INCOMPLETE DRAFT NOTES

(Part of CoSy deliverable DR.02.01:

Requirements study for representation)

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Towards an ontology for factual questions

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Contents

1 Introduction: the need for a question ontology

This paper started as a presentation of some ideas about the variety of types of questions that can elicit information or at least express a need for information, or specify a gap in information available to some information-user. This is not a question about communication between agents (e.g. asking questions) but about processing *within* an agent. An agent deciding what to do might discover that it needs some information, e.g. about the current environment, about whether preconditions for some action are satisfied, about what the consequences of the action could be, etc.

After some exploration of these ideas it became clear that something had to be said about the space of possible facts within which questions (information gaps) could arise. So the paper split into two strands, dealt with in separate documents. This document is concerned with how to form questions expressing information gaps, and the other document *'Towards an ontology for factual information for a playful robot'*[1], also subsumbed in CoSy deliverable DR.02.01 (Requirements for Representations), deals with the sorts of information a robot may have about its environment, restricted, for now, to an environment without other intelligent agents. Such an agent (e.g. an animal or robot) may sometimes discover gaps in its information, which can lead it to take steps to fill the gaps, such as looking in a new direction, processing its current sensory information differently (e.g. attending to specific features and relations), going somewhere else, making a prediction, recalling something, or deriving new information from existing information. If there are other agents who might know the answers it can also ask questions, but not all questions are concerned with getting information from another individual.

Both the analysis of required types of factual information and the analysis of possible information gaps and what to do with them are huge topics, but the present discussion is constrained by the needs of the two scenarios being developed within CoSy, initially focusing on the PlayMate robot scenario.[2] This scenario is based on a robot able to perceive, manipulate and talk about 3-D objects on a table top, including eventually assembling complex objects from components and talking about the process with a collaborator, a teacher, or a pupil. For present purposes we shall focus only on the physical environment, leaving for another paper the extension of the question ontology to include questions about beliefs, percepts, thoughts, capabilities, and current mental state of another individual (or oneself).

Although our scenario ultimately has to include linguistic competence, it is likely that such competence will build on more fundamental and general forms of competence shared by pre-verbal human children and other animals that manipulate objects – such as New Caledonian crows.[3] So this document is a first draft incomplete investigation into some of the kinds of information gaps that a pre-linguistic robot with perceptual and manipulative skills may need to cope with, especially one which needs to know what it is doing and why.

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[1]Available as CoSy Discussion Paper COSY-DP-0501
http://www.cs.bham.ac.uk/research/projects/cosy/papers/#dp0501

[2]See URL http://www.cs.bham.ac.uk/research/projects/cosy/PlayMate-start.html

[3]Betty, the New Caledonian crow in the Oxford Zoology lab made headlines in 2002 when she demonstrated that she could make hooks out of wire in order to retrieve food in a basket from the bottom of a tube. See URL http://users.ox.ac.uk/.kgroup/tools/tools.main.shtml

2 Self-knowledge may be about gaps in knowledge

There is growing interest in self-aware computing systems. See for example McCarthy (1995), and the position statements for a DARPA workshop on self-aware systems held in 2004[4]

What is not always appreciated is how important it is for an intelligent system to discover gaps in the information available to it so that it can take steps to fill the gaps. Later, we'll see that some kinds of intelligence require the ability to cope not only with gaps in information about *the current situation*, but also gaps in information about *hypothetical situations* that could arise, if certain actions were performed. Identifying and dealing with those gaps will require more complex architectures than simply noticing that you don't know what is behind you. For now we ignore those complications and discuss only gaps relative to what is the case.

3 The need for an abstract syntax

Asking questions externally requires formulating sentences in a public language using syntactic constructs of that language to express both that the utterance is a question and also what the semantic content of the question is, namely what information is required. In contrast, for internal purposes a robot or animal needs only a form of representation that expresses the *content* of the question, since the fact that it is a question could be determined by the information-processing context in which the question is being formulated.

This requires a means of representing those information gaps, which in ordinary parlance amounts to a means of expressing questions. We show how to derive a wide variety of question forms from a language that is capable of expressing factual information. The simplest example would be taking whatever expresses some fact (e.g. the internal representation of 'The blue box is empty') and treating it as having an unknown truth-value instead of treating it as true. More complex types of questions of various types, require more or less complex syntactic transformations of a propositional expression, as illustrated in the remainder of this paper. The presentation here is informal, since we do not presuppose any particular well defined formalism for expressing propositions, though we assume at least the richness of first-order, and possibly second-order propositional calculus. How exactly that kind of syntax is expressed in the mind of an animal or a robot is a separate question. We also leave open the possibility that some animals and robots, and of course young children, will be able to cope with only a subset of the forms and transformations described here. We postpone for now the task of explaining how to derive questions from non-propositional formats for expressing information, for example maps or diagrams, even though in biological evolution and child development it is possible that those came first.

4 Driving idea

Concerning questions, the driving idea is that every question content (every specification of a need for factual information) can be expressed by starting with a true/false propositional form then creating zero or more gaps in that form by removing components and then applying various question-forming operators to the resulting gappy structure, the simplest such operator being 'Is it true that...', which requires no gaps. This point is independent of exactly how the logical forms are rep-

[4]http://www.ihmc.us/users/phayes/DWSAS-statements.html

resented, as long as they are 'Fregean' representations, in the sense of [Sloman 1971][5]). There are many different syntactic forms with the same semantics that can be used in intelligent systems. The comments about question formation apply to all of them. In systems using hybrid representations, e.g. a mixture of logical forms and map-like structures (labelled 'analogical' in [Sloman 1971]), some generalisation of the method for deriving question forms from propositional forms would be required, but that is a topic for another occasion.

In general, several questions can be derived from any proposition, by creating gaps in different places, and by applying different question-forming operators to the gaps.

Obviously, developing the ontology for questions (information-gaps) presupposes a prior ontology for the kinds of propositions from which the questions could be derived. So a substantial part of the ontology presented here is common to both factual propositions and factual questions.

What follows is not a totally general ontology. The survey is restricted to types of factual information that may be discovered, or needed, or used, by an animal or machine with a physical body, located in space, enduring over time, and perceiving things, preforming actions and thinking about objects, events, and processes (including actions) that might be relevant to an animal or robot manipulating and thinking or talking about 3-D objects on a table top, as in the PlayMate[6] scenario of the CoSy project.

The survey is concerned mainly with factual information and gaps in factual information, though some of the ideas might be applicable to other forms of information (e.g. control information, as expressed in imperatives, discussed briefly below).

4.1 Questions for thinkers as well as communicators

Some suggestions are made about possible forms of propositions and forms of derived questions that can arise both in dialogues and in thinking. I believe that the ideas are widely applicable in the design not only of dialogues between agents (as in PlayMate) but also agents that have dialogues with themselves, for instance when planning or reasoning, or wondering what to do, or why something happened. In the latter cases the forms of question and answer need not necessarily be translated, or even translatable, into external linguistic forms. Some of them could be used by pre-verbal children or other animals. Exactly which subsets can be used by which types of individuals is an empirical question which this document does not address, though it ends with some brief comments on how this relates to pre-verbal cognitive processes in a predominantly altricial species. The altricial-precocial spectrum in organisms, and its possible application to robots, is discussed in another paper.[7]

I don't claim that any of this is original: the idea about questions arising out of gaps is based on something dimly remembered from my youth as a philosophy student in Oxford 1957-1962, but I cannot be more specific as to where the ideas came from, except that it builds heavily on the logical investigations of Gottlob Frege[8] about a hundred years ago. The powerful idea that gaps in propositions can be filled in many ways, including the use of quantifiers was, I believe, independently discovered by G.Frege and C.S.Peirce, breaking away from the previously held (Aristotelian?) view that in a sentence like 'All As are Bs' the subject of the sentence is some entity referred to as 'All

[5]See URL http://www.cs.bham.ac.uk/research/cogaff/sloman-analogical-1971.pdf, also available in HTML: http://www.cs.bham.ac.uk/research/cogaff/sloman-analogical-1971

[6]See URL http://www.cs.bham.ac.uk/research/projects/cosy/PlayMate-start.html

[7]See URL http://www.cs.bham.ac.uk/research/cogaff/altricial-precocial.pdf

[8]There are many other overviews of his work available online and in print, e.g. http://plato.stanford.edu/entries/frege, http://www-groups.dcs.st-and.ac.uk/.history/Mathematicians/Frege.html

As'. On Frege's analysis the sentence is to be understood as asserting that any gap-filler that makes '... is an A' true will also make '... is a B' true. (There are people, e.g. the philosopher Fred Sommers, who believe that Aristotle was right and Frege wrong, but I shall ignore that debate.)

Logicians will recognize that much of what is said about gaps here can be expressed using Lambda Calculus, the formal notation Alonzo Church developed inspired by the rather more clumsy formalisms invented by Frege. I have decided to keep this presentation informal, instead of using lambda expressions or a similar notation.

Looking for related work on the internet, I found a recent PhD thesis which develops ideas about question types very close to the ideas about questions presented here:

> Debra Thomas Burhans (2002)
> *A Question Answering Interpretation of Resolution Refutation*[9]
> PhD Thesis, State University of New York at Buffalo Department of Computer Science and Engineering.

Nils Nilsson kindly read a draft of this document and commented that some of the early work in AI used ideas similar to those presented here. For instance work by Cordell Green[10] and others in the 1960s. It was pointed out for example that an existentially quantified proposition could be interpreted as a question whose answer would be a list of possible values for the variable in the quantifier, a relationship which in natural language would be clear between 'Is it true that someone was at the party' and 'Jill, John, Jonas and Judy were at the party'. Closely related ideas led to the design of Prolog and other logic programming languages.

4.2 Varieties of non-information-seeking types of questions

Before moving on to the task of specifying types of information relevant to our project I'll make a few remarks about restrictions on the types of questions that are relevant at least to this document.

It is clear that questions can have many different pragmatic functions, apart from eliciting information, for example:

- testing someone's knowledge
- getting someone to think about a problem (Socratic questions)
- teasing someone
- challenging someone
- being ironic or sarcastic
- drawing attention to something
- being rhetorical (in various ways)
- making a request (i.e. trying to get something done)
- asking for a definition (I constantly have to say to people: 'what do you mean by "emotion"?' in response to some comment or question about emotions.)

[9] See URL http://www.cse.buffalo.edu/.burhans/debra.ps

[10] C. Green, Applications of Theorem Proving to Problem Solving, Proceedings 1969 International Joint Conference on Artificial Intelligence (IJCAI 69), pp. 219–240

Several taxonomies of question types have been proposed, including the taxonomy often referred to as "Bloom's Taxonomy", which distinguishes different sorts of pedagogical functions of questions.[11] Ways of classifying questions in terms of their communicative or other social functions functions will be ignored here. We are concerned only with the 'core' case: use of questions to specify missing but possibly required factual information. I consider *only* the semantic content of questions and answers, ignoring all pragmatic and performative issues, and leaving open the syntax to be used in a working system. Any syntax used here is illustrative only.

5 Definitions:

- *A question* as discussed here, is a specification of a factual information gap in an information user.
- *An answer to a question* is a an information structure that fills, or reduces, the gap (or in some cases, specifies how the gap could be filled).

This leaves completely open what kind of medium is used to express either questions or answers, and what syntactic forms are used within any particular medium. It also leaves open what kinds of use are made of the information, how gaps are detected, how they are filled, how genetic information, learning or development can produce any of the competence required, how brains operate, etc.

5.1 Key ideas:

The key ideas are:

1. There is a basic type of factual question, a Yes/No question, which refers to a proposition that is capable of being true or false and requests the information whether the proposition is true or false,
2. There are ways of generating other types of factual question by creating one or more gaps in the proposition and specifying requests for information about ways of filling the gaps so as to make the proposition true (an example would be 'Which individuals satisfy: X is P?')
3. Many, though not necessarily all, factual information gaps in information users involve needs that can be expressed as factual questions of the above kinds. (Note that two kinds of gaps are involved: information gaps in intelligent systems and gaps in propositions produced by removing components of those propositions.)

E.g. if a proposition asserts 'A did X' then the question form 'Who did X?' is a natural language expression of the logical question form requesting information that can fill the gap in '... did X?' so as to produce a true proposition. Some questions are related to a single gap, others to two or more gaps, as illustrated below. Some questions refer to a gap on the assumption that there is a unique gap-filler that would make the proposition true ('Who is the murderer?') whereas others allow the answer to specify any number of fillers that could produce true propositions, or to specify

[11] See http://honolulu.hawaii.edu/intranet/committees/FacDevCom/guidebk/teachtip/questype.htm and http://www.officeport.com/edu/bloomq.htm, and for a different type of taxonomy compare: http://www.usingenglish.com/glossary/question-types.html

the number without listing them, e.g. ‘Who saw the event?’ (answer: Tom, Trudy, Tim, ...) or ‘How many people saw the event?’ (answer: none, or five, or...).

Some questions specify two or more gaps and ask about individuals standing in some relationship (e.g ‘Who is taller than whom?’).

Since propositions can take many forms, with unbounded complexity, the variety of types of gaps and gap-fillers is essentially unbounded.

Sometimes the specification of information needed requires two gaps to be filled by the same thing. E.g. ‘Who shot himself?’ involves two linked gaps in the propositional form: ‘ ... shot ... ‘. Such linking is normally expressed in formal languages by the use of variables e.g. ‘x shot x’ or ‘Shot(x, x)’, In natural languages other devices are used e.g. use of pronouns, words like ‘himself’, ‘itself’, ‘themselves’, etc. (Failure to understand what’s going on here leads many people to believe that we all have spooky entities called ‘selves’ inside us.) The natural language devices are irrelevant to the aims of this paper, which is concerned only with cognitive structures and processes that may be common to users of many different languages and to some intelligent systems that do not use what we would call an external language.

5.2 Non-factual questions

A more general definition of ‘question’ would include *control* information gaps, as expressed in questions like the following, whose answers could be imperatives rather than factual statements:

- What should I do?
- Is it better to do X or Y?

For now these are not considered, though some of what is said here would also be applicable to such cases. E.g. some of the ways in which different question forms can be generated from a single factual proposition by inserting gaps and applying appropriate operators to the proposition with gaps, would also be applicable to ways in which different control questions can be generated by inserting various kinds of gaps in an instruction, or imperative, of the form ‘A, do X?’ (e.g. talking to myself: ‘Me, do X’). Questions like ‘What should I do?’ could be interpreted (at least sometimes) as requesting the gap to be filled in the self-directed imperative ‘Me, do ...’. The difference is that instead of depending on the notion of a true proposition, control questions depend on the notion of an imperative or instruction being accepted or acceptable. There are many complications that arise from the fact that two imperatives that are independently acceptable can be inconsistent in the sense that they cannot both be acted on whereas two true propositions cannot be inconsistent. Another complication is that often a control question is not about what to do but which of two options is better[12], a topic with many complications that we shall ignore.

5.3 Varieties of answers

Here we discuss only answers that provide information to fill gaps specified in factual questions. However, as indicated above, questions can have many different functions, and so can answers. In dialogues between information users there are things that we would call answers that perform other functions besides giving answers, such as apologizing for not knowing the answer or being too busy to respond, or refusing to give the information, or challenging some aspect of the question

[12] See URL http://www.cs.bham.ac.uk/research/cogaff/sloman.better.html

– e.g. its relevance to some shared goal context, its assumptions (e.g. that there is a unique gap filler), its politeness, the right of the asker to hear the answer, the availability of information that provides an answer, etc. None of those 'pragmatic' answers will be discussed here. The scope of this document is very limited.

I believe that every question of the types surveyed below can be expressed in English, though some of the questions have very complex structures and therefore expressing them accurately in English may be difficult, or at least clumsy. E.g. consider questions derived from various ways of creating gaps in this proposition:

> *A1, B1 and C1 are in the same order on line L1 as A2, B2 and C2 are in on line L2.*

(some English speakers would omit the second 'in'.) A possible question derived from that would be:

> *Which three things in the room are on the same order on line L2 as A1, B1, C1 are in on which line?*

Linguists may be interested in debating whether this really is English or not, and if not why not, whereas for my purposes that is irrelevant since, like many other non-English sentences, the meaning is clear, as in 'Me go home after me eat', and many of the things young children and non-native speakers say. This raises important questions about what is going on in a child who wishes to ask a question but does not yet have a way to express it that will be understood by others. However that is just a special case of the ability of children to have something to communicate without yet having the linguistic competence, a situation that will be familiar to every parent.

The answer to the above question may specify a complex set of alternative ways of producing true propositions by referring to objects in the room to fill the gaps formed by removing A2, B2, C2 and L1 from the original proposition.

Not only generating, but also understanding an accurate expression of a complex question may also be difficult. Often there is a formal mathematical way of expressing the question that mathematicians would find clearer or more succinct, though non-mathematicians may find it incomprehensible. One of the problems of learning to do mathematics is learning ever more sophisticated question-forming and answer-forming techniques, though I have no idea how many mathematics teachers understand this. It is very likely that some of the more complex forms of propositions and questions discussed here could never be understood by young children or other animals. Likewise some of them may be beyond the grasp of our robot. Nevertheless the theory subsumes them.

5.4 Questions and propositions in non-linguistic (pre-linguistic) information users

As far as I know every human language is capable of expressing all the forms of propositions and factual information-seeking questions mentioned here, but it is theoretically possible that some natural languages lack the syntactic expressiveness required for some forms of questions, just as young children do. Whether some natural language lack the expressive power to do everything described here is an empirical issue, that is not relevant here. The study of the precise forms of syntax used in a particular language to express one of these question types is part of empirical linguistics, and I have nothing to say about that. However, I conjecture that every information-seeking question that is expressible in any language is an example of the sort of schema for generating questions presented below, and every proposition that is expressible in any language is an example of one of the propositional forms we are discussing. (Though the actual list in this document is incomplete: the paper is unfinished.)

But there are more things to be thought and questions to be asked that we can express linguistically. For example, a person looking at a map to find a suitable route between two towns is engaged in acquiring information that is not necessarily expressible verbally. The answer may take the form of identifying a sequence of roads marked on the map, or if the terrain has no roads and the map shows contours (as in an orienteering map) the answer may be a trajectory that could be drawn on the map, or visualised while looking at the map. So some factual questions have contents and have answers that are expressed by non-linguistic means, e.g. using kinds of attention-focusing mechanisms ('virtual fingers' (Pylyshyn's FINSTs (1989))[13]) to specify entities or other things referred to for oneself (even if one is a robot). The work of Trehub(1991) is also relevant.

Public, external, languages used for communication between agents constitute only a subset of the forms of representation required by intelligent agents. Many kinds of information structures are used in various parts of a complex agent architecture, to store information of different kinds, referring to external or internal entities, states or processes, at various levels of abstraction, stored for different time scales, used for different purposes. There is no reason to believe that all such semantic contents are expressible in external languages, such as human languages.[14]

So there may be types of questions and types of answers that are not accurately expressible in any language but are important for the cognitive functioning of some non-linguistic animals and pre-linguistic children. It is possible that this kind of pre-linguistic mental function provides part of the infrastructure for natural language as used by humans and therefore needs to be understood in order to develop an accurate theory of language understanding by humans.

Pre-linguistic question formation and answer-seeking or answer-providing processes (within an individual) may also be important for some robots, in particular robots that are able to perceive and act intelligently while lacking the ability to communicate in any human-like language.

5.5 Types of question structures and answer structures

We turn now to a first draft informal elaboration of the points made above about ways of deriving information-seeking questions from gaps in propositions. This requires a specification of forms of propositions, on which more will be said in a later section. For now I am going to assume that all the propositions required are of a type that could be expressed in first or higher order predicate calculus, with certain modal operators added (e.g. to express causes, purposes, etc.) Instead of a general formalisation, I present only examples, which should suffice to explain the structure of the ontology of questions being presented here. Remember that arguments of predicates and functions need not be denoted by words or linguistic expression: they may be objects of current attention identified by their relationship to what is currently seen or thought about.

A question specifies a request for information or an information gap. The basic form of answer is "yes" or "no" answering a question that asks what the truth-value of a proposition is. More complex answers correspond to questions that are derived from a proposition in various ways, described below. A question has a structure, which may be more or less complex, as explained below.

Answers will be information structures (or structured information items) capable of filling such information gaps, or specifications for sets of information structures that can fill gaps. In many

[13] See URL http://ruccs.rutgers.edu/ftp/pub/papers/cognit89.pdf

[14] For some examples, see http://www.cs.bham.ac.uk/research/cogaff/challenge.pdf

cases the answer to a question can be given in alternative forms: e.g. if the question requests an example of something, different examples may be given in answers. However, in general the form of a question constrains the forms of appropriate answers. For example, if the question is "Is it raining?", the answer "thirty seven" is inappropriate, and if the question is "How many people are in the room?" the answer "yes" is inappropriate. If the question is "What happened next?" only a complete proposition is an appropriate answer (though the proposition may be identified by a referring device, e.g. "What I just saw happened next").

Despite the use of English to make all these points, it is important to stress that this is not a document about natural language syntax, but about kinds of factual information that may be needed by an information processing system.

6 Question forms

This section describes, rather informally, and incompletely, a principled collection of transformations of propositions in order to specify information gaps. A question, from this standpoint is just an expression of an information gap, and an answer is an expression of the information that fills the gap.

6.1 Yes-no questions: Proposition and its negation

Those are the fundamental sorts of questions, merely asking about the truth or falsity of a proposition.

6.2 Derived questions: operations on propositions with gaps

There are many question forms that can be generated by producing one or more gaps in a proposition. The gaps can be of many kinds: object, attribute-type, attribute value, relation, action, purpose, manner, instrument, cause, location (different sorts), time (different sorts),

Some of these occur so often that we have special words to identify the type of gap to be filled:

> who, what, which, where, when, how, why, ...

Sometimes there is more than one gap

> 'Who broke what?'
> 'Who murdered whom when?'

Different question forms relate to whether a unique gap filler (or a unique tuple of fillers) is requested, or a the set of all, or the number of the set of all, or some statistical property of the set (are most X's P?), whether referents are identical, or whether an identified entity fills some gap, etc. etc. For example:

> 'Is fred the person who...,?'
> 'Did fred solve it in the same way as Mary?'
> 'How many people solved it in the same way as Mary?'
> 'How many things did Fred do in the same way as Mary?'
> 'Is Fred cleverer, bigger than Joe, ...'

It is worth noting that from a logical point of view many things are clearly interpretable whose most ‘logical’ expression in natural language would be regarded as ill-formed or bad style, such as

> ‘How many people did fred solve it in the same way as?’ ‘Fred solved it in what as Mary?’
> Possible answers to the latter include: ‘in the same way’, ‘in the same room’, ‘in the same time’, etc.

From the present point of view the best way to express these questions in natural language, or even whether they can be expressed in a particular natural language, is of no consequence.

6.3 Some common question forms

- **WH-singular-unary:** Proposition with one gap, requests unique filler:

  Who married Mary?

- **WH-singular-binary:** Proposition with two gaps, requests unique filler-pair

  Who married whom? (also ternary, etc. ‘Who gave what to whom?’)

- **WH-plural-unary:** allows plural answer:

  Who was at the party?
  Answer: Fred, Mary, the man in the moon, and my uncle.

- **WH-plural-binary:**

  Who talked to whom at the party?
  Answer: Fred talked to Mary, Sue talked to Joe and to Tom, etc.

6.4 More complex derived forms

Note that for every type of proposition P more complex propositions can be formed by embedding P in a larger context, possibly including other propositions, Q, R, ..., and then creating one or more gaps in the context from which questions can be derived. Examples include:

- P because Q
  leading to “What caused P?”, or various sorts of “Why” questions about P.
- Q because P
  leading to “What effect did P have?”, and similar questions.
- P in order to Q
  where P describes an action that has been done, is being done, or will be done
  leading to “Why is P being done?” and similar questions. However this presupposes the existence of some sort of intelligent agent with intentions in the environment.
- Q in order to bring it about that P
  where P describes a state of affairs
  Possibly leading to something like “How was P done?” or related questions.

Other examples specify means by which something is done, route taken, style or manner, or other qualifiers of P.

For each question form and each situation determining an answer there may be varied verbal answer forms possible (e.g. different ways of identifying an object) with no context-independent means of saying which answer or answer form is best. Sometimes selecting between the different modes of expressing a request for the same information depends on facts about the dialogue context other than whatever is referred to in the question (e.g. the answerer may be impatient with the questioner, or may want to draw attention to a mistaken presupposition of the questioner, or ......)

6.5 Further ways of deriving questions from propositions after creating gaps

To be continued .... there is a lot of existing work on this, including work in linguistics, NLP, Burhans (2002) and others. Some sample ways of deriving questions by filling gaps

- How many ...?
- Are there more than N ...?
- Is the number of ... the same as the number ...?
- If P will Q ??
- Why P ? — possible answer: P because Q
- Why Q ? — possible answer: P caused Q
- Why P ? — possible answer: P in order to Q
- How P ? — possible answer: P using X
- etc.

The above set of points about forming questions by applying various kinds of operators to gaps in more or less complex propositional forms generates a VERY large variety of types of questions (And answers).

Since for any proposition different gaps and different numbers of gaps can be created in it, and for each gap or each combination of gaps different questions can be formed using different question-generating operators, the variety of forms of questions (or more precisely information requirement specifications) must be greater than the variety of types of propositions.

7 Categorical and hypothetical information gaps

A more detailed theory will need to specify features of cognitive architectures that allow an information-user to discover that it needs some information that it does not have. It will require mechanisms that allow the missing information to be identified with sufficient precision to generate actions to remedy the deficiency[15] which may involve

- re-focusing attention

[15] Jackie Chappell has demonstrated a video of Betty, the aforementioned New Caledonian crow, performing a task involving using a stick to pull or push food along a horizontal tube with a trap in the middle, into which the food may fall. At one point Betty seems to realise that she is not sure of the exact situation. So she releases the stick, goes to another position to get a side-on view of the tube, stick and food, then comes back and completes the task.

- re-processing current sensory information in some new way
- accessing and manipulating previously acquired information
- performing some external action to get more information (e.g. looking in a different direction)
- communicating with another agent in some way, whether non-verbally or verbally (e.g. a child may say ‘What’s that?’, and turn an adult’s head to look in the right direction.)

One very obvious way in which an AI system can encounter an information gap occurs if it is attempting to form a plan to achieve some goal by combining action operators for which preconditions and consequences are known (as in STRIPS, and many AI planning systems since STRIPS).

The system may discover that some potentially relevant action has a precondition, and then on attempting to decide whether the precondition is satisfied or not it may discover that it does not have the information, in which case it has to find out, perhaps by looking. (This is unlike a typical use of Prolog in which programs are written to work on the assumption that anything they cannot prove is false.) Another example would be a visual system attempting to identify some object or to perceive the relationship between two objects (e.g. whether they are touching), which then discovers that it cannot decide because some or all of what it is looking at is hidden by a large object. Having identified missing information an intelligent agent with sufficient meta-level knowledge may be able to take steps to fill the information gap. In more primitive animals or robots a purely reactive mechanism might generate information-acquiring actions without any self-knowledge about what is going on.

For a program which constructs a plan made of a sequence of actions, things get more complex. If a STRIPS-like forward-chaining planner has formed a partial plan, consisting of applications of operators, O1, O2, O3, and it then wishes to check whether operator O4 could continue the sequence, it should not check O4 for correctness in the *current* situation, but only in the *hypothetical* situation that would arise after performing the first three actions. The ability to ask a question about a hypothetical situation requires the ability to use expressions whose semantics do not refer to the world as it is. This requires architectures and mechanisms that probably do not exist in the vast majority of animals, and did not exist in machines until the development of AI.

Things get even more complex in a backward chaining planner. Such a planner may discover that the required goal state G would exist if it were to apply an operator Oa, because the effects of Oa include making G true. If Oa has no preconditions or all its preconditions are already true, then things are simple: required plan contains only the action Oa. However if Oa has preconditions, they may be false, and unlike the case of a forward chaining planner, there does not yet exist some specification of a hypothetical situation relative to which the planner can check the preconditions. Rather we have to ask whether there is some way building a sequence of actions starting in the current situation such that at the end of the sequence, the preconditions of Oa would be true.

So whereas previously there were two sorts of questions that arise when considering a possible action Oa, namely

- are the preconditions of Oa true now
- would the preconditions of Oa be true if the currently considered partial plan were executed

in backward chaining planners we have to ask

- is there a possible partial plan starting from the current situation such that if it were executed then the preconditions of Oa would be true

This is a more complex case because instead of simply checking Oa against reality, or against an existing data-structure, filling the information gap requires exploring many possible scenarios.

Thus we have at least three distinct kinds of question in a problem-solving system

- is P true now?
- would P be true in some already specified hypothetical context C?
- is it possible to find a way to specify a hypothetical context C, satisfying some constraints, such that P would be true in C?

Further complications arise if the preconditions of an operator include variables. For example a grasping operator may not specify which object is to be grasped, but it may specify that whatever the object is it should be clear for grasping. In that case where we have previously talked about checking whether a proposition is true (in reality or in some hypothetical situation), we would instead need to talk about a *propositional form* (e.g. 'x is graspable') and ask whether that form has instances that are true, or would be true in the hypothetical situation. Examples of a natural language expressions of such questions are

- Is anything that is graspable clear?
- Which graspable objects are clear?
- Would anything graspable be clear if I were to do ..... ?
- Which graspable objects would be clear if I were to do ..... ?

(The 'Which' questions, whose answers give a list of options tend to be more appropriate to breadth-first searching, the others to depth-first searching.)

As anyone familiar with AI planning and problem-solving programs will know, the need to identify and reason about information gaps in hypothetical situations can add considerable complexity to task of keeping track of all the actual and possible states of affairs that could arise if various actions were performed.

Humans vary in their ability to perform these tasks, and very young children seem to be quite incapable of processing information about a collection of hypothetical situations, so this ability is a product of learning or development in humans. It is also generally very limited, insofar as humans cannot match the combinatorial searching capabilities of even moderately powerful computers, though they may compensate for that in various ways, not discussed here. Moreover, some humans seem to have and use these abilities without being at all aware that that is what they are doing. It may be that some of the representations of information gaps are implicit in the states of activation of procedures and mechanisms for dealing with such gaps. It requires additional architectural sophistication to be able to represent such things explicitly and reason about them explicitly.

SOAR[16] is a well known example of a problem solver that can discover that in order to solve one problem it may have to solve another which includes discovering something. Many such mechanisms are theoretically possible and we shall not attempt a survey here.

We can expect different subsets of the theoretically possible variety of question forms and information-obtaining processes to occur in different species, in different robots, and perhaps in the same individual at different stages of development. Where linguistic forms are used, different languages will encode them in different ways. We can expect young children to be unable to cope with the linguistic forms required to ask questions relative to some hypothetical situation, and then only later to learn the extra syntactic constructs (subjunctive forms) required. Whether they can do

[16]See the SOAR homepage http://sitemaker.umich.edu/soar

it internally in thinking and reasoning about hypotheticals before they can do this using an external language is an interesting question.

Yet another variation on the theme discussed here is the ability to ask and answer questions about the mental states of other individuals, e.g. in predicting or explaining actions or trying to decide how to advise or explain something to them. AI research on this task has explored both explicit reasoning about mental states of others, for instance using doxastic/epistemic modal logics, and something closer to implicit reasoning using 'simulative mechanisms'.[17].

The ideas expressed here are very general. When they are applied to the full variety of forms of propositions described in the companion paper on ontology for PlayMate, it may turn out that there are additional possibilities and problems not allowed for here.

8 Some References [to be extended]

These references were found with the help of Google, after the first draft of these notes was written. The list is neither complete nor authoritative nor representative. It's just what I found in a fairly short time spent searching. The Burhans thesis mentioned at the beginning seems to be closest in spirit to what I have been proposing regarding question formation, though I have not yet read it all.

Debra Thomas Burhans (2002)
A Question Answering Interpretation of Resolution Refutation[18]
PhD Thesis, State University of New York at Buffalo Department of Computer Science and Engineering.

List of question types: http://www.usingenglish.com/glossary/question-types.html

Metzler, D. and Croft, W.B., (2003) "Analysis of Statistical Question Classification for fact-based Questions" *Information Retrieval.* PDF[19]

Jean-Pierre Ko (2000)
Any questions left? Review of Ginzburg & Sag's *Interrogative Investigations.* J. Linguistics 40 (2004), 131-148. f 2004 Cambridge University Press DOI : 10.1017/S0022226703002354, UK. PDF[20]

Jonathan Ginzburg and Ivan Sag, (2000) *Interrogative Investigations,* CSLI Lecture Notes 123. Stanford, California: CSLI publications,, Pp. xii + 449.

References

McCarthy, J. (1995). Making robots conscious of their mental states. In *AAAI Spring Symposium on Representing Mental States and Mechanisms*. Accessible via http://www-formal.stanford.edu/jmc/consciousness.html.

[17]Barnden's ATT-META project (http://www.cs.bham.ac.uk/˜jab/ATT-Meta/) has developed a tool using simulative reasoning mechanisms for dealing with metaphors, mental states of other agents (possibly nested) and which can also be used for general counterfactual or hypothetical reasoning

[18]See URL http://www.cse.buffalo.edu/.burhans/debra.ps

[19]See URL http://ciir.cs.umass.edu/pubfiles/ir-323.pdf

[20]See URL http://lingo.stanford.edu/sag/revs/koenig-rev.pdf