs of his application. RLL-1 is responsible for performing the necessary "truth maintenance" operations, (e.g. retroactive updates) to preserve the overall correctness of the system as a whole. As an example, RLL-1 recently "learned" how to deal with a more "representationally neutral" ([*Brachman79*]) representation, one which lacked slots altogether. It was then able to deal with Assert and Match commands *in lieu* of its native Gets and Puts; and consider propositions, rather than slots, as its most primitive "container" for information.

An rll is more like a stop organ than a piano. Each stop corresponds to a "pre-fabricated" representational part (e.g. a slot, inheritance, format, control regime, etc.), which all reside in the overall rll system. The initial rll system is simply one configuration of this organ, with certain stops "pulled out" -- *in RLL-1's case, to mimic* useful aspects of the Units package. These particular stops reflect our intuitions of what constitutes a general, powerful system. For example, some of the units initially "pulled out" (activated) define various standard inheritance regimes, such as Inherit-Along-*IS-A*-Links, which stores on Fido default information gathered from TypicalDog.

We chose to include a large assortment of common slots. There are fifteen types of slots in the initial RLL-1 system, including *ToGetValue*, *ToPutValue*, *MyToKillUnit*, and *ToAddValue*, which collectively define the accessing/updating functions. Another group of over one hundred types of slots, including *IS-A*, *SuperClass*, *BroaderHeuristics*, and *TypicalExamples*, are used to hierarchically organize the units. Over two hundred other additional types of slots are used to interrelate units in other useful, if non-hierarchical ways -- e.g. *NeighboringCountries*, *RangeOfFunction*, *SimilarHeuristics*, etc. (Each of these slots presuppose there are units representing countries, functions, range-spaces, and heuristics. We will expand on this "to every idea, a unit" motif in Section 5.5.)

The number of these slots grow daily. As new domains are explored, new concepts become realized as units. It is only natural to relate these to one another; and slots provide an obvious mechanism for describing and storing such connections. Many such domain-specific slots are used to induce (or record) an organization among these units. Examples include *FunctionalExtension* which points from a (unit representing a) function to those (units which represent) functions over a strictly larger domain; *LocatedInRegion*, which connects each geological region with the larger space in which it is located (e.g. mapping each country into a continent); or the familiar *PeckingOrder*, defined for poultry. Others serve to connect a new concept with other existing concepts -- such as *BelongsTo* or *NumberOfElements*. New slots also emerge as we refine the organizing relationships which were originally "smeared" together into just one or two kinds of slots. Consider, for example, the way *IS-A*, *TypicalExampleOf* and *SuperClass* were undifferentiated in *A-Kind-Of*; or the relationship

---

[5] RLL-1 is a frame-based system [*Minsky*], whose building blocks are called *Units* [*Stefik*], [*Bobrow & Winograd*]. In the initial RLL-1 system, each unit consists of a set of *Slots*, each with its respective value.

between *LocatedInRegion* and each of *LocatedInContinent*, *LocatedInCountry*, and *LocatedInCity*.

This bootstrapping system (the initial configuration of "organ stops,") does *not* span the scope of RLL-1's capabilities: many of its stops are initially in the dormant position. Just as a competent musician can produce a radically different sound by manipulating an organ's stops, so a sophisticated RLL-1 user can define his own representation by turning off some features and activating others. For instance, an FRL [*Roberts&Goldstein*] devotee may choose to use exclusively the kind of slot called *A-Kind-Of*, mentioned above. He may then deactivate those more specialized units (*viz. IS-A, Abstraction, TypicalExampleOf, PartOf,* etc.) from his system permanently. Another user who did not want to see his system as a hierarchy at all could simply deactivate all of these A-Kind-Of kinds of slots. He need not worry about the various immediate, and indirect, consequences of this alteration (e.g., deleting the Inherit-Along-*IS-A*-Links unit); RLL-1 will take care of them.

The alterations could be constructive as well as destructive. We saw above how *LocatedInRegion* can be expanded into more precise slots, and the more dramatic example in which the user abandoned slots altogether, replacing "Get" and "Put" units with others that acted as Assert (store proposition) and Match (retrieve proposition). As another example, a user who wanted to distinquish between proper and improper subsets could define the corresponding *ProperSubSet* and *ImproperSubSet* slots.

Any representational piece can be altered. In the examples which appear later in the paper we show how inheritance mechanisms, formats, datatypes, and the like can been changed. All such "tabs" can be manipulated; and it is by selectively pushing and pulling them the user is able to fabricate his personalized system. The versatility of this approach will be demonstrated by the ease with which the rll can be reconfigured to resemble any currently-used representation language, such as KRL, OWL and KLONE;[6] after all, an organ *can* be made to sound like a piano!

To understand RLL-1's self-encoding capability, within this organ metaphor, imagine our organ is without tabs. Instead of changing the organ's tonality by pulling out some stop, we change its tonality by playing a certain prescribed melody. This sequence of keystrokes will have two effects: in addition to outputting the expected sequence of sounds, it will also cause the organ to undergo a state change, emerging, say, a glockenspiel-simulating instrument. For example, playing the first three chords of Hindemith's *"Trauernusik"* would instruct this organ to go into its "viola-mode". In this state, the sounds it produces all have a viola-like quality. If the organist then played the (meta-)sequence corresponding to "*Greensleeves*", this organ will gradually ease into its flute-mode; and so forth.

The catch is that the melody required for the Viola-to-Flute metamorphosis is different from the sequence to go from Sackbutt-to-Flute -- i.e. the (meta-)effect of a given sequence depends on the current state (i.e. "instrumentality") of the organ. Playing the *"Trauernusik"* when the organ is not in its initial state may have no meta-effect at all; or it may, for no particular reason, switch the organ into its Oboe state. That is, the sequence which triggers a change to the organ is a function of the organ's state; so as the organ changes, so does its range of permissible alterations.

To be more precise, the organ's state follows a Markov process. Each special keystroke, by itself, may induces a minor incremental change; and it is the sum of these small effects that produces the new gestalt.

With this metaphor in mind, consider the complications of converting from slots to propositions. Initially all the facts in the knowledge base are stored as the values of slots, on various units. The first change may be to create and store the procedure for asserting some fact. Note this collection

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[6] This particular task, of actually simulating various existing representation languages, has not yet been done. It is high on our agenda of things to do. We anticipate it will require the addition of many new components (and types of components) to RLL-1, many representing decompositions of the space of knowledge representation orthogonal to the ones we now use.

of facts will still be stored as slots, as RLL-1 is still in its "Slot-Mode". As such, these proposition-related facts cannot yet be utilized. They can only be "activated" after a host of other units, (such as Match and AnyProposition, which are also not yet usable) have been created. At this point, RLL-1 is able to become truly proposition-based. The first operation involves fixing up the existing knowledge base, i.e. recoding every fact now stored as a slot as a proposition, taking pains to perform these alterations in the correct order. Only then are these proposition-units -- e.g. TypicalProposition -- actually usuable, and capable of describing themselves. RLL-1 has, at this point, eased its way into a new and different format for encoding information. The rll must have the smarts to guide the transformation, changing itself as it changes the data. It must know not only what to change, but when to perform this alteration, and be able to determine and use the ramifications of such changes as well.[7]

The initial RLL-1 system has been designed to be extremely flexible, and able to adopt readily to a new specified set of conventions. Note that this itself is just a particular convention, and is not sacred. Nothing prevents a cautious (or masochistic) user from eventually deactivating the modification facilities themselves. This would effectively lock him into the particular set of conventions then currently active.

Unlike musical organs, RLL-1 also provides each user with mechanisms for building his own stops (or even type of stops, or even mechanisms for building stops). An experienced RLL-1 user can use this system to build his own new components. Rather than building them from scratch, (e.g., from CAR, CDR, and CONS,) he can modify some existing units of RLL-1, employing other units which are themselves tools designed for just such manipulations.

The following examples may help solidify these abstract ideas:

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[7] As an intriguing research effort, RLL-1 might eventually have the "smarts" necessary to make these changes automatically. That would be like a smart organ, which knew enough to convert itself into its Lute mode whenever it started playing a Renaissance sounding piece of the appropriate harmonic range and tonality. A next step would be the ability to synthesize new sounds when appropriate, as opposed to simply retrieving some pre-existing instrumentalities. This would be like deciding a cannon boom would be appropriate for the "*1812 Overture*", based on its openning movements, and generating this new type of sound.

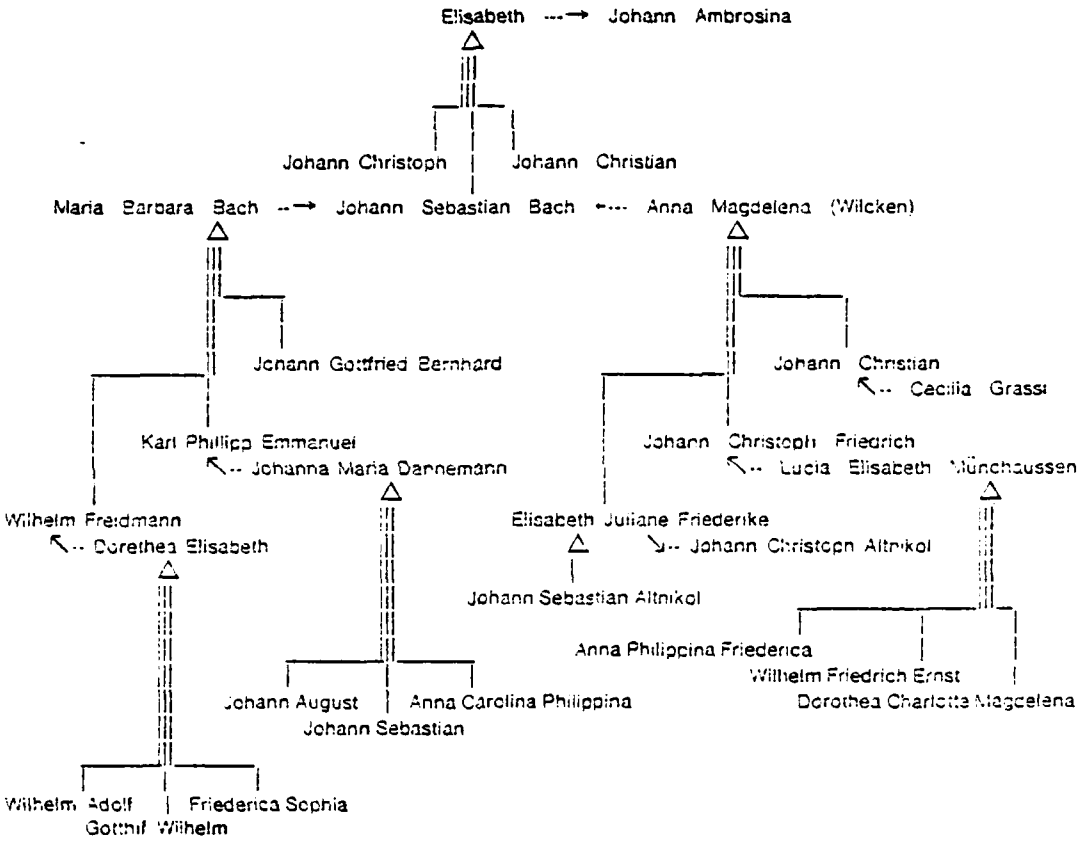

Figure # 1 - Selected members of the Bach family, with only *Mother* and *Husband* slots. △ refers to Mother Slots; the others. ←, →, ↗, ↘ all refer to Husband slots.

4. EXAMPLE - Creating & Using a Type of Slot

RLL-1 derives a considerable amount of power from one basic idea: that each component of a representation system must itself be explicitly represented. In RLL-1's case, these pieces are encoded as units, and can be examined or modified as easily as any other bit of data in the Knowledge Base. The following example illustrates this point, showing how the user can gain increasingly more control over RLL-1's actions, by exploiting his ability first to see, and then to alter the definition of a slot.

4.1. Definition of "Type of Slot"

An associative network consists of units, which are linked to one another, and to arbitrary values, by labelled arcs, called slots. Figure 1 shows an associate network whose units each represents a member of the Bach family, and whose slots are labelled either *Mother* or *Husband*. Each of these labels is, in RLL-1's vernacular, a type of slot. There are many things one can say about each type of slot. For example, the inverse of *Husband* is *Wife*; and each type of slot belongs to the class of types-of-slots. RLL-1 devotes a unit to store this information. Figure 2 shows a few such units, each of which describes a type of slot. Many of the slot-defining slots shown below are described later in this section; they are all defined in Appendix E.

a)

Name:	Husband
Description:	The male spouse of some woman.
IS-A:	(AnySlot)
ToGetValue:	DefaultGetValue
Format:	Single-Entry
Datatype:	ManType
	{I.e. the entry is a unit, representing a man.}
Inverse:	Wife
SubSlotOf:	Spouse
MakesSenseFor:	Any woman
MyTimeOfCreation:	4 July 1980, 7:23 PM
MyCreator:	DaveSmith

b)

Name:	IS-A
Description:	The list of classes to which I AM-A member.
IS-A:	(AnySlot)
Format:	List-of-Entries
Datatype:	ClassType
	{That is, each entry is a unit representing a class of objects.}
Inverse:	Examples
UsedByInheritance:	Inherit-Along-*IS-A*-Links
MakesSenseFor:	Any thing.
MyTimeOfCreation:	1 April 1979, 12:01 AM
MyCreator:	DougLenat

c)

Name:	Cost
Description:	The cost of this object.
IS-A:	(AnySlot)
Format:	Single-Entry
Datatype:	NonNegativeRealNumberType
	{I.e. the entry is a non-negative real number.}
DefinedAs:	Sum of *CostA*, *CostB*, and *CostC*.
MakesSenseFor:	Any sellable item.
MyTimeOfCreation:	24 April 1979, 5:27 AM
MyCreator:	RussGreiner

Figure # 2 - Units devoted to the "*Husband*", "*IS-A*", and "*Cost*" type of slots. Many other slots are appropriate for these units; each of their values will be deduced automatically, if requested.

4.2 Retrieving a Slot's Value (*Husband*)

Many representational systems have the view that all slots should be treated in exactly the same way. Others partition their slots (or more generally, relations) into a fixed collection of a few basic, disjoint types; and process all members of a given partition identically. As [*Brachman79*] points out, these approaches pose a major limitation, and lead to problems galore. RLL-1 is built on the basic premise that each type of slot should know how it should be handled. For convenience, RLL-1 includes a host of general algorithms, which a slot will inherit by default. These functions are all most of the slots will ever need. On the other hand, the user is not constrained to only these, as he is free to define his own procedures which dictate how to handle a particular slot. Later in this example we will see that RLL-1 provides a variety of tools to simplify this task. Given this overwriting ability, these default procedures are not at the expense of those slots which require a more complex process, or those which can utilize a less general but more efficient set of algorithms.

From this point of view, RLL-1's Knowledge Base functions (in particular, GetValue and PutValue) can be very simple: To retrieve the value of U:*S*[8], GetValue simply goes to the *S* unit -- that is, the unit devoted to storing information about the *S* type of slot -- and extracts the function stored on S:*ToGetValue*.[9] GetValue then applies this function to U and S; and returns the value that function returned. The real "smarts", notice, is distributed to the slots, not the GetValue function.

For example, we may ask who was the *Husband* of Johanna Maria Dannemann (represented by the unit JMD). The function call (GetValue 'JMD '*Husband*) would first retrieve the function stored on Husband:*ToGetValue*, and then apply that function to JMD and *Husband*. In the default case, Husband:*ToGetValue* would be DefaultGetValue. Calling DefaultGetValue on JMD looks for a value physically stored on the JMD unit, labelled *Husband*. Examining Figure 1, we see there is such a value, KPE (the unit which represents Karl Philipp Emmanuel Bach). Popping up, DefaultGetValue returns KPE to GetValue, which in turn simply returns this value.

We might imagine another form for this Knowledge Base, in which only marriage certificates are stored, instead of direct links from wife to husband. In this case, Husband:*ToGetValue* should be filled with the algorithm, FindHusbandUsingMarriageLicenses, which would scan the set of marriage certificates, looking for one whose "Wife" entry matches its first argument (here JMD). Finding such a form, FindHusbandUsingMarriageLicenses would return the value which filled the "Husband" parameter, which GetValue would then return. Note that we never wasted our time looking on the JMD unit for a slot we knew would not be there. Constructing such a definition for *Husband* is fairly easy, using the tools RLL-1 provides. The following example shows a more complicated way of finding a slot's value, using the slot's high level definition.

4.3 Creating a New Type of Slot (Father)

For obvious reasons, most slots are quite similar to one another. We exploited this regularity in developing a high level "slot-defining" language, by which a new slot can be defined precisely and succinctly in a single declarative statement.

Suppose we want to define a *Father* type of slot, in the sexist genealogical knowledge base shown in Figure 1, which contains only the primitive slots *Mother* and *Husband*. Creating this new *Father* type of slot is easy using this language: we create a new unit called Father, and fill its *HighLevelDefn* slot with the value (Composition *Husband Mother*). "Composition" is the name of a unit in our initial system, representing a "slot-combiner" which knows how to compose two slots,

---

[8] The expression, U:*S*, is a short hand for (GetValue 'U '*S*), which is, by definition, the value of the *S* slot of the unit U. The italized *S* follows our convention of italicizing the name of a slot, when it is acting *qua* slot. This is distinguished from the unitalicized S, which refers to the unit which represents the *S* type of slot.

[9] This recursive call to GetValue could easily lead to an infinite loop. Appendix A.1 shows how RLL-1 sidesteps this problem.

regarding each slot as a function from one unit to another.[10] We also fill the new unit's *IS-A* slot, to derive the unit shown in Figure 3.

Name:	Father
IS-A:	(AnySlot)
HighLevelDefn:	(Composition *Husband Mother*)

Figure # 3 - Slots filled in by hand when creating the unit devoted to the *"Father"* slot. Several other slots (e.g., the syntactic slots *MyCreator*, *MyTimeOfCreation*) are filled in automatically at this time.

Suppose the user now wishes to determine Karl Philipp Emanuel's *Father*, i.e., the value of KPE:*Father*. The initial knowledge base, shown in Figure 4, (a magnified portion of Figure 1) has units to represent various members of Bach's family.

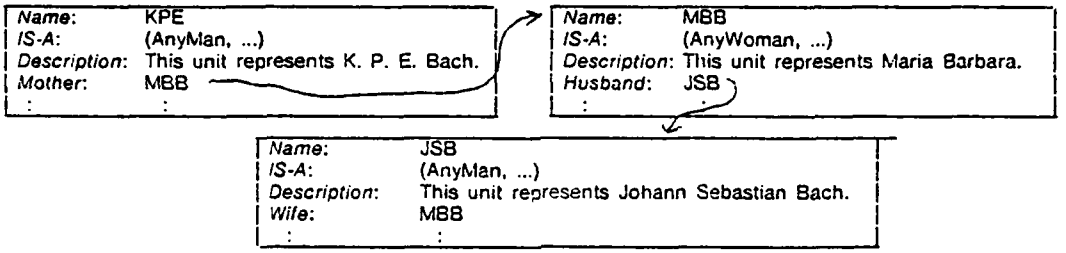

Figure # 4 - Units representing Karl Phillipp Emanuel, Maria Barbara and Johann Sebastian Bach.

In this case, GetValue asks the Father unit for a function to use to extract the value of KPE:*Father*. Based on what it was given, shown in Figure 3, the Father unit inherits the default mechanism, DefaultGetValue, for determining a unit's *Father*.[11] A simplified version of this algorithm is shown in Algorithm 1 below.

1. See if there is a value physically stored on the *Father* slot of KPE.
   If so, return that value.
   Otherwise, continue:
2. Get the function stored on Father:*ToCompute*.
3. Apply the function to the unit KPE.
   {This should return the value JSB.}
4. Store this computed value on the *Father* slot of the unit KPE.
5. Return this computed value.

Algorithm # 1.
Deducing the value of KPE's *Father*.

As there is no value to be found on KPE's *Father* slot, the test on Step 1 will fail. DefaultGetValue now must get the value of Father:*ToCompute*, which should be a piece of code, capable of calculating the value of a unit's *Father*. Getting this value uses essentially the same algorithm as the one shown above, *mutatis mutandis*. That is, GetValue recurs. (See Algorithm 2.[12])

---

[10] That is, we regard *Mother*: {Unit}⇒{Unit}, and *Husband*: {Unit}⇒{Unit}. Thus "*Mother*(GotthilfWilhelm) = DorotheaElisabeth" and "*Husband*(DorotheaElisabeth) = WilhelmFreidmann" are both well defined phrases. *Father*, as the composition of these two functions, will therefore also map units into units.

[11] It is important to realize that this procedure is only one of a host of retrieval mechanisms the initial RLL-1 systems offers; and that it is NOT hardwired into RLL-1. Appendix A.1 explains how RLL-1 can support this versatility and generality, without sacrificing efficiency; and Appendix B.1 shows an example in which a non-default accessing function was used.

[12] This also relies on the fact that, once again, the value of the slot's *ToGetValue*, (here ToCompute:*ToGetValue*) is DefaultGetValue.

1. See if there is a value physically stored on the *ToCompute* slot of Father. If so, return that value. Otherwise, continue: 2. Get the function stored on ToCompute:*ToCompute*. 3. Apply that function to the unit Father. 4. Store this computed value on the *ToCompute* slot of the unit Father. 5. Return this computed value.

Algorithm #2.
Deducing the value of Father's *ToCompute*.

Once again the test in Step 1 will fail, as this is the first time the *Father* of anything has been requested. So onto Step 2 of Algorithm 2. For this, we need the value of ToCompute:*ToCompute*. Algorithm 3 shows the now-familiar procedure followed, in a more general form.

1. See if there is a value physically stored on the *S* slot of the unit U. If so, return that value. Otherwise, continue: 2. Get the function stored on *S:ToCompute*. 3. Apply that function to the unit U. 4. Store this computed value on the *S* slot of the unit U. 5. Return this computed value.

Algorithm #3.
Deducing the value of U's *S*.

Binding U to the unit "ToCompute", and S to the slot "*ToCompute*" in Algorithm 3, we see RLL-1 then asks for the value physically stored on ToCompute:*ToCompute*. Fortunately there is a value there (else an infinitely recurring loop would ensue, as the value of ToCompute:*ToCompute* is required to deduce the value of X:*ToCompute* for any X, and in particular for X=ToCompute.) The ToCompute unit is shown in Figure 4.

Name:	ToCompute
IS-A:	(AnySlot)
Description:	*S:ToCompute* is the LISP function used to compute the value of U:S.
Format:	SingleEntry
Datatype:	Each entry is a LISP function.
MakesSenseFor:	AnyFunction
ToCompute:	(λ (x) (HighLevelExpand (GetValue x *'HighLevelDefn*))

Figure #4 - The infamous "ToCompute" unit.

We are now at Step 3, in Algorithm 2. This ToCompute:*ToCompute* function is applied to KPE. Omitting the irrelevant details, this uses the value of Father:*HighLevelDefn*, which, recall, we specified as "(Composition *Husband Mother*)" at the start of this example. The function HighLevelExpand then parses this high level specification into a LISP function -- one which takes a unit, X, and returns the *Husband* of the *Mother* of X. That is, this derived function will follow X's *Mother* slot to another unit, and then return the value of that unit's *Husband* slot. This function is then cached (that is, "physically stored"[13]) on Father's *ToCompute* slot, as per Step 4 of Algorithm 2, and then returned as the result of Father:*ToCompute*, as Step 5 instructs. At this point, the Father unit looks like:

Name:	Father
IS-A:	(AnySlot)
HighLevelDefn:	(Composition *Husband Mother*)
Description:	Value is *Husband* slot of *Mother* slot of this unit.
ToCompute:	(λ (x) (GetValue (GetValue x *'Mother*) *'Husband*)))

Figure #5 - Later form of the Father unit, after the value of the *ToCompute* slot has been calculated and stored.

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[13] This caching facility is an essential feature of RLL-1. It is discussed at length in Appendix A.2.

We now pop back to Step 3 of Algorithm 1. Applying this Father:*ToCompute* function to KPE, RLL-1 follows KPE's *Mother* link to MBB, and there finds the value of MBB's *Husband*, JSB. This value, JSB, is then cached on KPE:*Father*, and finally returned as the result of this call.

4.4 Other Facts Stored on the Type of Slot Unit

RLL-1 was able to automatically determine the value of every additional slot shown in Figure 6 from the *HighLevelDefn* of Father; calculating each (like *ToCompute*) only as it was needed. Much of the information RLL-1 needs is stored on the Composition unit, which "knows" about the composition of two functions. For example, as the domain of $f_1 \circ f_2$ is simply the domain of the function f_2, the domain of *Father* must be domain of *Mother*, i.e. any person. A similar analysis of the range of *Father* indicates that it is simply the range of *Husband*, i.e. any male person.

Such facts, which describe relevant attributes of this *Father* slot, are stored on the Father unit itself. Hence the datatype expected of each value stored in a *Father* slot is indicated by the value of Father:*Datatype*, which Figure 6 shows to be ManType. As Section 5.5 will reiterate, this is, in fact, a pointer to the "ManType" unit, which in turn holds the declarative and procedural information associated with (RLL-1's view of) men in general. Similarly the fact that each *Father* entry must be a single entry (as opposed to a matrix of entries or an unordered set of entries) is encoded by the "Single-Entry" value stored on Father:*Format*. The various accessing functions use such information when dealing with *Father*'s values.

Name:	Father
IS-A:	(AnySlot)
HighLevelDefn:	(Composition *Husband Mother*)
Description:	Value is *Husband* slot of *Mother* slot of this unit.
Format:	Single-Entry
Datatype:	ManType
MakesSenseFor:	AnyPerson
DefinedInTermsOf:	(Husband Mother)
DefinedUsing:	Composition
VerifyValue:	FVV
ToCompute:	(λ (x) (GetValue (GetValue x *'Mother*) *'Husband*)

Figure #6 - Later form of the Father unit, showing several slots filled in automatically.

For example, before storing a value of a unit's *Father* slot, the standard putting function will first check to be sure the value is of the correct type. That verifying function is stored on Father:*VerifyType*, and had been determined using the *Format* and *Datatype* of Father. That is, VerifyType:*ToCompute* is a function which takes a unit (here Father) and returns a value, FVV, which is then stored on Father:*VerifyValue*. (This FVV function takes a value, X, and returns T if X is an acceptable value to fill some unit's *Father* slot -- that is, if X is a single value, which is a unit which refers to a man.) FVV was constructed using the values of Father:*Datatype*=ManType and Father:*Format*=Single-Entry.

Since *Father* is defined in terms of both *Mother* and *Husband*, using the slot-combiner Composition, the Father unit states that a value stored on KPE:*Father* must be invalidated if we ever change the value for KPE's *Mother* or MBB's *Husband*, or the definition (that is, the value of the *ToCompute* slot) of Father. Recurring one level, as this Father:*ToCompute* function was defined using the definition of Composition, if this Composition:*ToCompute*[14] value is ever altered, Father:*ToCompute* must be updated correspondingly.

Appendix A.2 show that one easy invalidation technique is simply to erase the cached value. Section 5.2 elaborates this process, which is part of an idea called "Cognitive Economy".

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[14] Each unit which represents a function has a *ToCompute* slot, which holds the actual LISP function it encodes. Associating such a *ToCompute* slot with each slot reflects our view that each slot is a function, whose argument happens to be a unit and whose computed value may be cached away. (See Footnote 10.)

Notice how a user can "extend his representation" by enlarging his vocabulary of new slots. A similar, though more extravagant example would be to define *FavoriteAunt* as

(SingleMost (Unioning (Composition *Sisters Parents)*
(Composition *Wife Brothers Parents*))
Wealth).

"Unioning" and "SingleMost" are two other slot combiners which come in the initial RLL-1 system; their definitions and ranges can be inferred from this example. As before, this information given by the high level definition above is sufficient (1) to compute any unit's *FavoriteAunt*, (2) to determine whether a value proposed to fill this slot in fact qualifies or not, (3) to determine for which units the slot *FavoriteAunt* is meaningful and (4) to perform the necessary work to preserve consistency throughout the network whenever some slot's value is altered.

4.5: Modifying an Existing Type of Slot

Any frame-based system must allow the user to create a new type of slot. (This will require but a trivial declaration in those systems which treat all slots identically.) Few provide the user with a language to facilitate this task, or the tools required to specify such slots flexibility and concisely. RLL-1's capabilities in this capacity were demonstrated in the previous subsection. In even fewer systems is the user then able to modify such definitions. The following example shows how easy such alterations are in RLL-1.

Imagine someone wished to apply our geneological knowledge base to some polyandrous culture, in which a woman might have more than one husband. In this case, the obvious thing to do would be respecify the *Husband* type of slot, to allow each woman a set of husbands. This change would be as easy to make in RLL-1 as it was to describe here, and could be done as naturally. The user would simply refill the *Format* slot of the Husband unit (shown in Figure 2a),) with the value "Set-Of-Entries".

RLL-1 then uses its knowledge of the format units "Single-Entry" and "Set-Of-Entries", (in particular their differences) to do all the rest of the work. First, as a set consisting of one entry is stored differently than a single entry, RLL-1 would first map along the affected units, changing the value of each *Husband*'s slot appropriately -- so MBB:*Husband* would be changed from "JSB" to "(JSB)". (Note the domain information about *Husband*, stored here in Husband:*MakesSenseFor*, considerably shortens this scan; it tells RLL-1 the only units which might be affected are those which represent a woman.) Next, RLL-1 would examine those other slot types which might be affected by this change. Here it would note that, based on Father's current definition, Father:*Format* must be changed to correspond to Husband:*Format*. This modification would have similiar ramifications, cause other units to be altered, and so forth. For example, the value of KPE:*Father* would have to be listified to "(JSB)".

Notice these were the sort of dull, mundane updates a system programmer/maintainer would usually be called upon to perform. As [*Winograd*] points out, these are also the most standard sorts of modifications made; and it is a real loss to burden humans with so straightforward a task.

With this same ease the user could replace essentially any other slot of the Father unit, and RLL-1 would propagate the changes this evokes. In fact, this facility provides the user with another way of defining a new slot S (besides using only the *HighLevelDefn*): copy an existing slot, (choosing one which is functionally similar to S) and respecify just those one or two slots of this new unit whose values are inappropriate to S. Hence we could have built a *HusbandSet* type of slot in this incremental-change fashion: first create a new HusbandSet unit, filled with the slot/value pairs found in the unit Husband. Then change the value of HusbandSet:*Format* to be Set-of-Entries. This new *HusbandSet* slot would then perform in the manner we attributed to the changed *Husband* slot above; and leave the original *Husband* slot to do the singular thing its name implies.

A third, closely-related method of creating a new type of slot is to build the slot up in a piece-meal fashion, by filling in subordinate slots (e.g. *Format, Datatype, MakesSenseFor, ToCompute*) one by one. RLL-1 would then integrate these into the desired, working version, which the user may then use.

The purpose of this extended example was to demonstrate the sorts of things one can do using an rll. In particular, it should drive home the advantages of stating facts explicitly -- even those which pertain to processes, such as the inferencing required to retrieve a slot's value. The next section will describe this particular RLL-1 in more detail.

5. DESCRIPTION OF RLL-1
Initial "Organ Stops"

This section provides a general description of the RLL-1 system, to two levels of abstraction. The first half describes our overall philosophy of what an rll should be. The second part is more detailed, enumerating the particular conventions embodies in the initial RLL-1 system. These attributes may be viewed as the default positions selected for certain organ stops.

The heart of RLL-1 is its philosophy: keep every component of the system visible and modifiable. Towards this end, we encoded essentially every representational piece as a unit, so the user may use the same formalisms to examine and manipulate these that he uses when dealing with his other data. The next objective is to construct each of these pieces to be as general as possible. This is manifest in two ways: First we designed the Garden of Eden system to be sufficiently versatile that we imagine many users will be able to use it, unaltered, for their tasks.[15] Second, the essential functions are extremely simple. The unavoidable complexities has, instead, been distributed among the appropriate units, which can be perused and easily changed. For example, all of the accessing/writing functions (e.g. GetValue and PutValue) are trivial -- each simply asks one of its arguments for the value of a particular one of its slots, and applies the function stored there to the arguments passed to the original function. (Appendix A.1 shows this in detail.)

Of course, functions themselves might warrant being stored as units -- certainly the accessing functions qualify, as they each represent a legitimate piece of the represention. The problem is how to trick LISP to permit a user to "apply" a unit to some arguments, as if that unit was a function. At a linguistic level, one might, for example, expect *Father*(KPE) to return JSB, the value of KPE:*Father*. A hack to LISP's evaluator, described in the beginning of Appendix F, achieves this essential effect. The user can still treat these functions as he treats any other units -- only now he is creating or modifying executable processes; and doing so using the same operators which worked on arbitrary units.

The final "global" consideration is how easy such modifying operations are. RLL-1 provides a host of powerful tools, designed to perform the sort of manipulations most users will want to make. An example is the slot defining language illustrated in Section 4. Such high level specifications should be found throughout a good rll, to enable the user to perform standard manipulations on the standard types of units. Like the other suggestions above, this facility is undefined UNLESS the parts of the representation themselves are represented, and changable -- a slot defining language is meaningless unless one has slots to describe; and impotent unless there are meaningful, usable facts to assert about what a type of slot means.

There is still considerable flexibility within the philosophical guildelines outlined above. The following characteristics describe the initial state of the current RLL-1 system, when all "organ stops" are in their default positions. Each user will doubtless settle upon his individual settings, more suited to the representation environment he wishes to be in while constructing his application program.

5.1: Units and Slots: RLL-1's initial language is basically a frame-structured system, in which information is encapsulated into units, where each unit is composed of a list of slots, each with its designated value. This bias is largely for historical reasons, as RLL-1 grew out of the Units package [*Stefik*].

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[15] In fact, for pedagogic reasons we may describe this system to a user without mentioning its ability to metamorphosize. Only if she found this system limiting -- at the point she starts to grumble at RLL-1's inflexibility, or worse yet, begins to mold her data to conform to RLL-1's expectations rather than vice versa -- would she be told she could have constructed a new language of her own specifications at any time (... all she had to do was click her heels together three times ...)

5.2: Cognitive economy: There are many time/space tradeoffs involved with any complex process. Caching a computed value -- for example, the *Father* of KPE -- is only worthwhile if this value will be used again; otherwise it is a waste of (at least) two list cells. Similarly, it is often expediant to generate and retain multiple representations of some fact, using each for a particular purpose -- for example, using the source code for reasoning about a function, but actually executing the corresponding compiled version.

RLL-1's basic approach is to begin with a minimal collection of facts, sufficient to compute the other facts -- note this bag must include not only (at least) one version of each necessary fact, but also the mechanisms required to deduce the other values. If a new form of the data is needed, it will be computed automatically. In fact, the user need never know whether that value was laboriously calculated, or merely retrieved.[16] RLL-1 then explicitly considers whether or not to store this new information; and if so, where it should be stored. The retrieval algorithm must cooperate, by examining the storage location before considering calculating this value; in this way storing a value insures that it will not be recomputed. (Note that Algorithm 3 in Section 4.3 demonstrates this: it first checks if there is a value physically stored in U:*S*; and attempts to (re)compute this value only if that location is empty.)

For this procedure to work correctly many other parts must first be in place. Evaluating this space/time tradeoff requires a nontrivial process. RLL-1 delegates this computation to the function which fills the slot's *ToCache* slot. There are currently several pre-defined functions from which the user may chose, all shown in Appendix F. (Of course, the user always has the option of constructing his own.) Another concern is how to maintain consistency among these redundant pieces of information. Appendix A.2 shows one standard way of invalidating a no-longer-correct value; and Appendix B.2 shows an additional use for this facility. The final major problem is constructing the minimal set of facts, refered to above. This Garden of Eden must have enough of the essential funcions to calculate all the others; and include all the parts necessary to modify itself. For example, Section 4.3 shows why it must include ToCompute:*ToCompute* (at least if the standard default accessing functions are used).

As with other RLL-1 processes, the user can see just what will happen, and how. Storing the caching information on the *ToCache* slot of type of slot is an example of this explicitness. There are also hooks now in place for upgrading this into a more complex processes, such as the one outlined in Appendix B.2, which have not yet been used. This whole approach is labelled Cognitive Economy in [*Lenat, Hayes-Roth & Klahr*], and is similar the memo function idea discussed in [*Michie*].

5.3: Syntactic *versus* Semantic slots: The usual definition of a representational scheme is a structure, usually symbolic, which in some way reflects what actually happens in the real world. The nodes in most semantic nets, therefore, are intended to represent some real world entity -- i.e. something which lies strictly outside this (in-the-computer) simulation model. For efficiency reasons, a slightly augmented interpretation of "model" is required to understand the units used in RLL-1: In addition to facts about that entity outside this system, each unit is expected to house various bits of information which pertain to this particular unit, *as a unit within this system*. Hence, the usual definition of "the world out-there" has been extended to include our within-the-computer structure. This is a hack, and is, epistemologically, quite troublesome.

Essentially, RLL-1 simulates a meta-level KPEUnit -- one which represents the unit "KPE", the way "KPE" represents a unit in the real world. This logically distinct unit is physically merged into the KPE unit. This leads to a number of complicated situations, which we have worked through, one by one. One non-trivial issue revolves around inheritance. For example, KPE should inherit values for many slots from TypicalMusician, such as *Instruments*, *Birthdate*, and *Size*; but *not* from slots which refer to TypicalMusician *qua* data structure -- e.g. slots such as *NumerOfFilledInSlots* and

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[16] An appropriate metaphor is the refrigerator light -- which is always on, everytime you look. This laid-back "if-needed" attitude is not the only possible approach -- one could, for example, compute such values at first opportunity, in a "when-filled" manner.

DateCreated. RLL-1 treats these two classes of slots differently, e.g. when initializing a new unit. Appendix C justifies why we merged these two logically distinct units into one physical one, and then steps through the creation and initialization of a unit, to demonstrate how these two kinds of slots are handled separately.

5.4: Onion field of sub-languages: RLL-1 contains a collection of features (e.g., automatically adding inverse links, and unit initialization routines) which can be individually enabled or disabled, rather than a strict linear sequence of higher and higher level languages. The partially ordered set this forms is more like an onion *field* than the standard "skins of an onion" layering. We have barely begun the chore of designing and implementing additional facilities; and incorporating each at the appropriate layer of the appropriate onion. This is, obviously, an on going task. RLL-1 does provide the facility for physically storing a group of units into a clump, called a Knowledge Base or KB. The user can then load in just those KBs which are necessary for his task; these will collectively define his current system and language.

5.5: Economy via Appropriate Placement: Each fact is placed on the unit (or set of units) which are as general and abstract as possible. Frequently we create new units, or even new classes of units, to house this general information. In the long run, this policy of storing information towards the trunk of the tree, rather than on the leaves, will reduce the need for duplication of information.

Standard property inheritance is one example of this idea. Diagram #1 in Appendix E shows some of the classes which RLL-1 contains. There are classes which represent, among other things, classes, prototypes, slots, datatypes, formats, inheritances, and functions. Each of these class units represents the set of these members, e.g. AnySlot which represents the set of all slot. The typical example of each class, e.g. TypicalSlot, can be used to store facts common to all members of this class. So, for example, the fact that a slot is a function which maps from a unit onto a value is stored on TypicalSlot, and can be inherited, as needed, by any unit which descends from AnySlot -- that is, by any individual slot, such as Father.

Examining Figure 6, shown in Section 4.4, we see that many of the values stored on the Father unit are actually pointers to other units. For example, Father:*Datatype* points to the unit ManType, which codifies RLL-1's view of men; and Father:*Format* leads to the unit Single-Entry, which "knows" how to deal with those slots whose value is a singleton. Basically the chunks of information stored on this Single-Entry (respectively ManType) unit collectively help define what it means to be a single atomic value (respectively a man).

These format and datatype units represent the "logical placement" for these morsels of information. It is correct to assert that RLL-1 views List-of-Entries as representing "Listiness", in the way "ManType" encapsulates facts about "manishness". We saw in Section 4.4 that VerifyType was able to use this information to create a function for type checking; and Section 4.5 demonstrated that RLL-1 could reason about such singleton versus set values. RLL-1 can also exploit information derived from the organization of these units -- for example, the fact that ManType is a *SubDT* of both PersonType and MaleType helps to specify "mannishness".

Another slot, such as *Cost*, can also refer to this format Single-Entry; as might a LISP function such as CAR. "ManType" is also general enough to be widely used; as the datatype of *Uncle* or *MostContemptibleChauvinistPig*, or as part of the domain specification for the slot *Wife* or *Sired* (which maps a man to his offspring). This idea of appropriate placement of facts allows RLL-1 to store pertinent facts in this one well-defined location, rather than smearing such data throughout the Knowledge Base.

These format units are designed to house everything we may wish to say about that format; and so may be used for many other purposes, in addition to those mentioned above. A fact on the Set-of-Entries unit indicates that a set does not contain repeated elements. This fact is, of course, relevant for type checking. It is also used to construct the function which adds on a new element to an existing set -- instructing that function to add on an element only if it was not already there. Note that List-of-Entries has no such caveats, as values may be repeated in a list. We will see in Appendix D.4 that the empty set is stored as NoEntries; and this fact is housed, declaritively, in this

same Set-of-Entries unit.

As List-of-Entries is charged with storing all the facts which relate to (RLL-1's definition of) lists, modifying this List-of-Entries unit is sufficient to correct or augment any of the format-related characteristics (such as value verification) of any slot whose format is a list.

Another example of this idea is the use of appropriate conceptual units:

5.6: Clarity of Conceptual Units: RLL-1 can distinguish (i.e. it has devoted a separate unit to each of) the following concepts: TheSetOfAllElephants, (whose associated properties describe this as a set -- such as *#OfMembers* or *SubCategories*), TypicalElephant, (on which we might store *Expected-TuskLength* or *DefaultColor* slots), ElephantSpecies, (which *EvolvedAsASpecies* some 60 million years ago and is *CloselyRelatedTo* the HippopatamusSpecies,) ElephantConcept, (which *QualifiesAsA* BeastOfBurden and a TuskedPackyderm,) ArchetypicalElephant (which represents an elephant, in the real world, which best exemplifies the notion of "Elephant-ness"). It is important for RLL-1 to be able to represent them distinctly, yet still record the relations among them.

On the other hand, to facilitate interactions with a human user, RLL-1 can accept a vague term (here, "Elephant") from the user or from another unit, and use context to automatically refine it into the appropriate more precise term. While this appears a purely linguistic feature, it is vital for the representational system to allow this flexibility as well. For example, a term which is regarded as precise today may be regarded as a vague catchall tomorrow; and RLL-1 should have the facilities to perform such a modification easily.

RLL-1 readily accommodates distinct representations; but has not yet addressed the linguistic problem of automatic disambiguation; nor built in tools for "expanding" a unit into its more precise senses.

6. SPECIFICATIONS FOR ANY REPRESENTATION LANGUAGE LANGUAGE

The following are some of the core constraints around which this proto-rll, RLL-1 was designed. One can issue commands to RLL-1 which effectively "turn off" some of these features, but in that case the user is left with an inflexible system we would no longer call a representation language language. The first five points are fairly rigid guidelines for the overall rll system, while the last two are vague wants, pertaining only to the initial system. Further details may be found in [*Geneserethe&Lenat*]. The "current status" part which concludes each sub-section should indicate whether RLL-1's satisfies this constraint or not. (Recall the meaning of the "-1" in RLL-1's name.)

6.1: Self-description: Every part of an rll system must be visible; every one of its components, from individual slots and datatypes, to modes of inheritance, and even the data-accessing functions (e.g. GetValue and PutValue) themselves, must be explicitly represented within the system.[3] To avoid an infinite descent, (of having to describe the tools used to describe the tools which are used ...) it is essential that these description use the same formalisms that the representation uses for its other data -- in RLL-1's case, Units and Slots. To be *self-descriptive*, the rll must be described in terms the system itself can understand and reason about. A system may be described using LISP code, for example, only if the system has already axiomitized[17] facts about LISP.

Although this LISP code might satisfy the self-descriptive criteria, higher level constructs are required for the user to readily be able to reason about the behaviour or characteristics of some part of the system. As the process which translates from LISP to more natural form is a part of the overall self-described system, it will be well-described; and hence the higher level which resulted from its execution will also be well defined. In this manner we can bootstrap to successively higher level, more perspicuous, primitives.

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[17] These "axioms" need not be formal predicate calculus statements. We do insist, however, that this specification be versatile and have an unambiguous interpretation.

This approach has several intrinsic virtues. First, it guarantees that even complex operations, (such as the creation of a new Unit, or the determination of some *Slot*'s value by default) are transparent; and does so without affecting the range or versatility of permissible techniques. This visibility also provides the user with the opportunity to modify the parts -- a task not possible if these pieces can only be viewed as black boxes. This requirement is discussed in the next subsection.

Current status: While we have encoded essentially all of RLL-1 in its own formalism -- i.e. as units -- we do not feel this system is truly self-descriptive. One problem is that we (and hence it) do not have the vocabulary to describe what RLL-1 does or how it really represents a fact, in terms of useful well-defined primitives. While RLL-1 uses slots, for example, it does not understand what they are; certainly not to the level that it could reconfigure itself into a proposition-based system unassisted. In addition to the many things which are simply not described, there are many places where a description has been begun, but bottomed-out with primitives which were not themselves adequately defined. An example of this is RLL-1's attempt to specify functions: this stops at the level LISP code, which RLL-1 is not yet able to reason about. To be self-descriptive, RLL-1 has either to develop a set of well-defined primitives above this LISP level[18], or gain competency in reasoning about LISP itself. Either of these tasks qualifies as a major research effort.

6.2: All parts are modifiable: These parts must not only be visible, they should be alterable as well. As these parts really represent the rll's operations, performing such changes will actually change the rll system itself.

The question of how the user actually performs these modifications, while secondary, is an important concern. The guarantee given in the last subsection -- that these parts are encoded in the same formalism used for any other bit of data -- means these alteration can be made using the same tools which serve to alter the user's domain knowledge. It does not, however, mean such adaptations will be easy to make. For example, much of RLL-1 is written in LISP code. While this is visible, it is not at a level which facilitates easy modifications. RLL-1's approach has been to provide the user with a collection of powerful tools, designed to perform certain standard manipulations. Section 4 demonstrated one type of tool: high-level languages. The user can make a small change to this level of description, and RLL-1 will automatically propagate this change down to the level of LISP code. One can thereby trivially change the behavior of that part of RLL-1.

Current status: The requirement of self-description is obviously a prerequisite for this attribute -- how can you change any part which hasn't been described? Similarly there must be a connection between the unit and what it proports to represent -- otherwise a change to that description unit will have no effect on the overall system. As RLL-1 contains many facilities which are not fully and accurately described, for both of these reasons, it is not yet self-modifiable. There are many parts, including slots, processes, functions, formats, datatypes and inheritance modes, which have been authentically encoded as units and can be readily changed. Much additional effort is required to formalize many of the other components.

6.3: Epistemological Adequacy: The requirement is simply that the rll be Turing equalivalent -- i.e. that its processing power not have any obvious limitations. This guarantees that the representation language itself will not have any intrinsic restrictions on what a user can represent. This specification is automatically satisfied by any system which contains a language like LISP as a substructure.

Current status: Trivially achieved, as RLL-1 can always falls back on its LISP underpinnings.

Notice this epistemological issue does not address the question of how the data is actually encoded internally, or how it will appear to the user. The next two sub-sections discuss how the rll and the user, respectively, view the information.

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[18] We may use rule-like chunks of procedure knowledge as the primitive level. Each of these would be encoded as a unit, and contain both declarative and procedural information, as well as a precise "axiomatic" description. Appendix B.2 begins to illustrate these entities.

6.4: Linguistic Adaptability: Not only must the rll system be capable of expressing any statement, it should be able to do so in any manner the user wishes. That is, if the user wishes to encode his knowledge as units, the rll should not force him to use production rules. The actual language in which the user describes the task should be based on (the user's perception of) a natural decomposition of the problem, unhampered by the rll. The reasons for such user-interface considerations will be readily apparent to anyone who has tried to write a LISP program in Fortran. Although LISP and Fortran are epistemologically equivalent, each handles the data in its own manner. Things which are trivial to express in LISP may be next to impossible to encode in Fortran; and (conceivably) vice versa.

In an attempt to sidestep this limitation, many systems come equipped with a single "universal" dialect; while others are built conversant in a host of languages. In either case, the resultant system will, (by definition if not by construction) be adequate for every task the designer could envision. There will, however, always be other types of tasks, which the designer had not considered, and hence not designed for. There is also the danger this particular designer may have some strong bias, not shared by the future user. Besides, such hard-and-fast built-in specifications are contrary to rll's basic "open-ended and extensible" philosophy.

This requirement is simple: permit the user to define whatever language he wishes. The rll will, of course, provide the tools and mechanisms for such creations, as well as a library of known interfaces which the user may use or modify as he sees fit. In effect, we insist that the rll's interfaces be as transparent and modifiable as the rest of its operations. (Hence the requirements made in subsections 6.1 and 6.2 essentially subsume this argument. Note further that the requirement stated in 6.3 insures this will be possible, as any universal Turing machine can be programmed to simulate any language.) In this way, the representation language can adapt to the user's idiosyncrasies, rather than vice versa.

Of course, the user must be able to describe such a language to the rll, and this specification must be in terms this rll can understand. The obvious medium for this communication is rll's initial language. Here, indeed, the user must conform to some externally imposed set of conventions, but only long enough to deliver his medium-changing command.

Current status: RLL-1 is currently mono-lingual -- it can only receive and convey information in terms of units and slots. Although the user is free to code up his own vernacular, RLL-1 does not yet have the tools and basic high-level constructs which would make this task easy. This requirement has been postponed until the problems and issues relating to representational adaptability (next subsection) have been seriously addressed and answered -- we currently believe this linguistic mallibility should come for almost nothing, as a side effect of making RLL-1 representationally universal. Arguments suggesting why this should follow appear below.

6.5: Representational Adaptability: The last section insisted that rll be able to present the information in whatever form the user desires. This need not correspond to how rll, internally, sees the data. This is comparable to finding a person who speaks in English, but thinks in German. An rll could similarly fool the user: while it "spoke" in his language, it might actually process the data using some other representation.

Once again, this concern asks who should decide how the rll should process. Clearly the rll should be as flexible as possible. For example, it should be able to "think" in terms of wffs, production rules, or conceptual dependencies, as the situation warrants. As before, many existing systems provide one "universal" representational schema, or a fixed collection of diverse structures. This approach seems short-sighted, for reasons isomorphic to those presented in the last subsection.

To insure that an rll be able to represent the data internally in any form the user wishes, we once again place the responsibility of its design in his hands. As before, the initial rll should include a stock of very general processes which the user can then mold into one more to his liking. Imposing any additional system-convention inherently violates this goal, and may force the user to encode his data in awkward or unnatural forms. (Of course, any user may still insist on using his own, arbitrarily kludgey representation, if he wishes. The point here is that he alone is accountable for

such messes, and not the rll system.)

Current status: RLL-1 isn't yet clever enough to deceive the user. Its single unit/slot organization is all it is currently equipped to use. As other representational strategies are designed, RLL-1 will have to be told how to translate from that representation into RLL-1's *Lingua Franca*. We feel this translation process will eventually have other applications: First, it should provide the framework needed to simulate one language using another. It may also provide RLL-1 with the information necessary to converse in this tongue; thereby achieving the goal posed in subsection 6.4.

6.6: Unbiased initial system: The bootstrap rll, i.e. the representation language initially handed the user, is special in several repsects. First this is usually the *Lingua Franca* for subsequent languages -- that is, each will be defined using terms described and defined in this initial language. Secondly, it is in this language that the rll system itself is encoded.[19] For this reason, it should be as perspecutive and general a language as possible. Any bias here may adversely affect any representation language created on top of this underlying representation language; the way a faulty machine instruction can only be detrimental to any program which has to code around it.

Current status: As everyone has his own criteria for cleanliness and naturalness, this is more a subjective request than a hard-and-fast requirement. This hedge notwithstanding, we do not feel RLL-1's initial system, based on units and slots, is not as unbiased as it should be. Many facts, such as those presented in Appendix B.4, are clearly awkward to represent using these conventions. Subsequent systems can avoid this deficiency by using more general n-ary propositions.

There are a host of secondary concerns, which can be used to judge among several "equally unbiased" rlls. One is efficiency -- an aspect none of these seven points directly addresses. Ease of understanding is another important point. A final related issue asks what equipment should come with the initial system. A system which includes only the minimal set of representation pieces, including just those tools which are absolutely necessary to alter the system would clearly satisfy the first six points above. The next subsection addresses our view on this question.

6.7: Codification of Representation Knowledge: Many of these subsections might seem to imply that almost anything might qualify as an rll, as the user is permitted, (indeed encouraged!) to design both its external appearance and its internal operations. One may seriously question what, if anything, distinguishes an rll from, say, LISP. In terms of power or flexibility, the answer is nothing. A more meaningful response first examines the question of what separates LISP from the machine language in which *it* was written. The answer here is that LISP contains many useful, well-designed tools -- such as chunking commonly used bits of code into single instructions, (e.g. MAPC) or providing an enviroment which does nice things like spelling correction. Similarly an rll is expected to offer the user nice, natural pieces, along with a good user interface.

It should provide taxonomies of useful representational pieces, including a tree of usable inheritances, miscellaneous matchers, powerful data retrieval functions, etc. While not really required, an rll may also provide a structured array of other useful entities, such as general world knowledge, a facility to exploit analogies, or a clear consistent model of function invocation. Subsections 6.1 and 6.2 insist these should be easy to create and modify; for this, too, the rll should provide the necessary tools. This entire collection of parts and facilities correspond to all of the stops of the organ, using the analogy defined above.

Current status: This is some of the most exciting (and endless) research we foresee; as only a smattering of representation knowledge has yet been captured.[6]

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[19] This is NOT to imply that the underlying representation, in which the representation language language itself is described, must conform to that language, any more than a PL/I interpreter must be written in PL/I. It is enough that it can simulate that target language. (Of course, there are big wins derived from actually bootstrapping from a subset of the target language, as LISP and RLL-1 actually do.)

7. COMPARISON WITH OTHER SYSTEMS

The previous two sections described our particular rll, and defined what we meant by the term "representation language language". Given these models, we will now try to compare our system with various other systems; or rather, describe why analogous systems are difficult to find.

By its nature, RLL-1 is able to wear several hats, depending on who is viewing it, and what task this user has in mind. It may therefore useful to first describe what RLL-1 is not. It would be a type error to confuse RLL-1 with a reasoning system, (e.g. Mycin's inference engine) or with some mechanism devoted to communicating with a user -- such as a Question/Answer-ing or Natural Language Understanding facility. It is, instead, the language on which such applications can be built. As a general tool, it should not be restricted to competency in some single task. (That is unlike PUFF [*Kunz et al.*], whose single task is quite well defined: it was designed exclusively for diagnosis of pulminary lung disorders.) Nor is it only applicable to some particular process or strategy, as compared to systems like EMYCIN [*vanMelle*], which can only utilize a backward-chaining rule system. RLL-1 is, more or less, at the level of the underpinnings for such systems -- in the relation that a BlackBoard [*Erman&Lesser*] model is to Hearsay systems [*Lesser&Erman*], or production rules are to Mycin [*Shortliffe*]. That is, RLL-1 is a formalism for representing the knowledge which is to be used.[20]

Much of this paper has pushed the idea of "RLL-1, The Ultimate Representation Language". While this RLL-1 *qua* rl (rl=Representation Language) viewpoint is certainly accurate, it appears of a different genre from most rl's, in that it is designed to be changeable. This immediately eliminates those languages which have a host of specific built-in features (perhaps to facilitate performing some particular task efficiently,) from meaningful comparison. This camp includes Units [*Stefik*], FRL [*Roberts&Goldstein*], OWL [*Szolovitz*], KLONE [*Brachman*], DB [*Genereseth*] [*Mackinlay&Genesereth*], NETL [*Fahlman*], Conceptual Dependency Graphs [*Shank*] and OPSS [*Forgy&McDermott*].

These languages, however, are comparable with the initial RLL-1 system. This, recall, is the language each user sees when he first loads up RLL-1, (and is further specified in subsections 6.6 and 6.7). The user can then design his personal rl by molding this mallible language. This comparison must be made along several dimensions. The first concern is "power" -- what tasks can be performed in each of these systems. This question soon becomes uninteresting, as the "epistemological power" of all of these systems is clearly identical -- but so is LISP's or, for that matter, a Turing machine's. Time and space efficiency is another issue. This is rather hard to measure, as it is quite dependent on the actual task chosen on which to base the comparison. Any individual rl will, of course, perform better on some tasks than on others. For example, much of RLL-1 deals with functional specification, and so we would therefore expect this initial RLL-1 system to do well on any task which requires this type of expertise. On the other hand, any of these other systems could undoubtedly outperform this bootstrap RLL-1 on any of the tasks it was designed to perform. Altogether, RLL-1 would probably lose to any other system, counting the number of types of tasks which one can do more efficiently than the other. This is by design: RLL-1 was built for generality and flexibility, not for efficiency. This is no real loss to the overall RLL-1 system (i.e. beyond its bootstrapping neonatal self), as this system has the ability to reconfigure itself into a faster form, if necessary. So this deficiency is really not that great.

Another attribute is versatility: How many tasks, and types of task, can any of these rls handle "cleanly"? Using that "cleanly" hedge makes this characteristic quite hard to define, at least quantatively. One measure of elegance is the absence of extraneous and artificial "things" (e.g. units, rules, arrows) and naturalness of the remaining components. (By artificial, we mean entities not intrinsic to the problem, *per se*, but which were created solely to enable the system to do the "right thing".) For rather circular reasons, RLL-1 would probably force its users to endure fewer artifical units than any of these other systems. That is, RLL-1 permits the user to design his own

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[20] Notice RLL-1 is also a mechanism for building such tools; as well as one such tool.

constructs; and what user would intentionally employ an entity he personally considers unnatural or extraneous?[21]

Like KLONE [*Brachman78*], Lunar [*Woods*], and DB [*Genesereth*], we have attempted to address various epistemolgical issues. This is a different cut at what a representation language should do from the view taken by OWL [*Szolovits et al.*] researchers, who, following [*Quillian*]'s lead, were concerned primarily with linguistic issues, or from the psychological motivation which inspired much of KRL's early work. (An excellent article [*Brachman79*] addresses and helps delimits these diverse perspectives.)

Many previous rls have attempted to utilize such a self-referencing ability, for example, DABA [*Sandewall*], KRL [*Bobrow&Winograd*], Omega [*Hewitt et al.*] and [*Levesque&Mylopoulos*]. These approaches seemed to lack the two important ideas shown in subsections 6.1 and 6.2: First, that the elements of a representation can and should be viewed as simple data, and handled in the same manner as domain facts. Second, that this representation itself should be modifiable.

These are two of LISP's biggest assets -- as the code it runs is in the same form as all of its other data, (as S-expressions.) LISP is able to modify its own code, and thereby bootstrap indefinitely. Efficiency might seem one reason to avoid this approach. RLL-1, however, has solved this problem using a second major idea, Cognitive Economy, described in Section 5.2 This allows the system to contain many equivalent forms of its primitives -- using more declarative versions for inspection, while executing arbitrarily-efficient ones.

There is another whole class of systems which are closely related to rls, proper. These are programs which attempt to symbolically represent actions, and be able to reason about (i.e. propagate) their effects on the rest of that formalized chunk of the world. This category includes truth maintanence systems, (e.g. TMS [*Doyle*]/AMORD [*deKleer et al*]) their predecessors, (such as Strips [*Fikes&Nilsson*], Planner [*Sussman*] and Conniver [*McDermott&Sussman*]) program verifiers, (including [*Bledsoe*] and [*Manna&Waldinger*]) and proof checkers (like FOL [*Weyrauch*][22]). To insure that every appropriate update is performed in response to some action, the program must contain a fairly complete model of that segment of the world. It will, in addition, supply the user with a deductive mechanism for determining what action caused, (or was responsible for) some result; and rules which indicate what should happen as a premise is posited or retracted. (This deductive mechanism was not always built-in. Languages like Conniver instead provided an assortment of tools, such as a slot's *IfNeeded* facet. The user was expected to assemble these into the particular deductive strategy he wished.) This entire truth maintanence problem reduces to a rather straightforward search when the space is well-defined; the complicated part is determining that initial set-up. This operation is vastly simplified if each of the components, including the current and hypothesized states, type of responsibility pointer, etc., is made explicit and appropriately encoded -- i.e. if RLL-1's basic paradigm is followed. Indeed, much of the machinery necessary to following the appropriate links and perform the correct updates is included in the initial RLL-1 system.

As programs become more complex, their designers began building increasingly more powerful tools to aide in the construction and recoding processes. These tools are designed to perform the mundane translation instructions, given in a high level, natural language into code the machine can understand and execute. Simple programming languages, which converted the user's commands into machine code, were the first steps in this direction; these were followed by more sophisticated languages, which did more for the user per unit keystroke. Two types of AI systems are designed

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[21] The careful reader may point out here that this comparison was to be with the *initial RLL-1 system as it is presented to the user* (1), and not with RLL-1 *after that user has modified it* (2). The point where the system (1) becomes a system (2) is rather fuzzy, in that any rl must allow the user to add data; and in RLL-1's case, this data may cause the representation itself to change.

[22] METAFOL, an extension to the FOL system, was one of the first systems which managed to encode its operations within its own formalisms. It, as such, played a major role in this RLL-1 development, by providing a proof-by-existence that such a system was indeed possible.

to go one level further in providing the coder with a more abstract language for describing a task: Automatic Programming (e.g. [*Green et al.*]) and Expert System Building Systems or ESBSs (*àla* AGE [*Nii&Aiello*], EMYCIN [*vanMelle*], and EXPERT [*Weiss&Kulikowski*]).

Although RLL-1 has been used to build an proto-expert system (see [*Hayes-Roth, Waterman & Lenat*]), it is still difficult to compare it with these other systems. The major difference is RLL-1's self-modifiability. While all of these systems can assuredly construct one type of system, cleanly and efficiently, none of the other systems were designed to modify itself.

Basically, these tools appear to overlook the fact that they themselves are rather complex programs, which may be exceedingly difficult to modify without assistance. Consider what would be required to change the specification of the target language, even ever so slightly. For RLL-1, such an alteration would require editing a few (hopefully one) units; as opposed to actually going into the guts of the ESBS's code, and massaging the LISP code found there. It would be useful to build systems which "knew" how to construct automatic programming systems, for example; or which were actually experts at constructing ESBSs. This seems to lead into an infinite descent. The obvious solution is to insure that the program-generating system is capable of generating itself. As the program can reason about its own operations, (in the same way it "understands" other programming constructs) it can serve as a tool capable of modifying itself. The CHI automatic programming system, described in [*Phillips*], is also based on this idea.

This brief survey of AI representational systems (i.e. systems designed to facilitate the construction and manipulation of other large and complex bodies of knowledge) was intended to convey our basic philosophy: That making the internals of a system explicit, self-describing, and most importantly, modifiable,[23] is a big win. Such systems will remain viable and in common use considerably longer than their opague cousins, and will even be easier to use throughout their lifetimes. Many confusing issues are solved, or simply become non-issues, when the system itself no longer has covers to hide under. For example, when the interpreter is visible, there is no longer any question what the semantics of, say, a link *really* means -- it is simply what happens when one explicit well-defined structure, called the interpreter, evaluates another well-defined construct, the link.

8. CONCLUSION

The RLL-1 system is currently at a plateau -- stable and usable, but by no means complete. It is only through continued use, by a wide cross section of researchers, that optimal directions for its future effort will be revealed. Requests for additional documentation and access to RLL-1 are encouraged. We see a myriad of future directions for RLL-1 to take. We have attempted to indicate throughout this memo what has been done, and what is still pie-in-the-sky; these are especially noted in Sections 5 and 6. In addition, RLL-1 should one day be able to do all the examples suggested in Appendix B. Much future research, in a number of sub-disciplines, will be required before it can successfully act in a "Eurisko-like" manner -- in particular, effective utilization of rules and ability to derive and use apt analogies and super-concepts. Beyond all of these, a complete RLL-1 system should have a sophisticated front end, capable of handling the linguistic nuances associated with data (dare I say "Knowledge") communication; and be truly able to integrate diverse representational pieces, at a level beyond the primitive one it has now achieved.

The additional tasks fall into many different categories. Some merely require a large amount of work (e.g., incorporating other researchers' representational schemes and conventions); while others will have to wait until important philosophical decisions have been reached (such as how to handle

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[23] Evolution, as well, seems to agree with this last idea, preferring adaptable organisms over those which contain, built-in optimized features. Compare the extinct dinosaur, unable to adapt to new situations, with two of nature's most successful species: Man, who can modify himself to his environment using technological devices (e.g. putting on a coat), or the insect, which uses it fast reproductive cycle to "reconfigure" its species as new situations arise (such as the introduction of DDT).

intensional objects and beliefs, and how to attain "epistemological purity" of the initial RLL-1 system).

To support our "universally applicable" arguments, we intend to exhibit a large collection of distinct representation languages which were built out of RLL-1; this we cannot yet do. Several specific applications systems live in (or are proposed to live in) RLL-1. Knowledge bases already started include RLL-1's original *raison d'etre* EURISKO (discovery of heuristic rules), E&E (combat gaming), FUNNEL (taxonomy of LISP objects and functions) and PROVER (a non-resolution theorem prover written by Larry Hines). WHEEZE (a diagnosis program for pulminary function disorders, reported in [*Smith&Clayton*]) has been written in a sister system to this RLL-1. ROGET (Jim Bennett: guiding a medical expert to directly construct a knowledge based system) and VLSI (Mark Stefik and Harold Brown: a foray of AI into the VLSI layout area) are two tasks in search of a representational scheme; both are seriously considering using RLL-1.

It is the philosophy of an rll, more than our particular implementation, that we hope this paper will convey. There is a great need for a flexible and extensible high level language in which to create and maintain the sophisticated procedures an AI task requires. The user should have ready access to a stockpile of commonly-used parts, together with the tools required to modify, and compose these pieces. Experience in AI research has shown this goal has been all but neglected. A representation language language addresses this challenge. In addition to providing these tools, an rll will leave the pieces of a representation in an explicit and modifiable state. By performing simple modifications to these representational parts, (using these specially-designed manipulation tools) the user can build new representation languages, which can be created, debugged, modified, and combined with ease. This should ultimately obviate the need for dozens of similar yet incompatible representation languages, each usable for but a narrow spectrum of tasks.

It is our hope that RLL-1 will spawn a new generation of such foundation systems, all designed to be flexible and extensible. Eventually, we envision, such languages will together synthesize a single rll system, sufficient to handle every need a user will ever have -- much in the manner LISP has served the AI community all these years; only at a higher level of abstraction and usefulness.

ACKNOWLEDGEMENTS

The work reported here represents a snapshot of the current state of an on-going research effort conducted at Stanford University. Researchers from SAIL and HPP are examining a variety of issues concerning representational schemes in general, and their construction in particular (viz., [*Vii&Aiello*] and [*VanMelle*]). Professor Douglas Lenat initiated many of the ideas presented here, and supplied essentially all of the research directions. I especially thank Michael Genesereth for his frequent insights into many of the underlying issues, and for his near-continuous encouragement and assistance in preparing this document. He and David Smith have been instrumental in developing and honing many of the ideas presented here. Critiques by Tom Pressburger, Steve Tappel, Sue Angebranndt, and Paul Cohen did much to help shape this paper, as well as many of my views. Mark Stefik, Terry Winograd, Danny Bobrow, and Rich Fikes conveyed enough of the good and bad aspects of KRL and UNITs to motivate us towards an rll. Greg Harris implemented an early system which performed the task described in Section 4 and Appendix A. Others who have directly or indirectly influenced this work include Bob Balzer, John Brown, Cordell Green, Johan deKleer, and Rick Hayes-Roth. Finally, I am grateful to David Smith, for providing the demand unit swapping package ([*Smith*]) we used to sidestep InterLisp's space limitation. The research is supported by NSF Grant #MCS-79-01954 and ONR Contract #N00014-80-C-0609.

A. APPENDIX - Use of the *Father* Slot

This appendix expands the example shown in Section 4. It is designed to illustrate how the initial version of RLL-1 actually goes about generating and caching appropriate slot values. As we have emphasized several times earlier, this only represents one particular method RLL-1 allows; any user may chose to follow this set of conventions, or design his own.

A.1: How (GetValue U S) really works:

Suppose immediately after creating the Father unit, as done in Section 4.3, the user asks for Karl Philipp Emanuel's father, by typing

```
(GetValue 'KPE 'Father).
```

The GetValue function is very simple -- it calls Father:*ToGetValue* on the arguments KPE and Father. Technically, this would require determining

```
(GetValue 'Father 'ToGetValue),
```

which would, in turn, necessitate looping endlessly on the call

```
(GetValue 'ToGetValue 'ToGetValue).
```

To avoid this trap, the GetValue function has "pre-compiled" the result of this (GetValue 'ToGetValue 'ToGetValue) call in the appropriate place in GetValue. Hence, GetValue is defined as

```
(DEFINE GetValue (Unit Slot) (APPLY* (GetAccessFn Slot 'ToGetValue) Unit
                                                                  Slot),
```

where GetAcessFn is the function stored on ToGetValue:*ToGetValue*,[24] rather than the desired, but unrunnable

```
(DEFINE GetValue (Unit Slot) (APPLY* (GetValue Slot 'ToGetValue) Unit Slot).
```

Note GetValue is the only trouble-maker. All of the other accessing/modifying functions, such as PutValue or RenameUnit, avoid this added hassle.

This GetAcessFn function is also fairly simple. (GetAcessFn 'Father 'ToGetValue) first checks if a value is physically stored on the the *ToGetValue* slot of the unit Father, and finds none. (Had GetAcessFn found a value there, it would have returned that value.) Otherwise, GetAcessFn falls back on FindDefault's method of inheritance, (shown in Appendix B.1) and so scans the prototypes of Father, in order, searching for the first prototype it can find which has a *ToGetValue* slot. Here, this search will walk all the up to TypicalSlot, find DefaultGetValue stored there, and return that value.

Like GetAcessFn, DefaultGetValue first tries a simple associative lookup (essential a GETPROP), but finds there is no *Father* property stored on KPE. DefaultGetValue then tries a more sophisticated approach: rather than look up the prototypes of Father (as GetAcessFn would have done,) DefaultGetValue asks the Father unit how to compute the *Father* of any person. This information is stored on Father:*ToCompute*. Thus the (GetValue 'KPE 'Father) call effectively becomes

```
[Apply* (GetValue 'Father 'ToCompute)  'KPE].
```

Notice this calls GetValue recursively Once again there is no value stored here, on the *ToCompute* slot of the unit called Father. The call therefore expanded into

```
[Apply* (Apply* (GetValue 'ToCompute 'ToCompute) 'Father) 'KPE].
```

Luckily, there *is* a value on the *ToCompute* slot of the unit ToCompute. The functional stored in ToCompute:*ToCompute*, TCTC, takes an argument, X, (the name of a slot,) and returns a function which, given a unit U, computes the value of the X slot of that unit. TCTC instructs RLL-1 apply the function HighLevelExpand to the *HighLevelDefn* of X, HLD. This function first finds the slot-combiner S which X employs, (this is the CAR of HLD) and applies S:*ToCompute* function on the relevant arguments -- the other elements of HLD. Our call is now expanded out into

```
[Apply* (Apply* (GetValue 'Composition 'ToCompute) 'Husband 'Mother)
                                                          'KPE].
```

---

[24] In fact, an essential invariant of our system is that GetAccessFn be a fixed point of *Fn* = (*Fn* 'ToGetValue 'ToGetValue). By the definition of GetValue, this implies that *Fn* = ToGetValue:*ToGetValue* (where we have replaced "GetAccessFn" with *"Fn"* in GetValue).

The slot-combining unit called Composition does indeed have a ToCompute slot; after applying it, we have (roughly)

```
[Apply* '(λ (x) (GetValue (GetValue x 'Mother) 'Husband)) 'KPE].
```

This asks for the *Mother* slot of KPE, which is always physically stored in our knowledge base, and then asks for the value stored in the *Husband* slot of that unit. The final result, JSB, is returned. It is also cached (stored redundantly for future use) on the *Father* slot of the unit KPE. Section 5.2 elaborated the details of this process.

A.2: How (and why) caching really works

Consider what will happen the next time the user requests KPE:*Father*. As before, Father:*ToGetValue* will be called, and return DefaultGetValue. This will be invoked and, as before, see if there is some value stashed in KPE's *Father* slot (this is Step 1 of Algorithm 1). This time that test returns successfully, and the result, JSB, is returned. Notice all the other running around has been avoided. Much of this work, such as determining the value of Father:*ToGetValue* can be done at compile time, through the use of clever macros, (see Appendix D.3) to speed up this process ever more. Our goal is for such standard cases -- i.e. retrieving a stored valued -- to be about as fast as a simple GETPROP (see Appendix D.1).

We might later ask for, say, the *Father* of Wilhelm Adolf Bach (WAB). As usual, Father:*ToGetValue* ≡ DefaultGetValue is used. It, finding no value is stored on WAB's *Father* slot, now need Father:*ToCompute*, and so "enter" Algorithm 2. This time Father:*ToCompute* will be found in the first step and simply returned. When this function is applied to WAB, it will return the value of WAB's *Father*, Wilhelm Freidman Bach; after caching that value for future use.

Note the efficiency in the mechanism -- only if a value, such as KPE:*Father* or Father:*ToCompute*, is requested will RLL-1 actually compute this value; at which point it does only the work required. If such a request is never issued, no effort will be wasted, as this therefore-useless value, (e.g. Father:*ToCompute*,) will never be calculated. Subsequent calls to x:*Father* will not recompute this function, but will merely use the value stored in Father:*ToCompute*. Section 5.2 expands and generalizes this point.

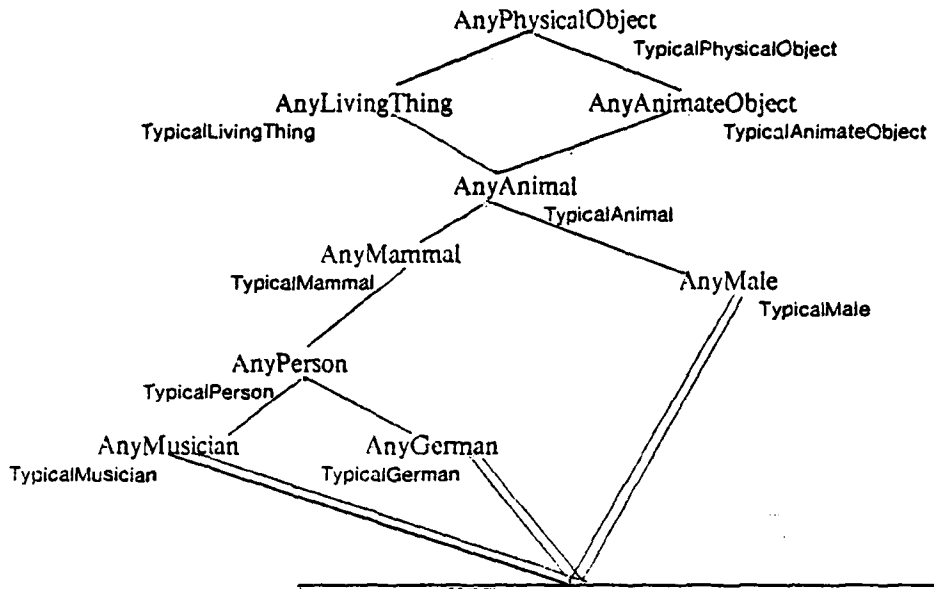
There is an obvious space-time tradeoff going on here: retrieving a cached value does take much less time than would be spent recomputing that value; but it does cost that additional storage. To simplify this example, we implied RLL-1 would always decide to cache, i.e. in favor of saving time over space. In general, RLL-1 tries to weigh time versus space considerations in determining whether, and how, to preserve a value. For example, RLL-1 may then decide to "SELF-COMPILE" the function now stored in Father:*ToCompute*. That is, the first time this function is run, it will compile itself into machine-level code, and store this more efficient form where it will be sought before the interpreted, source code. In this way frequently used functions can become faster and faster.

A.3: Other Accessing Functions

To demonstrate another accessing function, suppose the user wished to enter a value into KPE:*Mother*. This could be achieved by typing

```
(PutValue 'KPE 'Mother 'AMB).
```

As before, PutValue is a very simple function. It asks the Mother unit for its *ToPutValue* slot, and then applies this function to KPE, Mother and AMB. By the same process outlined above, Mother:*ToPutValue* requires ToPutValue:*ToGetValue*. This function has been stored, and is again GetAccessFn. (This same GetAccessFn function is used in all of the accessing and updating functions.) As before, (GetAccessFn 'Mother 'ToPutValue) first asks Mother for its *ToPutValue* slot. Finding not value there, it examines Mother's prototypes, $\{P_i\}$, stopping and returning the first nonNIL P_j:*ToPutValue*. Unless intercepted, (see Appendix B.1.) this (GetAccessFn 'Mother 'ToPutValue) will return the value living in TypicalSlot:*ToPutValue*, DefaultPutValue. This default function verifies that AMB is an acceptable value for a *Mother* slot, then stores AMB on the *Mother* slot of KPE, does various knowledge base truth maintanence tasks, and stops.



KPE	
IS-A:	(AnyMusician, AnyGerman, AnyMale)
AllIsas:	(AnyMusician, AnyGerman, AnyPerson, AnyMammal, AnyMale, AnyAnimal, AnyLivingThing, AnyAnimateObject...)
Prototypes:	(TypicalMusician, TypicalGerman, TypicalPerson, TypicalMammal, TypicalMale, TypicalAnimal, TypicalLivingThing, AnyAnimateObject...)

Figure #7 - Portion of the frame hierarchy which dominates KPE.

B. APPENDIX - Additional Examples

B.1: Creating a Whole New Family of Types of Slots

RLL-1 comes equipped with several inheritance and retrieval mechanisms. One powerful and useful one exploits the [*Minsky*] frame-like hierarchy which structures the RLL-1's initial knowledge bases. Many slots can derive an If-Needed value by default, extracting this value from the nearest relevant prototype. Thus, the facts that "Clyde is an Elephant" and "Elephants are grey" should be sufficient to deduce that "Clyde is grey". The constructs and mechanisms which allow such deductions are shown below.

As part of a frame-like system, every RLL-1 unit has an *IS-A* slot which lists the classes to which this unit belongs. For example, KPE:*IS-A* is the list (AnyMusician, AnyMale, AnyGerman). Each of these units, in turn, points to a list of superclasses of that set -- AnyPerson is included in AnyMusician:*SuperClasses*. Note, as these *SuperClasses* links encode the superset relation, KPE will be a member of the class represented by AnyPerson, as well as AnyMusician, AnyMale, and AnyGerman. The *AllIsas* type of slot encodes this more complete "∈" relation. See Figure 7.

Associated with each class, "AnyX", is a unit which houses facts which are typically true of each member of that set, by convention named "TypicalX".[25] So TypicalMusician:*HasInstrument* will be True, whereas TypicalPerson:*HasInstrument* is False, as most people do not own an instrument. The *Prototypes* of a unit, U, is a list of the typical members of each member of the list U:*AllIsas*, (in order of increasing generality). So KPE:*Prototypes* is (TypicalMusician, TypicalGerman, TypicalPerson, TypicalMammal, TypicalMale, TypicalAnimal, TypicalLivingThing, TypicalPhysicalObject, TypicalThing).

As suggested above, facts true of each[26] instance of AnyX should be stored on the unit TypicalX. If the user then asks whether some member of AnyX, U, has this property, P, this FindDefault retrieval mechanism will go up U's *Prototypes* until it finds a prototype which says something about P. Unless intercepted, this search will terminate when it encounters TypicalX, and return the value P implied. So we would expect KPE:*HasInstrument* to be True, as TypicalMusican:*HasInstrument* is True. The fact that TypicalPerson:*HasInstrument* is False is, here, irrelevant, as the FindDefault search will never reach TypicalPerson. (This inheritance mechanism is essentially the same as the one FRL and KRL use.)

Thus the AnyMusician and TypicalMusician units were used to implicitly define a new class of objects, by indicating new default values for members of this class. (In this case, the value for the *HasInstrument* slot.) We can exploit the way FindDefault works to define a new subclass, AnyS, of an existing class, AnyC. In the same way all musicians (such as KPE) "preferred" to get their values from TypicalMusician over TypicalPerson, values placed on TypicalC override those stored on TypicalS. The semantics of *TypicalExample* corresponds to our intuitive ideas. Figure 8 below shows how we, and RLL-1, can allow Duckbill Platypuses to lay eggs, even though every duckbill platypus is a mammal, and "all" mammals give live birth.

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[25] We have attempted to follow a few naming conventions: The unit "AnyX" represents the class of all Xs. "TypicalX" is a unit which stores information which is typical (that is, defaulted) for each element of the class "AnyX".

[26] This "each" criterion is not really required. We saw earlier in the TypicalMusician and TypicalPerson example that assertions stored on TypicalX units reflect default, as opposed to universal, statements. In addition, the right thing would happen if we later add to the Elephant example above that "Clyde is an Albino" and "Albinos are, by definition, white". The value of Clyde:*Color* would then be White, not Grey. This requires placing an epistemological mark on TypicalAlbino:*Color* to indicate this definitional quality; Appendix B.4 will show one way of doing this. RLL-1 can handle the standard problems which arise when dealing with non-monotonicities [*AI Journal*] and "default reasoning" [*Reiter*]. The above example intentionally avoids such complexities.

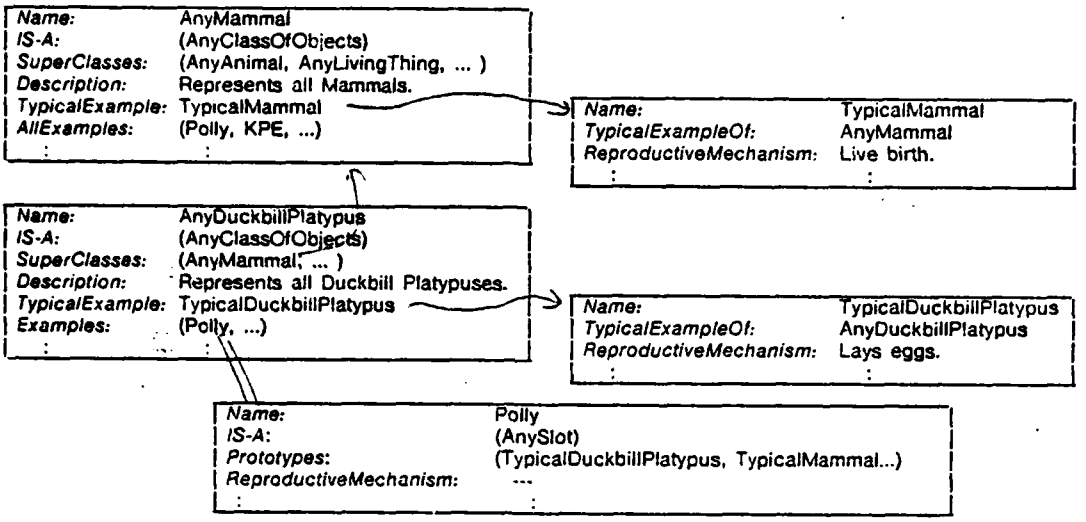

Figure #8 - Framework permitting egg-laying mammalian platypuses.
(The value of ReproductiveMechanism:*ToCompute* has to be FindDefault for this to work.)
[The value "--- " indicates NO value has been stored in this slot, and is only shown here for emphasis.]

This same mechanism can be used for types of slots as well. As slots are themselves encoded as units, they too can have defaulted properties. By creating a new class of types of slots, we can provide its members with a different set of defaults; inherited only by these members.

Examples 4.2 and 4.3 above intentionally glossed over details of the actual retrieval mechanism used. As shown in Appendix A.1, computing KPE:*Father* actually requires first asking Father for its *ToGetValue* value, and then applying this function to KPE. The value of this Father:*ToGetValue* will be inherited from one of Father's *Prototypes*. Similarly, storing a value in the *Father* slot of KPE, (or any other unit,) requires first determining the value of Father:*ToPutValue*. As with *ToGetValue*, the value of (GetValue 'Father 'ToPutValue) will be inherited from the first one of its prototypes which has some stored *ToPutValue* value. Unless intercepted, this will reach the value DefaultPutValue, stored on TypicalSlot:*ToPutValue*. This information is portrayed in Figure 9. Note (GetValue 'Father 'ToPutValue) = (GetValue 'TypicalSlot 'ToPutValue) = DefaultPutValue.

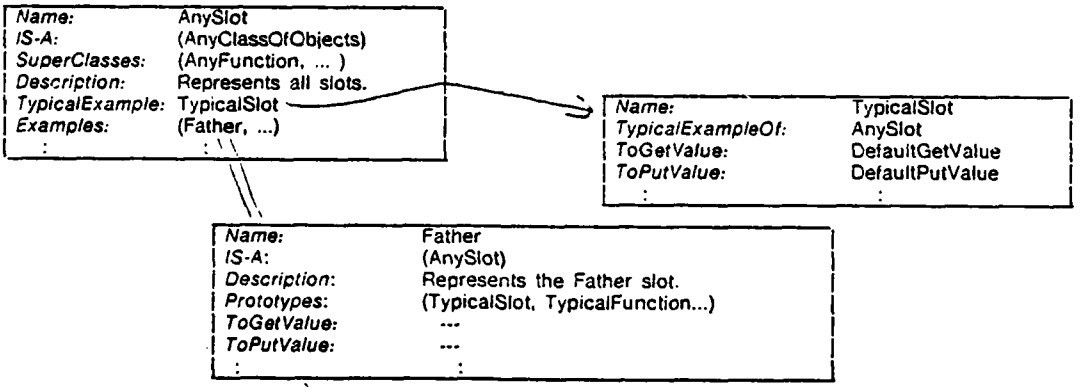

Figure #9 - Current framework for Father slot.

Suppose we want to create a whole different category of types of slots -- one which, for example, prints a message before performing each of its knowledge base consistency modifications. (In Appendix A.2 we saw that a unit's *Father* slot is deleted whenever that unit's *Mother* slot is updated -- this is such a modification.) A general way of doing this requires first creating a unit representing a new class -- named, say AnyChattySlot -- and its associated typical example,

TypicalChattySlot. Now TypicalChattySlot:*ToPutValue* is filled with the function ChattyPutValue, which resembles DefaultPutValue, (the function found on TypicalSlot:*ToPutValue*) but which prints that updating message where appropriate. In Figure 10, we show Mother as an *Example* of AnyChattySlot, by replacing the value AnySlot with AnyChattySlot in Mother's *IS-A* slot. In this state, the user will be told that KPE's *Father* slot was being deleted if KPE:*Mother* is ever reassigned. Here (GetValue 'Mother 'ToPutValue) = (GetValue 'TypicalChattySlot 'ToPutValue) = ChattyPutValue. Note (GetValue 'Mother 'ToGetValue) is still DefaultGetValue, inherited from TypicalSlot; this is true only because TypicalChattySlot had nothing to say about *ToGetValue*.

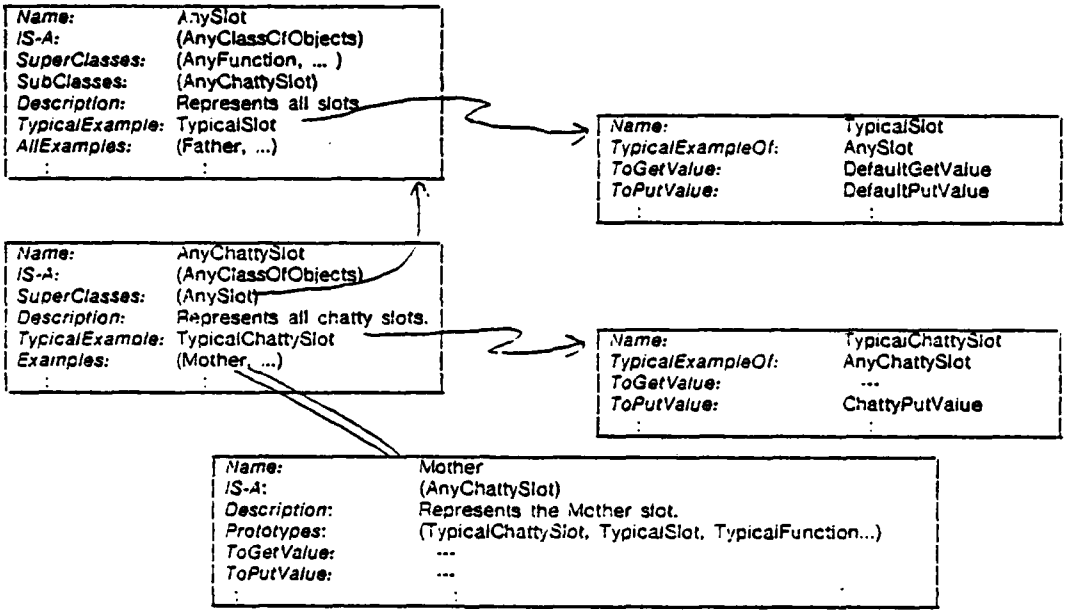

Figure # 10 - Altered framework for Mother slot.

In terms of this inheriting mechanism, there is nothing special about slots, or classes of slots. We could, with equal ease, have generated new categories of poultry by this same mechanism. All slots whose "inheritance criteria" matched *ToGetValue*'s (i.e. whose *ToCompute* was set to FindDefault,) would inherit features from this new typical chicken, as the descendants of AnyChattySlot inherited slot values from TypicalChattySlot, examples of AnyMusician could derive properties from TypicalMusician, or examples of AnyDuckbillPlatypus found default values on TypicalDuckbillPlatypus.[27]

B.2: Overview of EURISKO System
Use of Agendae, Tasks and "Generalized Production Rules"

This RLL-1 work developed from a desire to produce (the foundations) of EURISKO -- a system capable of discovering new heuristics. To facilitate this pursuit, a very flexible processing structure had to be created. One mechanism selected employed multiple agendae, each containing a host of domain-specific tasks, pertinent to a single coherent topic. To "run" a task, EURISKO first finds the set of relevant heuristic rules, and then invokes each rule as appropriate, until reaching some termination criterion (such as exhaustion of all allotted resources). What complicates this process is the fact that determining such rule sets is itself a task, which appears on an agenda. Similarly,

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[27] It is worth repeating the comment stated in Footnote 11: This inheritance mechanism is NOT built into RLL-1, and is never forced on the user. It is simply one of a large collection of parts he may use in whatever manner he chooses. In fact, only some of RLL-1's initial slots use only this inherit-by-default method to deduce a needed value; many others will use it as a last resort, after a prefered alternate method (such as parsing the *HighLevelDefn*) has failed; and yet others never even consider it.

deducing how to execute such a collection of rules is a task, as is essentially every other non-trivial process.

The standard flavor of production rules, containing just an "IF" predicate, followed by a set of "THEN" actions, is unnecessarily restrictive. Furthermore, in most systems, these rules are placed in an unordered list, which must be scanned, *in toto*, to find all relevant rules. Several other recent projects have also found standard rule systems severely lacking. Attempting to address (and hopefully solve) such inadequacies, [*Fagan*] put additional data into each rule; and [*Lenat*], [*Aikins*], and [*Smith&Clayton*] found natural (and useful) ways to organize collections of rules into a hierarchy. These, and other limitations of "Pure Production Rule Systems", are discussed in [*Lenat&McDermott*].

Rules still possess too many good qualities to pass them up. One would still like to store the procedural as well as the declarative knowledge in small chunks, each including not only this morsel of information, but also some idea of when it should be used, and how. The obvious drawback to this is efficiency: considering just the overhead each subunit will require, this segmented body has to take more space to hold than a comparable single program. Furthermore, it will usually require more time to interpret a collection of rules than to run that equivalent piece of code. EURISKO has finessed this dilemma by retaining both versions (i.e. distinct encodings) of an operation (and possibly others) and utilizing each when that encoding is most appropriate. The most inefficient, but easiest to modify, version will be this set of rules.

Maintaining consistency amoung these versions, of course, is a non-trivial problem. However, the mechanism shown in Appendix A.2, with respect to slots, is adequate for the task. Basically, we would need to associate with each successively more complex version the procedure for building it out of simpler forms -- a compiler of sorts. Then when, for example, the collection of rules is modified, EURISKO would simply invalidate (e.g. erase) the source code version. (This might start a cascade, which would cause the compiled version and possibly other things dependent on this function to be erased as well.) If this function is later needed, EURISKO would try to retrieve the now-erased function. This would, in turn, trigger an If-Needed procedure, which would construct (and cache) this source code from the rules; and EURISKO goes on.

To accommodate a system as complex and self-referential as EURISKO, it is necessary to store a vast assortment of information in each rule; and to organize them into a usable structure. For obvious reasons, we chose to represent each rule as a full unit, whose slots indicate not only how and when to fire it, but other usable, if not executable, facts as well (e.g. *HowCreated*, *AverageRunningTime* or *OverallWorth*).

A task's first step is to search the knowledge base for the set of relevant rules. (Recall this selection and gathering process is itself just another example of a task to be performed, which in turn, will be based on a collection of rules, and so forth. By appropriately caching necessary values, RLL-1 avoids the problem of infinite regressions.) Running this task will, at first, require slowly interpreting these rules, with a meta-level process observing. During such early runs this collection will be modified to optimize the order of rule firing, and prune away extraneous and superfluous rules. Once a stable rule set has been determined, this collection will be composed into another encoding of this procedural information: a single piece of runnable code.[28] At this point, the generating body of rules can simply be swapped out, in much the same way source code need not be present when its compiled form is being executed.

In general, the result of this arduous process will be cached. The next time this task, or any sufficiently similar one, is to be run, this "compiled information" will be used, (which avoids

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[28] We have not yet begun to write this rule-composition procedure. Recent research by [*vanMelle*] and [*Forgy*] has indicated this will be quite a complex undertaking. The first version planned will be fairly straightforward -- using only local and totally syntactic operations. Subsequent iterations may perform various optimizations to the output code. Eventually we would like to see EURISKO both propose and implement such improvements.

rerunning the entire task-generating process outlined above). If trouble is encountered later, or when considering applying this operation to a new domain, the original rule set can easily be retrieved and reanalyzed, to be corrected or augmented as required. In most cases, however, the efficient code is simply executed. Hence, in the long run, all of this flexibility is at essentially no long-term cost, using only the mechanism we saw used for Example 4.3!

With this model, rules fit naturally into RLL-1's Cognitive Economy framework (see Section 5.2) and we have attempted to incorporate them extensively in RLL-1's internal processing as much as possible.

B.3: Creating a New Inheritance Mode

Suppose a geneticist wishes to define a type of inheritance, one which skips every second generation when determining the properties of a new unit. He browses through the hierarchy of units descending from the general one called Inheritance, until he finds an existing unit, InheritSelectively, which closely resembles his goal inheritance facility. This he copies into a new unit, InheritFromEvery2ndGeneration. Editing this copy, he finds a high level description of the path to be taken during the inheritance. To achieve the generation skip, he replaces each single occurrence of "*Parent*" by "*GrandParent*" (or by two occurrences of *Parent*, or by the phrase (Composition *Parent Parent*)) in this part specification. After exiting from the edit, the new type of inheritance will be active; RLL-1 will have translated the slight change in the unit's high-level description into a multitude of low-level changes. If the geneticist now specifies that Organism#34 is an "InheritFromEvery2ndGeneration offspring" of Organism#20, this will mean the right thing: that Organism#34 has about the same chance of glacouma as Organism#20 had, and that we should expect their political slants -- e.g. Radical/Conservative -- to be similar. It is worth noting that the tools used (browser, editor, translator, etc.) are themselves encoded as units in RLL-1.

It is no harder to create a new type of slot format (OrderedNonemptySet), slot combiner (TwoMost, Starring), or datatype (MustBePersonOver16), than it was to create a new slot type or inheritance mechanism. Explicitly encoding such information helps the user (and us) understand the precise function of each of the various components. We do not yet (and probably never will) have a complete set of any of these components, but are encouraged by empirical results like the following: The first two hundred slots we defined required us to define thirteen slot combiners, yet the *last* two hundred slots required only five new slot combiners.

B.4: Epistemological Status

There are many ways of handling the wealth of problems associated with representing the epistemological status of things like facts, assertions and beliefs. We assumed, in designing the initial RLL-1 system, that most statements are, in fact, facts. Based on this, it is efficient to leave these completely "unmarked", and realize the additional cost of handling statements with other "epistatuses" (shorthand for "epistemological statuses"). Hence, to represent the statement that John believes that Mary is 37 years old, RLL-1 adds the ordered triple (*Do* SeeUnit AgeOfMary0001) to the the *Age* slot of the Mary unit.[29] RLL-1 creates a unit called AgeOfMary0001, fills its **valUe** slot with 37 and its *EpiStatus* slot with "John believes". See Figure 11. Note this mechanism suffices to represent belief about belief (just a second chained SeeUnit pointer), quoted belief ("John thinks he knows Mary's age", by omitting altogether the **val.ue** slot in some AgeOfMary0001 subunit), situational fluents, etc. This mechanism can also be used to represent arbitrary n-ary relations (such as "John gave the ball to Mary"), thereby escaping the limitations associated with associative triples (i.e. Unit/*Slot*/value). Other ways of handling these are discussed in [*Genesereth&Lenat*].

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[29] This "*Do*" prefix is special. Appendix D.4 shows this notation sufficient to handle effectively all special cases of slot value, if awkwardly.

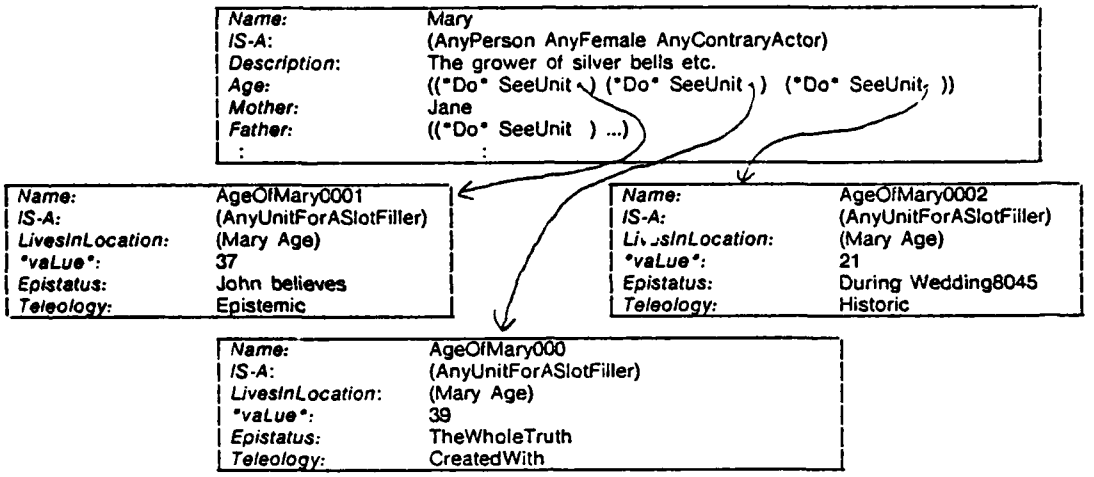

Figure # 11 - Representing "John believes that Mary is 37, but she's really 39. When she was married, she was 21".

C. APPENDIX - Syntactic vs Semantic Types of Slots, Revisited

In Section 5.3 we distinguished semantic slots from syntactic ones. Technically, syntactic slots of a unit U belong in the meta-node above U, as they refer to the unit U *qua* unit. We could create such a meta-unit, e.g. *FactsAboutTheUnitKPE*, to store all the facts about the KPE unit, and store this within our system. This *FactsAboutTheUnitKPE* unit would have slots like *TimeOfCreation*, or *Size*. The values stored there, such as *3 October 1980*, or *96 Lisp Cells*, are facts about the KPE unit, and NOT about KPE himself, who was born on *8 March 1714*, and is actually *5'10"* tall. The obvious question is "When was the *FactsAboutTheUnitKPE* unit created?". To find this answer, one should logically go to the *FactsAboutTheUnitFactsAboutTheUnitKPE* unit. And when was that unit created? and so on...

So we have chosen to compress these two, logically distinct units into a single physical entity. In addition to the argument above, empirical evidence has shown that these two units consistently are used together; and so should be, for example, swapped into core together. Epistemological marks are used to distinquish those slots which refer to that external entity, from those which, in fact, pertain to this unit itself.[30] Slots in the first category, the semantic slots, work cleanly for all of our functions. There were several difficulties which arose when dealing with Syntactic slots - those which pertain to this unit *qua* unit.

Diagram#1, in Appendix E, shows that essentially all of the units of the system descend from the "AnyConcreteThing&Unit" class. Our intend was that each such "concrete-thing-&-unit" represent both some entity in the "external" world, and itself. The cleanest way of achieving this was as follows:

Consider first the class of all centaurs. To indicate that each centaur is both a man and a horse, we would place on the TypicalCentaur unit a *ComposedOf* slot, whose value is the list (TypicalMan TypicalHorse). The meaning of this is straightforward: each centaur should inherit characteristics from both its manliness and its horsiness.

Now examine the TypicalConcreteThing&Unit unit. This unit, *qua* unit, is in fact composed of two parts -- its pieces come from the fact it represents a unit, and the fact that it represents a concrete thing. So its meta-unit, the FactsAboutTheUnit*TypicalConcreteThing&Unit*, should have the *ComposedOf* value of (TypicalUnit TypicalConcreteThing). As this meta-unit is NOT disjoint from the object-level TypicalConcreteThing&Unit unit, we give it a *MyComposedOf* slot, whose value is that (TypicalUnit TypicalConcreteThing) list. (Note TypicalAbstractThing&Unit is handled the same way.)

The next difficulty arose when dealing with inheritance. Consider the task of creating a new unit, say KPE, which is defined to be an *Example* of AnyMusician. A simple scheme, which would work ideally for semantic units, would be to map through the set of inheritable slots of TypicalMusician (note this is value stored on TypicalMusician:*MyInheritableSlots*.) and, for each slot, *S*, store on KPE:*S* the value held in TypicalMusician:*S*. So KPE:*Size* would receive the *Size* of TypicalMusician, which is what you would want.

Now we know that every unit representing a musician will be created by Procedure#114, the musician creating routine. It would be nice to store this syntactic slot, *MyCreator*, on TypicalMusician, and let each new musician inherit this information. Unfortunately, this TypicalMusician unit was itself created by the routine which specialized in creating typical examples, Procedure#21.

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[30] We indicate this difference by a simple naming convention: The name of each syntactic slot will begin with "*My*" -- i.e. *TimeOfCreation* versus *MyTimeOfCreation*, or *Size* versus *MySize*.

The solution we used is for each type of slot to know to which category it belongs - Syntactic vs Semantic. Semantic slots work unhampered. However, the unit for each syntactic type of slot has a special slot, *StoredInTypAs*, which points to the name of another slot, on which the value to be inherited is stored. Here, MyCreator:*StoredInTypAs* had the value *Creator-Instances*. The value stored on TypicalMusician:*MyCreator* is Procedure#21, and refers only to this particular TypicalMusician unit. The inheritance scheme, on seeing *MyCreator* on TypicalMusician:*InheritableSlots*, knows enough to use the value stored on TypicalMusician:*Creator-Instances*, which, happily, is Procedure#114. This is the value to which KPE:*MyCreator* is initialized.

(NOTES: The Inheritance mechanism demonstrated above is a vastly oversimplified version of one of the several inheritance schemes resident to RLL-1. Like the rest, it is encoded as a unit, and can be modified by any user to serve his particular needs.)

D. APPENDIX - IMPLEMENTATION PRINCIPLES

D.1: Make Standard Case Fast: This system should perform not only correctly, but expediently as well. Towards this end, a self-imposed design criterion is to optimize what we expect to be the standard, most common case; even at the anticipated increased cost for less common situations. Note this philosophy is reflected in CORLL's retrieval strategy as well -- we have minimized the speed of accessing a slot's value when that unit is in core, and accept the longer times required when that unit must be read in. The underlying assumption is that after a unit has been accessed once, it will probably be used several more times before being read out. Furthermore, this reading process has to be fast, as it will undoubtedly be central to the inner-most loop of RLL-1's operations.

For similar reasons, we have chosen to optimize retrieving a slot's value, at the expense of storing such a value. RLL-1 will, in general, also spend extra time storing a computed value; as this is a one time expenditure, and it is likely this value will be needed often.

D.2: Least Commitment: Throughout RLL-1's ongoing design we have attempted to minimize the constraints the RLL-1 functions force upon the unit, as every eventual user will have to tolerate these. (This point is closely related to the issue of having an unbiased initial system, discussed in Section 6.7.) To accomplish this, while still permitting the basic RLL-1 package to perform the various detailed tasks expected of a usable knowledge base system, this system includes a versatile KB manipulating subsystem. The functions this requires are stored as the values of various slots of certain high-level units, where they belong (see Section 5.5). As shown above, the user with a more specialized task in mind can readily override these general functions, by simply rewriting these slots' values with functions of his own.

(These specific functions, while essential for the *starting* system to work, are not sacred. Indeed a self-serving designer may use them for the single task of storing a different set of functions in their places. Thereafter all GETs and PUTs would go through these just-entered functions. The bootstrapping functions used to prime the pump are documented in Appendix F.2. These were designed to demonstrate one possible, easily extendable, way in which this system could work.)

D.3: Compile Time Macros: Associated with each type of slot is a pointer to the routine which this slot uses to perform write and retrieve its value from a unit. (See Section 4 and Appendix A.) Determining, say, the *Wife* of JSB requires first asking the unit Wife for its *ToGetValue* slot, and then applying that function to the unit JSB. (Similar RLL-1 functions are used for putting a value, or initializing a unit, etc.) In most cases, Wife:*ToGetValue* will remain fairly constant over long periods of time -- in particular, from the time a function which asks for the *Wife* of some unit is compiled, until the time that function is actually executed.

To shorten the run-time cost, we employ various sophisticated macros for these basic accessing functions. Whenever possible, these run-around the Knowledge Base at compile time, determing the specific getting or putting function associated with this slot. This function is called directly at run time, avoiding the overhead mentioned above. Note that RLL-1 has stored on the Wife unit the set of "macro-ed" functions, which enables it to invalidate the compiled form of these functions if Wife:*ToGetValue* is later changed.

D.4: Special Slot Values: By definition, the value of the *S* slot of the unit, U, is what (GetValue U S) returns; and this, in turn, depends on the function stored (or virtually stored) on S:*ToGetValue*. Unless intercepted or overwritten, the value of a S:*ToGetValue* will be DefaultGetvalue. With this in mind, this section discusses what this standard retrieval function, DefaultGetValue, regards as values.

The standard value of a slot (i.e. the value returned by DefaultGetvalue) is exactly the value physically stored there, except for the following few cases. To disambiguate the case when a unit does not have a slot from when the value of that slot is actually NIL, the values NoEntries (indicating that this value is known to be the empty list) and NoEntry (meaning an empty single value,) are used. (Following the delegation of responsibility comment mentioned in Section 5.5, it is the various

individual formats which "know" and use this fact -- N.B. it is NOT built into any of the retrieval functions.) When the value of this slot is not known, the value RecomputeMe will be stored as its value. This is built into the basic defaulted accessing functions, in that none of them distinguish this RecomputeMe value from the case of finding that this slot does not physically appear in the unit.

The only other special case allows the user to specify a more arbitrary format for the value of this slot. The value (*Do* <format-name> v_1 v_2 ... v_N) indicates the values (v_1 v_2 ... v_N) should only be regarded with respect to the format (or epistemological mark) <format-name>. For example, (*Do* OneOf Red Yellow) indicates the value of this slot is either Red or Yellow. Note the semantics of that statement are based on the unit OneOf, which is, of course, accessable and modifiable by the user.

As Appendix B.4 shows, there are times a full unit is devoted to store the information associated with Unit:*Slot*. Here, the entry stored associated with *Slot* on the unit, Unit, is of the form (*Do* *FSeeUnit SlotOfUnit*). This uses the format unit *FSeeUnit* which knows that the real value of *Slot* is stored in the **vaLue** slot of the unit, *SlotOfUnit*. RLL-1 is equipped with several other subspecies of indirect pointers; and the user, of course, is free to concoct his own.

Everything described above has been implemented. There is, however, considerable concern that this mixes and confuses epistemological and notational marks. This is now being hammered out; and the way subsequent generations/releases of RLL-1 will handle this situation will depend on these discussions.

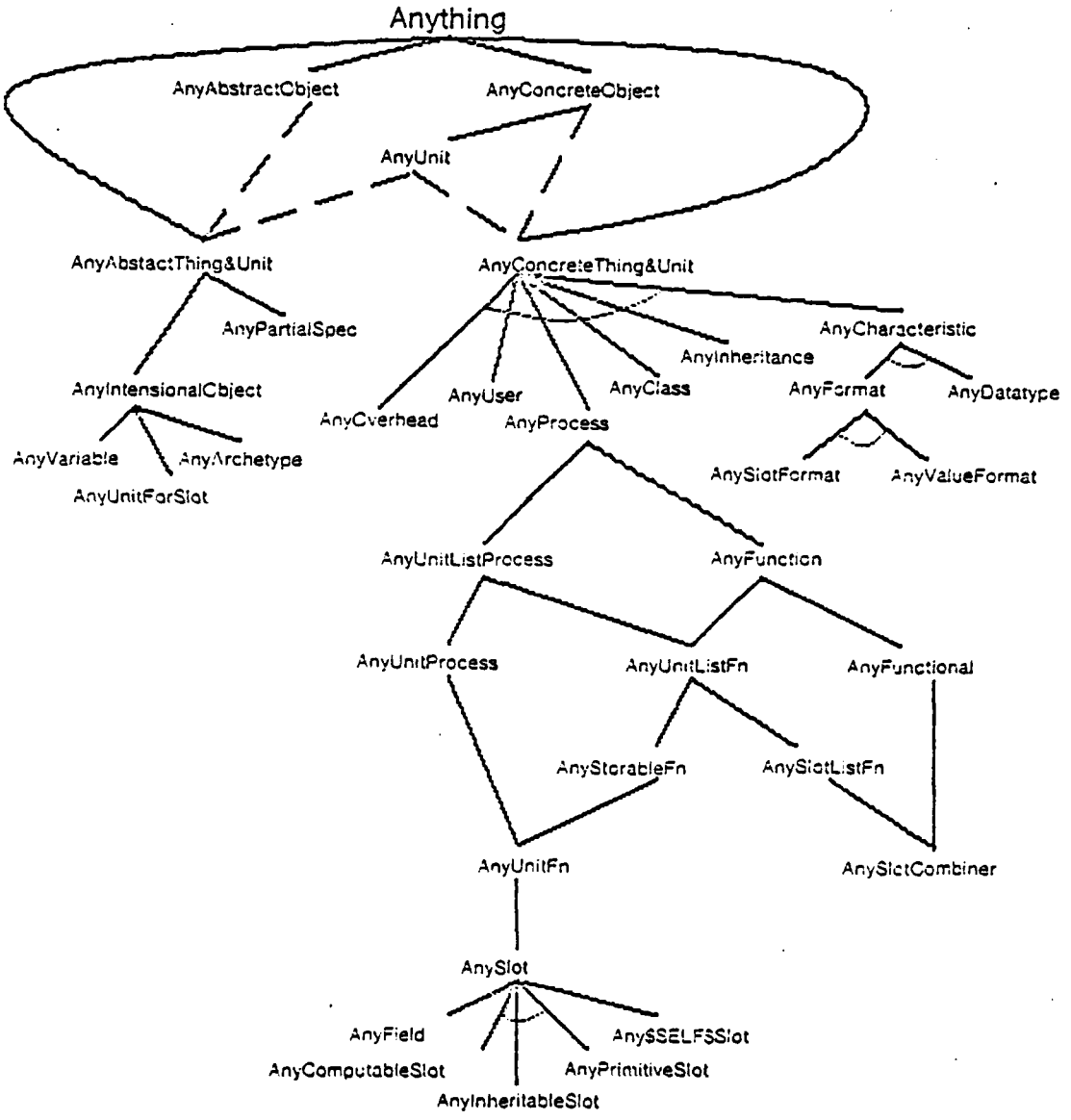

Diagram #1 (cf Appendix)

Classes of Units

BIBLIOGRAPHY

Artificial Intelligence: An International Journal, April 1980 (Special Non-Monotonic Logic Issue,) Volume 13, Numbers 1 and 2.

Aikins, Jan, "Prototypes and Production Rules: An Approach to Knowledge Representation from Hypothesis Formation", HPP Working Paper HPP-79-10, Computer Science Dept., Stanford University, July 1979.

Bledsoe, W. W., "Non-resolution Theorem Proving", *Artificial Intelligence: An International Journal*, Volume 9, Number 1, August 1977, pp. 1-36.

Bobrow, D.G. and Winograd, T., "An Overview of KRL, a Knowledge Representation Language", 5-IJCAI, MIT, August 1977.

Brachman, Ron, "What's in a Concept: Structural Foundations for Semantic Networks", *International Journal of Man-Machine Studies* 9, 127-152 (BBN report 3433, October 1976).

Brachman, Ron, "On the Epistemological Status of Semantic Networks", in Associative Networks, Nicholas V. Findler (ed.), Academic Press, 1979, pp. 3-49.

deKleer, Johan, Doyle, Jon, Steele, Guy L. Jr., and Sussman, Gerald Jay, "AMORD: Explicit Control of Reasoning", SIGART Newsletter, Volume 12, No. 8, August 1977, pp. 116-125.

Davis, Randy, "Applications of Meta Level Knowledge to the Construction, Maintainance and Use of Large Knowledge Bases," Stanford AI Laboratory, Memo AIM-283.

Doyle, Jon, "A Model for Deliberation, Action, and Introspection," PhD Thesis, Massachusetts Institute of Technology, June, 1980.

Erman, L. D., and Lesser, V. R., "A multi-level organization for problem solving using many, diverse, cooperating sources of knowledge", 4-IJCAI, Tbilisi, USSR, 1975, pp. 483-490.

Fagan, Lawrence, "Representing Time Dependent Relations in a Medical Setting", PhD Thesis, Stanford Univerisity, 1980.

Fahlman, S. E., "*NETL:* A System for Representing and Using Real-World Knowledge", MIT Press, Cambridge, Massachusetts, 1979.

Fikes, R. F., and Nilsson, N.J., "STRIPS: A New Approach to the Application of Theorem Proving to Problem Solving," *Artificial Intelligence* 2, 1971, pp. 189-208.

Findler, Nicholas V. (ed.), Associative Networks, NY, Academic Press, 1979.

Forgy, C. L., "On the Efficient Implementation of Production System", PhD Thesis, Carnegie-Mellon University, Department of Computer Science, Feb 1979.

Forgy, C. L. and McDermott, John, "OPS, A Domain-Independent Production System", 5-IJCAI, MIT, 1977, pp. 933-939.

Genesereth, Michael, "Fast Inference Algorithm Based on a Constraint Propagation of Marks in a Semantic Network", MathLab Memo 4, MIT, Cambridge, Massachusetts, 1976.

Genesereth, Michael, and Lenat, Douglas B., "Meta-Description and Modifiability", HPP Working Paper HPP-80-18, September, 1980.

Green, Cordell, Richard P. Gabriel, Elaine Kant, Beverly I. Kedzierski, Brian P. McCune, Jorge V. Phillips, Steve T. Tappel and Stephen J. Westfall, "Results in Knowledge Based Program Synthesis", 6-IJCAI, Tokyo, 1977.

Greiner, Russell, "Details of RLL-1", Stanford HPP Report HPP-80-23, Computer Science Dept., Stanford University, October 1980.

Hayes-Roth, Frederick, Waterman, D. A. and Lenat, Douglas B., Designing Expert Systems, in construction.

Hewitt, Carl F., "Description and Theoretical Analysis (using schemata) of PLANNER: a language for Proving Theorems and Manipulting Models in a Robot," MIT AI Laboratory, TR-258,

1972.

Hewitt, Carl F., Attardi, Guiseppe, and Simi, Maria, "Knowledge Embedding in the Description System Omega," 1-AAAI, Stanford, 1980, pp. 157-163.

Kunz, J. C., R. J. Fallat, D. H. McClung, J. J. Osborn, B. A. Votteri, H. P. Nii, J. S. Aikins, L. M. Fagan and E. A. Feigenbaum, "A Physiological Rule-Based System for Interpreting Pulmonary Function Test Results", HPP Working Paper HPP-78-19, Computer Science Dept., Stanford University, November 1978.

Lenat, Douglas B., "AM: Automated Discovery in Mathematics", 5-IJCAI, August 1977

Lenat, Douglas B. and Harris, Gregory, "Designing a Rule System That Searches for Scientific Discoveries", Pattern-Directed Inference Systems, D. A. Waterman and Frederick Hayes-Roth, (ed.), Academic Press, Inc., 1978, pp. 25-52.

Lenat, Douglas B., Hayes-Roth, F. and Klahr, P., "Cognitive Economy", Stanford HPP Report HPP-79-15, Computer Science Dept., Stanford University, June 1979.

Lenat, Douglas B. and McDermott, John, "Less Than General Production System Architures", 5-IJCAI, MIT, 1977, pp. 928-932.

Lesser, V. R. and Erman, L. D., "A Retrospective view of the HearSay-II Architecture", 5-IJCAI, MIT, 1977, pp. 790-800.

Levesque, Hector, and Mylopoulos, John, "A Procedural Semantics for Semantic Networks", in Associative Networks, Nicholas V. Findler (ed.), Academic Press, 1979, pp. 93-120.

Mackinlay, Jock and Genesereth, Michael, "DB Reference Manual", Internal HPP Memo, August, 1980.

Manna, Zohar and Waldinger, Richard, "A Deductive Approach to Program Synthesis", 6-IJCAI, MIT, 1977, pp. 542-551.

McDermott, Drew and Sussman, Gerald, "The Conniver Reference Manual", MIT AI Laboratory, TR-?, 1974.

Michie, Donald, "Memo functions: a language facility with 'rote learning' properties", Reasearch Memorandum MIP-r-29, Edinburgh: Department of Machine Intelligence and Perception, 1967.

Minsky, Marvin, "A Framework for Representing Knowledge", in The Psychology of Computer Vision, P. Winston (ed.), McGraw-Hill, New York, 1975.

Nii, H. Penny, and Aiello, N., "AGE (Attempt to Generalize): A Knowledge-Based Program for Building Knowledge-Based Program", 6-IJCAI, Tokyo, August 1979.

Phillips, Jorge, "Self-Described Programming Environment: An Application of a Theory of Design to Programming Systems", forthcoming PhD Thesis, Stanford University, December 1980.

Quillian, M. R., "Semantic Memory", in Semantic Information Processing, Marvin Minsky (ed.), MIT Press, Cambridge, Massachusetts, pp. 227-270.

Reiter, Raymond, "On Reasoning by Default", Theoritical Issues in Natural Language Processing-2, Urbana, Illinois: Association for Computing Machinery, 210-218.

Roberts, R. B., and Goldstein, Ira P., "FRL Users' Manual", A.I. Memo 408, Artificial Intelligence Laboratory, MIT, Cambridge, Massachusetts, 1977.

Sandewall, Erik, "Ideas about Management of LISP Data Bases", 4-IJCAI, Tbilisi, Georgia, USSR, 3-8 September 1975, pp. 585-591.

Schubert, Lenhart K., Goebel, Randolph G., and Cercone, Nicholas J., "The Structure and Organization of a Semantic Net for Comprehension and Inference", in Associative Networks, Nicholas V. Findler (ed.), Academic Press, 1979, pp. 121-175.

Shank, Roger C. and Abelson, Robert P. Scripts, Plans, Goals and Understanding: An Inquiry into Human Knowledge Structures, Hillsdale, NJ: Lawrence Erlbaum Associates, 1977.

Shortliffe, E.H., Computer-based Medical Consultations: MYCIN, New York: American Elsevier, 1976.

SIGART Newsletter, February 1980 (Special Representation Issue; Brachman & Smith, eds.).

Smith, Brian, "Levels, Layers, and Planes: The Framework of a System of Knowledge Representation Semantics", Master's thesis, Artificial Intelligence Laboratory, MIT, Cambridge, Massachusetts, 1977.

Smith, David and Clayton, Jan, "A Frame-based Production System Architecture", 1-AAAI, Stanford University, August 1980.

Smith, David, "CORLL: A Demand Paging System for Units", HPP Working Paper HPP-80-8, July 1980.

Stefik, Mark J., "An Examination of a Frame-Structured Representation System", 6-IJCAI, Tokyo, August 1979.

Szolovits, Peter, Hawkinson, Lowell B., and Martin, William A., "An Overview of OWL, A Language for Knowledge Representation", MIT/LCS/TM-86, Massachusetts Institute of Technology, June 1977.

van Melle, William J., "A Domain-Independent System for Constructing Consultation Systems", PhD Thesis, Stanford University, June 1980.

Waterman, D. A. and Hayes-Roth, Frederick, editors, Pattern-Directed Inference Systems, Academic Press, Inc., 1978.

Weiss, Sholom M., and Kulikowski, Casimir A., "EXPERT: A System for Developping Consultation Models", 6-IJCAI, August 1979, pp. 942-947.

Weyhrauch, Richard W., "Prolegomena to a Theory of Formal Reasoning," Stanford AI Laboratory, AIM-315, December 1978.

Winograd, Terry, "Beyond Programming Languages", Communications of the ACM, pp. 361-ff., July 1979.

Woods, W. A., "What's in a Link, Foundations for Semantic Networks", in D. G. Bobrow & A. M. Collins (eds.), Representation and Understanding, Academic Press, 1975.