

# A Simulated Physiological/Cognitive “Double Agent”

Sergei Nirenburg, Marjorie McShane and Stephen Beale

Institute for Language and Information Technologies  
University of Maryland Baltimore County  
ITE 325, 1000 Hilltop Circle, Baltimore, Maryland 21250, USA  
{sergei, marge, sbeale}@umbc.edu

## Abstract

This paper describes the cognitive capabilities of artificial intelligent agents in Maryland Virtual Patient (MVP, an environment that provides interactive, open-ended simulations of virtual patients for the training of medical personnel. The environment is implemented as an agent network that includes one human agent – the user – and a network of artificial agents. Some of the artificial agents have cognitive capabilities, like decision-making and the ability to communicate using natural language. It is on the virtual patient’s decision-making capabilities that this paper focuses.

## Introduction

The utility of simulated “real-world” environments is well established in many application areas, such as pedagogy and entertainment. Learning to diagnose and treat patients by way of immersion in a simulated environment is particularly attractive because it allows the learner to play the role of attending physician on a large number of cases without the responsibility associated with treating real patients. Many of the main research tasks in pedagogical simulation relate to making simulated environments more realistic than the current state of the art, which offers, on the one hand, fixed or minimally variable lesson scenarios, and on the other, mannikin-oriented simulations that do not train the cognitive capabilities required of an attending physician.

Progress in clinical simulation presupposes the capability of modeling and dynamically simulating both the physiological processes and the human cognitive capabilities of a virtual patient. Moreover, to be truly realistic, a system of this kind must reflect the complexity of real-world health provider teams. As a member of such a team, the attending physician can typically rely on assistance from other medical professionals, such as lab technicians and specialist consultants. Finally, if the primary purpose of the simulation environment is training help and not, say, assessment, then it is desirable to add a tutoring capability to provide the learner with help and feedback.

The above desiderata readily suggest a computational model to implement this environment, namely, a mixed

network of human and software agents. Multi-agent systems are currently a very active area of research in artificial intelligence as can be construed, for example from Huhns et al. 2005, which gives an assessment of the achievements in this field of study and a broad and ambitious research program for its further development. In clinical applications, the affinity of the problem space with multi-agent network solutions has been noticed, for example, by the Anthropic Agency project (Amigoni et al. 2003), where an agent is used to automatically regulate the glucose-insulin metabolism processes of diabetes patients. In the area of simulation for assessment, Sumner et al. (1995, 1996) propose a “parallel health state network” approach that, while not overtly mentioning agents, is, we believe, readily expressible in terms of multi-agent systems.

Our Maryland Virtual Patient<sup>1</sup> (MVP) project is developing a multi-level heterogeneous agent-oriented environment for automating certain facets of medical education (McShane et al. 2007a,b; McShane et al. 2008; Jarrell et al. 2007). This environment includes a network of human and software agents. The human agents include the user – typically, a physician in training – who is carrying out the duties of an attending physician and, optionally, a human mentor. The software (simulated) agents include the virtual patient, lab technicians, specialist consultants, an automatic tutoring agent and an array of lower-level (not humanlike) software agents.

At the core of this network is the virtual patient (VP) – a knowledge-based model and simulation of a person suffering from one or more diseases. The virtual patient is a “double agent” in that it models and simulates both the physiological and the cognitive functionality of a human. Physiologically, it undergoes both normal and pathological processes in response to internal and external stimuli. Cognitively, it experiences symptoms, has lifestyle preferences (a model of character traits), has memory (many of whose details fade with time), and communicates with the human user about its personal history and symptoms.

The medical knowledge encoded in MVP is derived from that used daily by real clinicians managing real patients. It embodies biophysical functions that have clinical relevance in the maintenance of health, the production of disease, and the bidirectional transitions between the states

of health and disease. It includes structure and function information derived from well-understood aspects of anatomy and physiology, and ranges from the molecular level up to the level of organism. Where gaps exist in the knowledge of biomechanisms, they are bridged with knowledge from practical clinical experience and evidence-based findings from the medical literature. What makes virtual patient modeling feasible – considering that comprehensively modeling human physiology would be a boundless endeavor – is our task-oriented approach: we are not trying to recreate the human organism in all its details, we are modeling it to the extent necessary to support its realistic autonomous functioning in applications aimed at training and testing the diagnostic and treatment skills of medical personnel.

So far, MVP covers six diseases of the esophagus, and the modeling of heart disease is underway. The disease on which we will focus here is achalasia, a disease that renders swallowing progressively more difficult as the sphincter between the esophagus and the stomach – called the lower esophageal sphincter, or LES – becomes progressively hypertensive, not permitting food to pass to the stomach. Achalasia cannot be reversed, its progression cannot be slowed, and no lifestyle modifications can alter its progression. All interventions aim to “loosen” the LES either by chemical means (BoTox injections), by tearing it with an endoscopically inserted balloon (pneumatic dilation) or by surgically cutting it (Heller myotomy).

In this paper, we concentrate on the following aspects of the functioning of the cognitive side of the VP:

1. experiencing, interpreting and remembering symptoms
2. deciding to go see a doctor, initially and during treatment
3. deciding whether to ask knowledge-seeking questions about a test or intervention suggested by the doctor
4. deciding whether to agree to a test or intervention suggested by the doctor.

In order to concentrate on the cognitive side of the VP, we will provide only enough information about other aspects of the system to place this agent in the context of the network in which it operates. Interested readers will find descriptions of other aspects of the system as follows: disease modeling (Jarrell 2007, McShane 2007a,b), the creation of a population of patients from a single parameterizable disease model (McShane et al. 2008), the agent network (Nirenburg et al. 2008, Submitted), the ontological-semantic knowledge substrate of our work (Nirenburg and Raskin 2004), and language processing in MVP (McShane et al. 2008).

## The Physiological Side of the VP

Before moving on to the cognitive functioning of the VP, we must describe, if only briefly, the physiological side of the VP since it is interoception – the process of perceiving

physiological events – that impels the cognitive agent to seek medical attention in the first place.

The physiological side of the VP is modeled as a set of interconnected ontological objects representing human anatomy. Each object is described by a set of ontological properties and their associated value sets. Crucial among the properties are those that link the objects to typical events in which they participate. These events are usually complex – that is, they include other, possibly also complex, events as their components. Following Schank and Abelson (1977), we call these complex events scripts. There are two major classes of scripts: domain scripts and workflow scripts. Examples of domain scripts are swallowing by a healthy VP, swallowing by a VP with an esophageal disease, the progression of a disease, and its course in response to treatment. Examples of workflow scripts are the patient consulting the doctor, the doctor diagnosing and treating the patient, and the patient deciding whether or not to follow the doctor’s advice.

At first blush, it might seem preferable to record in domain scripts a maximally complete model of normal human anatomy and physiology before progressing to disease modeling, but we have found this not to be the case for three reasons. (1) Creating formal models of everything known about human physiology would require an unsupported amount of time and resources. (2) Even if such models could be created, they would represent a grain size of description not needed for our applications. (3) Many of the processes of human physiology – both normal and pathological – are not understood by the medical community, meaning that modeling must anyway combine aspects of known causal chains and clinical observations that we call *bridges*. In short, all modeling in the MVP system is task-oriented, with both normal and pathological processes being modeled on an “as needed” basis. Achieving a useful balance between causal chains, bridges, and grain size could be considered the art of application-oriented modeling.

At any given time, the model of the normal human contains whatever normal anatomical and physiological knowledge was compiled to cover the diseases currently available in the system. So, although at present our virtual humans do not have a highly developed model of the circulatory system, as soon as we have completed the circulatory model – which is currently under development to support the modeling of heart disease – all virtual humans will be endowed with all the associated functionalities and property values.

In MVP, diseases are modeled as processes (low-level agents) that cause changes in key property values of a patient over time. For each disease, a set number of conceptual stages is established and typical values or ranges of values for each property are associated with each stage. Relevant property values at the start or end of each stage are recorded explicitly, while values for times between stage boundaries are interpolated. The interpolation currently uses a linear function, though other functions could as easily be employed.

A disease model includes a combination of fixed and variable features. For example, although the number of stages for a given disease is fixed, the duration of each stage is variable. Similarly, although the values for some physiological properties undergo fixed changes across patients, the values for other physiological properties are variable across patients, within a specified range. The combination of fixed and variable features represents, we believe, the golden mean for disease modeling. On the one hand, each disease model is sufficiently constrained so that patients suffering from the disease show appropriate physiological manifestations of it. On the other hand, each disease model is sufficiently flexible to permit individual patients to differ in clinically relevant ways, as selected by patient authors.

### The Cognitive Side of the VP: Overview

The cognitive side of the VP is at present capable of two types of perception: interoception and the perception of linguistic input from the human user. Responses to interoceptive input are remembering a sensation (typically a symptom) and deciding whether or not to do anything about it at the given time. Responses to language input include learning (augmenting the agent’s ontology, whenever appropriate, as a result of understanding user input), responding to a question or suggestion, and generating a question based on information or advice just provided.

MVP uses agenda-style control and goal- and plan-based simulation. We represent goals as ontological instances of properties.

### General-Reasoning Goals and Plans of the Cognitive Agent

The main top-level goal of our VPs is *be-healthy*, which is ontologically represented as

```
HEALTH-ATTRIBUTE
DOMAIN VP
RANGE I
```

This means that the VP seeks to achieve the highest possible value, on the abstract scale  $\{0,1\}$ , for the ontological attribute that generalizes over its state of health. Any time the patient experiences medical symptoms, the value of the range of *health-attribute* is reduced in accordance with how many symptoms it has and how severe they are. Other goals that we will not describe here, as they are not relevant for the disease under discussion, are pleasure goals, like eating what one likes rather than what one should; lifestyle goals, like pursuing a career despite the potentially health-impacting stress it imposes; and so on. These goals are more relevant for the modeling of diseases like heart disease, where lifestyle choices have a significant impact on states of health and disease. Goals can appear on the agenda in four ways:

*Perception via interoception.* The moment the patient perceives a symptom, the symptom appears in short-term memory. This triggers the addition of an instance of the goal *be-healthy* onto the agenda, with the symptom as a parameter. Other interoceptive events include feeling hunger, craving caffeine, and so on, which put other goals on the agenda, like *satisfy-physical-desire*.

*Perception via language.* A user input that requires a response from the VP – be it a direct question or an indirect speech act interpreted as a question – puts the goal to respond to the question on the agenda. In our application, dialogs are always “shop talk”, so the goal that dialog is supporting is always *be-healthy*.

*A precondition of an event inside a plan is unfulfilled.* For example, most patients will not agree to or refuse an intervention if they know nothing about it; so finding out about it is a subgoal of making such a decision.

*The required period of time has passed since the last instances of the events be-diagnosed or be-treated have been launched.* This models regular check-ups and scheduled follow-up visits.

The goal *be-healthy* is put on the agenda when a patient begins experiencing a symptom. It remains on the agenda and is reevaluated when: (a) its intensity or frequency (depending on the symptom) reaches a certain level; (b) a new symptom arises; (c) a certain amount of time has passed since the patient’s last evaluation of its current state of health, given that the patient has an ongoing or recurring symptom or set of symptoms: e.g., “I’ve had this mild symptom for too long; I should see a doctor.”

When making decisions about its health care, the VP incorporates the following types of features, which are used in the decision-making evaluation functions described below.

- (a) its physiological state, as perceived via interoception and remembered in its memory – particularly the **intensity** and **frequency** of symptoms
- (b) certain character traits: **trust**, **suggestibility** and **courage**
- (c) certain physiological traits: **physiological-resistance** (e.g., how well the VP tolerates chemotherapy), **pain-threshold** (how much pain the VP can tolerate) and the **ability-to-tolerate-symptoms** (how intense or frequent symptoms have to be before the VP feels the need to do something about them)
- (d) certain properties of tests and procedures: **pain**, **unpleasantness**, **risk** and **effectiveness**. Pain and unpleasantness are, together, considered typical side effects when viewed at the population level; the VP’s personal individual experience of them is described below.
- (e) two time-related properties: the **follow-up-date**, i.e., the time the doctor told the patient to come for a follow-up, and the **current-time** of the given interaction.

The values for scalar attributes are measured on the abstract scale {0,1}. All subjective features, (a) – (c), are selected for each individual VP by the person authoring that VP. That is, at the same time as a patient author selects the physiological traits of the patient – like the pace of disease progression and the VP’s response to treatments, should they be administered – he selects certain traits specific to the cognitive agent as well as the amount of relevant world knowledge that the patient has in its ontology. The complete “best medical knowledge” features of tests and procedures (point d above) are stored in the general ontology and are the same for every agent instance. (The general ontology contains all the knowledge the system has about events, objects and properties; the ontologies of individual agents contain less knowledge and can, in principle, contain erroneous knowledge, though we have not yet modeled that state of affairs in our system.) However, two of these features – pain and unpleasantness – are combined with the patient’s own traits to yield its personal side effect intensity, should that intervention be carried out.

**personal-pain-intensity =**

$(2 - \text{ability-to-tolerate-symptoms} - \text{physiological-resistance}) * \text{pain.intensity}$

**personal-unpleasantness-intensity =**

$(2 - \text{ability-to-tolerate-symptoms} - \text{physiological-resistance}) * \text{unpleasantness.intensity}$

The above illustrates that the cognitive aspects of each individual VP instance scope over the events of its simulated life, providing a rich choice space that permits the creation of a sizeable population of differentiated patients with a given disease. Such variability helps to elicit different behaviors during simulation.

Below we present a sketch of several of decision making evaluation functions (EvalFunctions) of the VP. These evaluation functions determine when the VP will consult a doctor, whether it will request information about tests and procedures – collectively referred to as “interventions” – and whether it will agree to proposed interventions. Of course, the patient must also make many decisions at the level of language interaction, but considerations of space preclude a description of those here.

### **EvalFunction: See-doctor-or-do-nothing**

Each time the patient evaluates its health it has a choice of at least four actions: do nothing, see the doctor, self-treat, or go to the emergency room. For the current discussion, since we focus on the disease achalasia, we limit the options to the first two, since there are no self-treatment options and no emergency situations are associated with this disease. The patient’s evaluation function is as follows; note that it applies both when the patient is deciding whether to see the doctor for the first time and when it is deciding whether or not to schedule a visit earlier than its next planned follow-up visit – e.g., if its symptoms get drastically worse.

IF follow-up date is not set

AND symptom-severity > ability-to-tolerate-symptoms  
THEN see-MD  
*; this triggers the first visit to the MD*

ELSE IF follow-up date is not set

AND symptom-severity < ability-to-tolerate-symptoms  
AND symptom-has-been persisting for 6 months  
THEN see-MD  
*; a tolerable symptom has been going on for too long*

ELSE IF there was a previous visit

AND at the time of that visit symptom-severity <=.3  
AND currently symptom-severity > .7  
AND symptom-severity – ability-to-tolerate-symptoms > 0  
THEN see-MD  
ELSE do-nothing  
*; there was a big increase in symptom severity from low to high, triggering an unplanned visit to MD*

ELSE IF there was a previous visit

AND at the time of that visit symptom-severity ∈ {.3 .7}  
AND currently symptom-severity > .9  
AND symptom-severity – ability-to-tolerate-symptoms > 0  
THEN see-MD  
ELSE do-nothing  
*; there was a big increase in symptom severity from medium to very high, triggering an unplanned visit to MD*

ELSE IF there was a previous visit

AND at the time of that visit symptom-severity > .7  
AND currently symptom-severity > .9  
THEN do-nothing  
*; symptom severity was already high at last visit – do not do an unplanned visit to MD because of it*

ELSE IF the time reaches the follow-up time

THEN see-MD

ELSE do-nothing.

As should be clear from the evaluation function, patients with a lower ability to tolerate symptoms will see the doctor sooner in the disease progression than patients with a higher ability to tolerate symptoms, given the same symptom level. Of course, one could incorporate any number of other character traits and lifestyle factors into this function, such as the patient’s eagerness to be fussed over by doctors, the patient’s availability to see a doctor around its work schedule, and so on. But for our current stage of development, this inventory is sufficient to show reasonable variability across patients.

### **EvalFunction: Agree-to-an-intervention-or-not**

Among the decisions a patient must make is whether or not to agree to a test or procedure suggested by the doctor, since many interventions carry some degree of pain, risks, side-effects or general unpleasantness. Some patients have such high levels of trust, suggestibility and courage that they will agree to anything the doctor says without question. All other patients must decide if they have sufficient information about the intervention to make a decision and, once they have enough information, they must decide

whether they want to (a) accept the doctor’s advice, (b) ask about other options, or (c) reject the doctor’s advice. A simplified version of the algorithm for making this decision – the actual decision tree is too detailed to be included here – is as follows:

1. IF a function of the patient’s trust, suggestibility and courage is above a threshold OR the risk associated with the intervention is below a threshold (e.g., in the case of a blood test) THEN it agrees to intervention right away.
2. ELSE IF the patient feels it knows enough about the risks, side-effects and unpleasantness of the intervention (as a result of evaluating the function enough-info-to-evaluate?) AND a call to the function evaluate-intervention establishes that the above risks are acceptable THEN the patient agrees to the intervention.
3. ELSE IF the patient feels it knows enough about the risks, side-effects and unpleasantness of the intervention AND a call to the function evaluate-intervention establishes that the above risks are not acceptable THEN the patient asks about other options  
IF there are other options  
THEN the physician proposes them and control is switched to Step 2..  
ELSE the patient refuses the intervention.
4. ELSE IF the patient does not feel it knows enough about the intervention (as a result of evaluating the function enough-info-to- evaluate?) THEN the patient asks for information about the specific properties that interest it, based on its character traits: e.g., a cowardly patient will ask about risks, side effects and unpleasantness, whereas a brave but sickly person might only ask about side effects.  
IF a call to the function *evaluate-intervention* establishes that the above risks are acceptable  
THEN the patient agrees to the intervention.  
ELSE the patient asks about other options  
IF there are other options  
THEN the physician proposes them and control is switched to Step 2.  
ELSE the patient refuses the intervention.

This evaluation function makes use of two other evaluation functions, sketched below.

**EvalFunction: Enough-info-to-evaluate**

Patients differ with respect to how much ontological knowledge they have about various things, medicine in particular. When a patient author is selecting parameter values for a patient instance, among these values is whether or not the patient knows the four features of each test and procedure listed in Table 1. A patient might know about these, for example, because a relative or friend underwent the procedure.

The features of interventions are conceptually tied to personality traits, meaning that if, for example, a VP is cowardly, it will want to know about many features of a

proposed intervention, whereas if it is brave but has low physiological resistance it will only be concerned with potential side effects. Table 1 shows these correlations:

Table 1. Character traits associated with intervention features.

| Feature of Intervention | Associated Character Trait           |
|-------------------------|--------------------------------------|
| effectiveness           | <i>not applicable</i>                |
| risk                    | courage                              |
| side effects            | courage and physiological resistance |
| unpleasantness          | courage and unpleasantness-threshold |

We assume for the time being that VPs will not have incorrect ontological information about interventions: if they have knowledge, it will be correct.

The algorithm for deciding whether the VP has enough information about an intervention is as follows:

IF the VP is not very courageous (its value for *courage* is < .8)  
AND any of the four features of an intervention is unknown  
THEN the VP asks the doctor to provide the unknown feature values

ELSE-IF the VP is very courageous (>= .8)  
AND its physiological-resistance is not stellar (< .8)  
AND the side-effects are unknown  
THEN the VP will ask the doctor to provide side-effect information

ELSE-IF the VP is very courageous (>= .8)  
AND its ability to tolerate unpleasantness is not stellar (< .8)  
AND the level of unpleasantness is unknown  
THEN the VP will ask the doctor to provide information about the level of unpleasantness

ELSE the VP requires no information from the doctor.

**EvalFunction: Evaluate-intervention**

Once the patient has enough information about the suggested intervention (assuming it is not one who immediately agrees to any intervention), it must evaluate the intervention in light of that information. The associated evaluation function is shown below:

$$f = \text{effectiveness} + \text{courage} + (\text{courage} + \text{physiological-resistance})/2 + (\text{courage} + \text{unpleasantness-threshold})/2 - \text{risk} - \text{side-effects} - \text{unpleasantness}$$

This function incorporates properties of both the VP and the procedure. It takes into consideration (a) that courage is associated with three different properties of interventions, and it should not get three times the weight of other features and (b) that for some features a high value on the abstract scale {0,1} is “good” whereas for other features it is “bad”.

To summarize, for patients experiencing achalasia, several functions are used to determine when to see the doctor and, when the doctor suggests an intervention, whether to find out more about it and, ultimately, whether or not to

agree to it. Different decisions at any of these choice points leads to very different simulated “lives” of virtual patients.

## Illustration of System Operation

To illustrate system operation, we present an example of one of many possible user interactions with a virtual patient named Michael Wu. Mr. Wu must be diagnosed with and treated for achalasia. The key physiological, pathological, psychological and cognitive aspects of his profile are established before the session begins (see below). They are encoded by a teacher or a researcher using a graphical patient creation interface. Of course, the user does not have direct access to any of this information. Everything the user will learn about Mr. Wu will be learned through patient interviews, tests and procedures.

### Physiological Traits

- trust: .2
- suggestibility: .3
- courage: .4

### Physiological Traits

- physiological resistance: .9
- pain threshold: .2
- ability to tolerate symptoms: .4

**Patient’s knowledge of medicine:** minimal, meaning that the patient does not know the features of any interventions the user might propose.

### Duration of each stage of the disease

- preclinical: 7 mos.
- stage 1: 7 mos.
- stage 2: 8 mos.
- stage 3: 8 mos.
- stage 4: 9 mos.

### Response to treatments

- BoTox: effective, wearing off over 12 mos.
- Pneumatic dilation: effective with regression over a number of years
- Heller myotomy: effective permanently

In this example we do not include the operation of the tutoring agent; for that, see Nirenburg et al., Submitted.

There are actually dozens of interesting paths through the case of Mr. Wu. Some are clinically well grounded whereas others reflect poor decision-making on the part of the user. There are also countless trivially different paths, since at any minute during the simulation the user can take any clinically appropriate or clinically inappropriate action. Here we show one clinically reasonable albeit not flawless (as we would know if the tutoring agent were turned on) path through this simulation.

1. Mr. Wu presents with the chief complaint “difficulty swallowing”. This is day 361 of the progression of his disease, which includes the preclinical, symptom-free period. The user will not know this temporal information. Mr. Wu has had symptoms for some time but until now the evalua-

tion of see-doctor-or-do-nothing has returned the answer “do nothing”.

2. The user asks about difficulty swallowing, chest pain, regurgitation and heartburn. The dialog runs as follows:

**User:** So, you have difficulty swallowing?

**Mr. Wu:** Yes.

**User:** Do you have difficulty swallowing solids?

**Mr. Wu:** Yes.

**User:** Liquids?

**Mr. Wu:** No.

**User:** Do you have chest pain?

**Mr. Wu:** Yes, but it’s mild.

**User:** Any heartburn?

**Mr. Wu:** No.

**User:** Do you ever regurgitate your food?

**Mr. Wu:** No.

**User:** How often do you have difficulty swallowing?

**Mr. Wu:** Less than once a week.

**User:** It is too early to take any action. Please come back in 9 months.

**Mr. Wu:** OK.

Note that the user’s ability to monitor a patient over time, with or without intervention, is a crucial aspect of clinical medicine not covered by any other tutoring systems known to us.

3. After 9 months (on day 661 of the disease progression) Mr. Wu comes back. His evaluation function **see-doctor-or-do-nothing** did not cause him to come back any earlier than the scheduled appointment. The user asks questions about difficulty swallowing, chest pain and regurgitation, possibly using paraphrases and any ordering of questions. Mr. Wu responds that he has moderate chest pain, experiences regurgitation a few times a week, has difficulty swallowing solids daily and difficulty swallowing liquids occasionally. (The progression of difficulty swallowing from solids to liquids is a key diagnostic point that the user should catch: this suggests a motility disorder rather than an obstructive disorder.)

4. The user posits the hypothesis that Mr. Wu has a motility disorder and advises Mr. Wu to have a test called an EGD (esophagogastroduodenoscopy). Mr. Wu evaluates whether he will accept this advice using the function **evaluate-intervention**. He asks about risks. When the user assures him that there are extremely low risks, he agrees.

5. A lab technician agent produces results for this test based on a simulated instance of the test that measures specific attributes of the physiological side of the VP. A specialist agent returns the results with the interpretation: “Narrowing of LES with a pop upon entering the stomach. No tumor in the distal esophagus. Normal esophageal mucosa.” These results include positive results and pertinent negatives.

6. The user reviews the test results, decides that it is still too early to intervene, and schedules Mr. Wu for another follow-up in 4 months.

7. When Mr. Wu presents in 4 months, the symptom that has changed the most is regurgitation, which he now experiences every day. The user learns this, as always, from questions he asks the patient. Note that the patient chart is populated with responses to questions, results of tests, etc., so the user can compare the VP's current state with previous states.

8. The user suggests having another EGD and Mr. Wu agrees immediately, not bothering to launch the evaluation function for EGD again since he ended up agreeing to this test the last time: this is reasoning by analogy. The results are the same as last time.

9. Then the user suggests having two more tests: a barium swallow and esophageal manometry. Mr. Wu asks about their risks, is satisfied that they are sufficiently low, and agrees to the procedures. The former returns "Narrowing of the lower esophageal sphincter with a bird's beak" and the latter returns "Incomplete relaxation of the LES, hypertensive LES, LES pressure: 53". Lab technicians and specialist agents are involved in running the tests and reporting results, as described earlier.

10. The user decides that these test results are sufficient to make the diagnosis of achalasia. He records this diagnosis in Mr. Wu's chart.

11. The user suggests that Mr. Wu have a Heller myotomy. Mr. Wu asks about the risks and pain involved. The user responds that both are minimal. Mr. Wu agrees to have the procedure. The user tells him to come back for a follow-up a month after the procedure.

11. Mr. Wu has the procedure.

12. Mr. Wu returns in a month, the user asks questions about symptoms and there are none. The user tells Mr. Wu to return if any symptoms arise.

Some key aspects of this simulation run must be underscored. First, this is a fully functioning system: the VP's physiological and cognitive agents can respond to both expected (clinically correct) and unexpected (clinically incorrect) moves by the user. Second, the course of the simulation could be very different for this particular patient based on user decisions, and the course of simulation for different patient instances could be very different based on their own physiological and cognitive features.

Due to space constraints, we cannot discuss the dialog and general natural language processing capabilities of our system. We can say, however, that natural language processing is central to our system, and a lot of effort is expended on treating the many phenomena and complexities involved in it. Our general approach is task-, not method-oriented. This means that we use different (e.g., knowledge-based and statistical) types of language processing engines for different ends within the overall system. Our overall strategy is to strive for high-quality output. In our understanding, the key to this goal is the

availability of knowledge to make a variety of decisions (notably, ambiguity resolution decisions of all kinds) during the processes of text understanding and generation. As a result, we accept the need for extra knowledge acquisition work than would not have been required in approaches that can claim success at, say, 70 or 80% correctness of results. In a nutshell, on the language front the VP is capable of:

- understanding the meaning of the text incoming from the user;
- recognizing speech acts (statements, requests for information and requests for action);
- deciding upon and creating the content of a text to be generated and communicated to the user (this activity belongs to the general cognitive reasoning capabilities of the VP)
- realizing the above content in a natural language.

Our language processing approach and systems are described in Nirenburg and Raskin 2004, Beale et al. 2003, and many other publications devoted to the OntoSem text processing system.

## Final Thoughts

The MVP project encompasses theoretical and system-building work in simulation, cognitive modeling, natural language processing and knowledge acquisition and management. The practical goal of the work on MVP is to create a society of artificial and human intelligent agents that models the clinical experience of both patients and physicians. Agents in the system are endowed with different capabilities. For example, the automatic tutoring agent possesses the maximum clinical knowledge of all the agents and is also capable of processing language – this is needed for monitoring user-patient dialogs and engaging the user in a dialog as needed for pedagogical reasons. The virtual patient is a "double agent" in that it combines the physiological agent, which is a simulation of the physiological and pathological properties of an organism, with a cognitive agent capable of perception, reasoning, and communication in natural language. At the current stage of development, the remaining agents in the system – expert specialists and lab technicians – have been kept relatively simple.

Virtual patients are distinguished not only by their physiology and pathology but also by the extent of their knowledge about the world (notably, clinical knowledge) and their character traits. In addition, the different instances of virtual patients can be endowed with different goals, plans and, in general, knowledge-processing rules and operators. In other words, different agent instances can be made smarter or less so. These distinctions allow the creation of libraries of virtual patients that behave differently with respect to a) their disease progression and response to treatment and b) their communications with the human user.

Another distinguishing characteristic of our model is the uniformity of its knowledge substrate. The physiological, general cognitive and language processing capabilities of all the agents in the MVP project rely on the same ontological substrate, the same organization of the fact repository (agent memory) and the same approach to knowledge representation. This approach was originally developed for the knowledge-based semantic processing of language, and has been in use in the OntoSem semantic analyzer and its predecessors for almost two decades.

Our theoretical and application-oriented work pursues the development of complex systems with multi-faceted capabilities. As a result, it, by necessity, touches upon many important areas of research, all with a rich research and development history. A partial list of areas relevant to our research includes cognitive architectures, simulation, intelligent agent systems, AI in medicine, intelligent tutoring, knowledge representation, knowledge acquisition, knowledge-based reasoning, extraction and manipulation of natural language meaning, text generation and dialog modeling. Lack of space prevents us from discussing related work by others in any detail. Needless to say, our choice of tools and approaches has been informed both by work by others and our own history of research. We will discuss our system's similarities and differences vis á vis other approaches on a different occasion. As regards our own earlier work, it was mostly in the area of knowledge-based natural language processing. This being the case, it is not surprising that we decided to use our existing knowledge and processing environment (OntoSem, the ontological-semantic text analyzer) as the most economical basis for extensions into physiological simulation and goal- and plan-oriented reasoning.

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