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INTRODUCING PAP: A PLASMA APPRENTICE PROGRAM

By

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INTRODUCING PAP: A PLASMA APPRENTICE PROGRAM

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MASTER

ABSTRACT

Although current capabilities of symbolic computation and artificial intelligence are not adequate to do all the types of thinking a physicist does in solving physics problems, much of what the human theorist does can be effectively imitated by a computer. This paper describes an early stage of implementation of an apprentice program for aiding plasma theorists in developing plasma physics theory, by performing some of those tasks which the theorist normally must do, but which are now amenable to machine imitation. The apprentice has a "knowledge base" containing its understanding of plasma theory, which can be accessed by the human user for pedagogic purposes, as well as by the apprentice itself, and some ability to do the kinds of qualitative or heuristic reasoning necessary to the human theorist in solving problems. These facilities enable the apprentice itself to do plasma calculations, informing the user of the progress of the calculation, and prompting him when a decision is needed which the apprentice is not equipped to handle. Some extensions planned for the future are discussed.

1. INTRODUCTION

This paper describes an early stage of implementation of PAP, a Plasma Apprentice program. By "plasma apprentice" is meant a program designed to do as much as possible of what a human plasma physics theorist does, and to interact with the human theorist, to aid him in doing his job. Techniques of artificial intelligence (AI) and symbolic computation figure prominently in writing such a program.

Doing physics research is one of the quintessential human pursuits for which genuine intelligence is required. However, the capabilities of AI programming have seen a great deal of growth in recent years [1], so that it is sensible to see how far one can get, using these capabilities, in trying to reproduce the activities of a human physicist. Moreover, while it is certainly true that present day AI techniques are still inadequate for doing some of the more refined or "intuitive" types of reasoning a human theorist is sometimes called upon to do, much of a theorist's activity has a structure which is reasonably clear, and therefore amenable to machine imitation. A machine apprentice able to direct itself for even 30 to 50% of a calculation, to recognize when it has reached an impasse or a decision it cannot make alone, and to explain to the human user what it has done so far and what, if anything, it cannot resolve by itself, could produce a tremendous enhancement of the productivity of the human theorist. In this paper I will discuss in some detail a sample transport calculation performed by PAP, in which a much larger percentage than this of the calculation is done by PAP itself.

In its fullest state of development, in which maximal use has been made of what is currently known about both plasma physics and about AI methods to handle the plasma information, the PAP project is obviously a very broad one, which might require many man-years to implement. Therefore, there are many

more facilities one might think of beyond those already implemented, or extensions of these already-developed facilities, whose realization appears fully within the grasp of methods available today, but which simply requires a certain investment of time and manpower. In the development thus far, discussed in this paper, the aim has been to demonstrate some of the possibilities. Taking as a primary goal the development of a facility to do plasma calculations in a semi-autonomous fashion (probably the most challenging one from an AI standpoint), the need for most of the other facilities presented here, several potentially quite useful to the human user in their own right, was automatically indicated. Included among these are PAP's "knowledge base" (KB), containing its understanding of plasma theory, routines for numerically evaluating given physical quantities, using parameter values either prescribed by the user or specified by the KB, and a set of routines for developing the sorts of qualitative or heuristic arguments which play such an important role in the way in which human theorists analyze problems. These facilities will be described more fully in later sections.

In previous work [2-6] done on applying symbolic manipulation programs (in particular, MACSYMA) to doing plasma physics, the goal has been to automate a calculation procedure in one narrow, clearly defined problem area. Such facilities thus encapsulate the individual mathematical tools which a theorist has at his disposal, and calls upon at the appropriate point in the process of analyzing a physics problem. In contrast, here, the emphasis is on developing the control structure necessary to making the decision of which of these tools to use in the course of the calculation, normally made by the human theorist. Additionally, because they are developed in order to treat specific individual problems, the specialized facilities, once developed and used to treat the particular problem which motivated their

creation, tend to fall by the wayside. As a result, a great deal of duplicated effort results, as each new project of this sort must redevelop an overlapping body of capabilities and knowledge about plasma theory. This, in turn, tends to discourage use of such facilities. Here, the potential advantages of having a unified body of mathematical tools and plasma knowledge available are pointed out.

The current implementation of PAP is written mostly in MACSYMA, with a few auxiliary routines written in LISP. In terms of optimization for speed and memory usage, this is almost certainly not optimal. However, MACSYMA was used where possible because of the overriding importance of having a good algebraic capability in doing physics theory, because the programming language in MACSYMA has many of the features of the LISP language, a standard for AI and symbolic computation, and because routines user-written in LISP are readily utilized by MACSYMA, so that those routines not easily implemented in MACSYMA are nevertheless easily provided. Particularly because of the resemblance of the MACSYMA language to LISP, once PAP has become sufficiently developed that its structure has become fairly stable, a rewrite to optimize its performance should be relatively simple.

The remainder of the paper is organized as follows. In Section 2, I describe those of the subsidiary facilities mentioned above which have already been implemented, at least in preliminary form. Section 3 describes a transport calculation carried out semi-autonomously by the PAP control structure, which makes use of the facilities introduced in Section 2. Section 4 contains some assessment of the work done so far, discusses some additional facilities or extensions of present ones whose future implementation seems useful and promising, and makes some comments of a more general nature on the possibilities for a facility like PAP. Because of the

interdisciplinary needs of the PAP project, not only across the boundaries of plasma physics and AI, but across the various subfields of both disciplines, rather than providing a literature survey in this introductory discussion, references to relevant (or potentially relevant) work will be noted at appropriate points in the course of the exposition.

2. SOME SUBSIDIARY FACILITIES

To perform its calculations, PAP draws on a knowledge base, containing its understanding of plasma theory. This includes not only the important equations and physical quantities of plasma physics, but also information on the relations among them, both mathematical and conceptual. For example, the KB "knows" not only the Boltzmann equation, but also something about what it is used for, e.g., that it is the equation to solve when the distribution function f is desired (cf. Section 3). Theoretical results in the KB which arise from more fundamental equations have these connections indicated. Thus, PAP would be able to answer the question "why?" for such results, both for its own purposes, as well as for the user. In this way, a fully fleshed-out version of the PAP-KB would serve a powerful archival and pedagogic function, able to resurrect quickly the origin of results or the exact form of results which have become hazy in the memory of a human expert, or to teach a novice in some plasma subdomain what the important results are, and exactly from where they come. Presently, this function is served by the collection of textbooks, papers, and personal notes with which the theorist becomes familiar in the course of his plasma physics education. While these will still have their place in a post-PAP world, particularly in the early stages of a theorist's plasma education, the PAP-KB would have the advantages of being a single, unified, readily accessed body of knowledge, easily updated and

expanded as new results and better ways of reaching old results become available. It must be made clear that, in serving this pedagogic function, the KB is not restricted to only mathematical statements. Conceptual statements and qualitative explanations of physical effects or the reasoning underlying mathematical arguments would also be available, not simply for the human user, but also to be actively made use of by PAP.

One simple but quite useful PAP facility drawing heavily on the KB is the function NUMVAL. In getting a feel for the size or importance of physical effects, a theorist is often called upon to draw out a set of relevant formulae, and plug in typical values for the variables occurring there, or sometimes to see the scaling of these expressions with important parameters. If the expressions to be evaluated are short, and the number of times they are to be evaluated few, one typically pulls out his plasma formula y and a calculator, and spends time guiding the calculator through a procedure which is tedious, time consuming, and error prone. If the calculation is more involved, one often writes a modest computer program, whose structure is clear, but which takes time to assemble. NUMVAL uses the KB as an on-line formulary, and given an expression to evaluate, effectively writes the program the theorist normally writes by hand, accessing the appropriate formulae in the KB, and performing the evaluation. The following briefly illustrates some uses of the KB and NUMVAL:


```

(C1) get(tftr,params);
(D1) [RR = 2.55d+0, A = 0.83d+0, BB = 5, Q = 2, Densi = 1.0820,
                                           TTI = 2000, TTE = 1000]

(C2) boltzeqa;

              d      dF
              (--- (AA ---)) NUH
              dY      dY
(D2)      dF THDT + -- RDT = -----
            dTH   dR      AAP

(C3) why('boltzeqa');
(D3)      (BOUNCEAVG(BOLTZEQ), NEGLECT(%, [1]))

(C4) englishdef(dd);
(D4)      [diffusion coeff]

(C5) instances(dd);
(D5)      [DDBN, DDBP, DDRP] (1)

(C6) englishdef(ddbn);
(D6)      [diffusion coeff, banana regime]

(C7) get(ddbn,givenby);

              2      2
              NU Q  RHG  SGBN
(D7)      -----
              1.5d+0
              EPT

(C8) numval(ddbn,[mm=mmi,tt=tti,egykev=tti]);

              2
              1.7743B-20 Densi Q  SGBN
(D8)      -----
              2      1.5d+0      0.5d+0
              BB  EPT      SQRT(MASS) TTI

(C9) numval(%, [per(tftr),ept=.5*a/rr,mass=1]);
(D9)      9.6686B-2 SGBN

(C10) numval(wci,[]);
(D10)      9.5808B7 BB

(C11) numval(wc,[per(species=ion)]);
(D11)      9.5808B7 BB

```

In (1) above, the numbers (C1), (D1) appearing on the left are the usual MACSYMA line-numbering. The MACSYMA command GET(v,p) retrieves property p of variable v. Some of the types of information in the KB are shown by use of this command. Thus, in (C1), the values of typical parameters for a given device of interest (in this case, TFTR) are recalled. If the user needs to know the physical meaning of a symbol appearing, for example, in some formula, it may be obtained from the function ENGLISHDEF, as in (C4,C6). Often, physical quantities may be grouped into "inheritance networks" [7], hierarchies where the higher level nodes are more general, and the lower level nodes more specialized instances of the same concept. The more concrete, instance variables should inherit the properties of their more general "parents," both for pedagogic purposes, and for PAP's computational functions. The pedagogic function is illustrated in (C4,C6) by ENGLISHDEF, and by (C5,D5), where the particular instances of diffusion coefficients the current embryonic KB knows about are requested. Of the three particular examples the KB knows there, ddbn (D_{bn}), the expression for the diffusion coefficient in the tokamak banana regime, is given in (D7).

ENGLISHDEF uses the conceptual hierarchical structure of the KB, returning a list of successive refinements of the term whose definition is requested which, taken together, define the concept to the requested level of specificity. Thus, the definition in (D6) for ddbn includes, as its first, most fundamental "qualifier," the same general term ("diffusion coeff") as fully defines the symbol dd in (D4). A somewhat fuller taxonomy of transport results is illustrated in Fig. 1. Similar hierarchies exist for plasma waves or instabilities, for types of confinement devices, and for many other aspects of plasma theory, and would be used by the PAP-KB to access known results in a sensible and efficient fashion.

Another type of interrelation among the entities in the KB is illustrated in (C2-D3). In (C2) a particular variant of the Boltzmann equation, here named "boltzeqa," is requested. This is a bounce-averaged form of the full Boltzmann equation, which is used by PAP in the transport calculation discussed in Section 3. In (C3), the origin of this equation is requested, using the function WHY. The response, in (D3), is a MACSYMA-type sequence of operations, which may be translated into English as "First, bounce-average the full Boltzmann equation, boltzeq. In the result of this, neglect the first term (which is the time-derivative term, $\partial f / \partial t$). The result is boltzeqa." This form of "explanation" [8-11] of the origin of boltzeqa makes it possible not only for a human user, but also for PAP, to obtain derivations of past results, to check those derivations for their validity, and perhaps to use the derivation procedures as a guide to approaching new but related problems. In this way it is envisioned that a user will be able to teach PAP new results and their origin, thus extending its KB. Guidance of this sort will be most useful to PAP (as it is for human problem solvers) when a large amount of search would be necessary to find a successful derivation "path" of the result in question in the absence of the explanatory derivation.

In (C8), a numerical evaluation of ddbn is requested, by applying NUMVAL to it. The second argument is a list (parmvals) in which relevant parameters are specified beyond the information PAP can already find in its KB. There, the particle mass (mm) and the temperature (tt) are set to the ion values (mmi,tti) of those quantities, and the particle energy in keV (egykev) is also set to tti. When NUMVAL cannot determine the numerical value of a quantity from either its KB or parmvals, it simply returns the symbol itself. In this way, the scaling of a given expression with relevant parameters is generated, e.g., the scaling of ddbn with density (densi), magnetic field (bb), or

temperature (tti) in (D8). A second application of NUMVAL to this expression in (C9) reduces ddbn to a pure number, times a numerical coefficient (sgbn), whose value has not yet been put in the KB. Note the use of "per(tftr)" in parmvals there, which effectively includes the set of typical TFTR parameters of (D1) in parmvals. (The Latin word "per" is used instead of the English "for" for the moment, because "for" is a special word to the MACSYMA reader.)

A computational use of the inheritance-network structure of the PAP-KB is illustrated by (C10-D11). In (C10), NUMVAL is applied to the ion gyrofrequency wci, with no additional information given in parmvals. NUMVAL first looks under the "givenby" property of wci for a formula by which to evaluate wci, but finds none. Failing this, it finds that wci belongs to an inheritance network, and so looks at the next more general concept in that network, the particle gyrofrequency wc, and looks for a formula for wc, finding $ec \cdot bb / mm$. When moving about on the inheritance network, NUMVAL keeps track of the generalizations and instantiations made in the list cmpentxt, which contains the "computational context" of the calculation. Thus, the initial goal of evaluating wci, with cmpentxt=[], translates into one of evaluating wc, with cmpentxt=[species=ion]. Having found the formula for wc, its constituent elements are evaluated within that cmpentxt. Thus, for example, mm is instantiated to mmi, found by using the inheritance network connecting those two quantities (mmi is then further evaluated to its known numerical value.) Elements in the computational context may be specified within the 'per' entries in parmvals. Thus, (C11) calls for the same calculations as (C10). However, the same sort of specification also permits computing quantities not having a special symbol (such as wci) in the KB. For example, there is no special symbol in the KB for ddbn specialized to ions, but the function call

```
numval(ddbn,[per(species=ion),egykev=tti])
```

calculates this. This is done in (C6) as well, but in (C8) one must decide beforehand which constituent quantities in it (e.g., mm and tt) are species-dependent, and explicitly put each of these in parmvals.

When analyzing and talking about physics problems, physicists frequently engage in various types of "heuristic" or "qualitative" reasoning. These heuristic arguments often communicate in a simple manner what the essential features are entering into a given physical phenomenon or mathematical result, providing guidance in the more rigorous and detailed (and often more obscure) formal derivations which ultimately provide the solid basis of a physical theory. Giving PAP the ability to engage in these kinds of heuristic reasoning is important, in order for it to be able to derive the same benefits for problem solving as its human practitioners do, and to be able to "understand" in an efficient manner arguments communicated to it by a human user. In this section we discuss one facility presently implemented, the function HEURMAP and some related routines, developed with this capability in mind. In Section 4, we discuss some other planned functions to extend this qualitative reasoning capacity.

Often, in a preliminary analysis of the sorts of solutions one may expect for a given differential equation, one maps the equation into a simpler one by, for example, replacing a complicated function by a simpler one which (in some approximation, perhaps) reflects the rough behavior of the function, or by replacing the derivatives appearing in the original equation by characteristic scale lengths over which the functions on which the derivatives act vary. HEURMAP (for "HEURistic MAPping") is a function which gives PAP

this kind of ability. In Section 3 we present an example in which PAP autonomously calls HEURMAP in attempting to decide an appropriate ordering for the Boltzmann equation. Here, we first illustrate HEURMAP by some user-directed examples:

(C3)ballooneq;

$$(D3) \quad \frac{d}{dS} \left(\frac{K^2 dV}{dS} \right) + \frac{2 K^2 KP dP}{3 dR} = 0$$

(C4) [any,s,1/(q*rr),any,r,1/a];

$$(D4) \quad [ANY, S, \frac{1}{Q RR}, ANY, R, \frac{1}{A}]$$

(C5) heurmap(d3,d4);

$$(D5) \quad \frac{6 K^2 V}{BB Q^2 RR} + \frac{2 K^2 KP P V}{3 A BB} = 0 \quad (2)$$

(C6) subst(p=beta*bb^2,d5);

$$(D6) \quad \frac{6 K^2 V}{BB Q^2 RR} + \frac{2 BETA K^2 KP V}{A BB} = 0$$

(C7) solve(d6,beta);

$$(D7) \quad [BETA = \frac{3 A}{2 KP Q RR}]$$

(C8) diffeq1;

$$(D8) \quad \frac{dN}{dT} = \frac{d}{dR} \left(\frac{dN}{dR} \right)$$

(C9) [any,t,1/tau,any,r,1/a];

$$(D9) \quad [ANY, T, \frac{1}{TAU}, ANY, R, \frac{1}{A}]$$

(C10) heurmap(d8,d9);

$$(D10) \quad \frac{N}{TAU} = \frac{3 DD N}{2 A}$$

(C11) solve(d10,tau);

$$(D11) \quad \left[\text{TAU} = \frac{A^2}{3 \text{ DD}} \right]$$

(C12) schroedeq;

$$(D12) \quad \frac{\text{EC}^2 \text{ V}^2}{\text{R}} - \frac{\text{HB}^2 \frac{d^2 \text{ V}}{d \text{ R}^2}}{2 \text{ MM}} = \text{EGY} \text{ V}$$

(C13) htrms(d12,[any,r,2*%pi/r]);

$$(D13) \quad \left[\frac{\text{EC}^2 \text{ V}^2}{\text{R}}, \frac{2 \text{ \%PI}^2 \text{ HB}^2 \text{ V}^2}{\text{MM} \text{ R}}, \text{EGY} \text{ V} \right]$$

(C14) solve(part(d13,1)=part(d13,2),r);

$$(D14) \quad \left[\text{R} = \frac{2 \text{ \%PI}^2 \text{ HB}^2}{\text{EC} \text{ MM}} \right]$$

(C15) subst(d14,d13);

$$(D15) \quad \left[\frac{\text{EC}^4 \text{ MM}^4 \text{ V}^4}{2 \text{ \%PI}^2 \text{ HB}^2}, \frac{\text{EC}^4 \text{ MM}^4 \text{ V}^4}{2 \text{ \%PI}^2 \text{ HB}^2}, \text{EGY} \text{ V} \right]$$

(C16) solve(part(d15,2)=part(d15,3),egy);

$$(D16) \quad \left[\text{EGY} = \frac{\text{EC}^4 \text{ MM}^4}{2 \text{ \%PI}^2 \text{ HB}^2} \right]$$

In (C3,D3) above, we introduce a slightly simplified version of the ballooning equation [12]. The first term represents field line bending, and the second represents the pressure(p)-curvature(kp) destabilizing term. The perpendicular displacement is denoted by V. In (D4), the "replacement list" rplst is introduced, which determines the mapping to be made from the derivatives present. rplst runs in segments of three elements

[...vs,x, κ_x ,...], where vs denotes which variables are affected, x denotes the variable of differentiation, and κ_x gives the inverse scale length into which the x-derivative maps. vs may be either a single variable, a list of variables, or [as in (D4)] the wildcard variable "any." Thus, the first triplet in (D4) means $\partial(\text{any})/\partial s \rightarrow \langle \text{any} \rangle / qR$, i.e., the usual mapping one makes in ballooning mode theory that the scale for variation along a field line is the connection length qR. By "any" here is meant any variable not known to be independent of s from other information in the KB. Additionally, the KB can provide the information for these heuristic mappings, overridden by the explicit input rplist of (D4).

In (C5) HEURMAP is applied to the ballooning equation, resulting in (D5). The numerical factors are an indication of the number of separate terms in the differand having nonzero derivative. Replacing p in favor of beta (β) in (D6), in (D7) we solve for β , arriving at (up to numerical factors) the expression for the critical β for ballooning stability.

A similar heuristic analysis is made for the diffusion equation given in (D8), using the rplist of (D9). Applying HEURMAP in (C10) and solving for tau, in (D11) one finds the usual expression for the characteristic diffusion time. In (C12-D13) a variant function, HRTRMS, is illustrated, applied to the Schrödinger equation. HRTRMS applies HEURMAP to each term in a given equation or expression, returning a list of the corresponding results. This variant is useful for comparing the size and scalings of the terms in an equation. It is the form used by PAP in an ordering analysis of the Boltzmann equation described in the following section. From balancing the terms in (D13), in (C14-D16) one readily finds the expressions (up to a numerical factor of order unity) for the Bohr radius [in (D14)], and the ground state energy [in (D16)] of the hydrogen atom. The ability to perform the kind of balancing of terms

done in (C14) is among the additional heuristic facilities planned for PAP.

3. AN AUTOMATED TRANSPORT CALCULATION

In this section we describe in some detail a model transport calculation performed by PAP. In the course of the calculation, the lower level facilities discussed in Section 2 which PAP makes use of will enter the discussion. The protocol of the interchange between PAP and the user for this calculation (edited slightly to eliminate some irrelevant diagnostic messages) is listed in Appendix A.

PAP is instructed to calculate the radial flux "gamr" by the function call:

calc(gamr); (3)

When this command is issued, PAP refers to its KB, to see if it knows what gamr is. There it finds that it does know that symbol, defined in terms of the algebraic expression

$$\text{gamr} = \text{int}(\text{aap} * \text{rdt} * f, [\text{th}, y], [0, \text{indef}], [2 * \pi, \text{indef}]), \quad (4a)$$

or in noncomputerized algebraic notation

$$r_r = \int_0^{2\pi} d\theta \int dy A' \dot{r} f \quad (4b)$$

Here, θ is the poloidal azimuth, y is a pitch-angle variable, $\dot{r}$ is the particle radial drift velocity, A is a function of y , giving the proper phase-space Jacobian, with A' its derivative, and f is the particle distribution function. The precise definitions of y , A , A' , etc. are not needed in

understanding the calculation procedure, the issue of interest here. We use "INT" instead of the standard MACSYMA function "INTEGRATE" because of some peculiarities in the way the latter function is handled in MACSYMA, which make it difficult to deal with integrals in a formal fashion. A theorist (including PAP) frequently wants to do this, but MACSYMA was developed with the idea of doing concrete integrals in mind, and this has to some extent made its conventions inconvenient for our purposes, as well as being inconsistent with the way in which DIFF is handled. Additionally, INT can be used to denote multiple integrals, as in Eq. (4). Expression (4) for the radial flux is a slightly simplified version of the full expression, since the integration over particle energy has been omitted, and the limits in the y -integration have been left unspecified, as denoted in Eq. (4a) by the symbol "indef."

Examining the right-hand side of Eq. (4), PAP sees which variables are present. For each, it checks to see if it already knows to what that variable evaluates, first by seeing if it is something which has already been evaluated elsewhere in the calculation, or is already on the stack to be evaluated. If not, it adds the variable as a subgoal to this stack, and proceeds with it as it does with the main goal, gamr . In this way a "solution tree" is developed, which describes the plan by which PAP intends to generate a solution to the task it has been given. The tree it develops for the problem given in Eq. (3) is shown in Fig. 2. When PAP comes upon constants, or variables it regards as fundamental, it can evaluate them immediately, these becoming the "leaf nodes" of the tree [e.g., v_b (v_B) in Fig. 2], at which point the direction of traversing the tree is reversed, from a downward, node-creating pass, to an upward, node-evaluating pass.

The calculation process described thus far is one which might be effected simply by defining CALC as a recursive function, obviating the need for

keeping an explicit stack or record of the developing solution tree. However, these objects are important for a number of reasons. First, it often happens that a given variable v arises more than once in a calculation. Examples of this in Fig. 2 are θ (nd7), which arises in nodes nd2, nd8 and nd10, and f_{10} (nd22), used in both nd21 and nd25. A human theorist would notice this, only doing the subcalculation for v once, and one would like PAP to do the same, particularly if the calculation for v requires an appreciable amount of effort. A simple recursive program would recompute v as many times as it was called for. At the very least, the recursive routine would have to be enhanced with a list of variables already computed, checked before entering into any new subcalculation. Also, it often happens that the structure of the equations used to compute quantities of interest is such that a variable v is determined by expressions involving itself. One example is in the derivation of the self-consistent plasma response to a perturbation. In this case, v will occur as a direct "descendant" of itself in the solution tree, and a simple recursive approach to doing the calculation will result in an infinite loop. (By the term "descendant" here, we are viewing the solution tree in a genealogical way, where the set of subnodes spawned by a higher level node are regarded as its children.) To avoid this problem, it is useful to keep a record of the tree structure, by which to detect when such a situation has occurred, and to modify appropriately the tree-generating procedure in that case. Because of the possibility of multiple uses of the result of a single node, and the scrambling of the ancestor/descendant notion this causes, it should be noted that what we are calling a "tree" here might somewhat more accurately be called a "network," or "graph."

The detection of direct descendants is just one instance of a situation in which a human problem-solver will use some feature of his mind's own

"solution tree" to detect that a modification of the solution plan represented by that tree is appropriate. Another example occurs in certain transport calculations, where an integration by parts of the expression for r_p brings it into a symmetric form, which permits one to avoid having to go to one higher order in a perturbative solution for f in computing r_p . For a human theorist, such "clever" manipulations are usually noticed and performed because he has learned from related calculations that trying such a thing can be helpful in a given situation. PAP's use of an explicit stack and the solution-tree structure permits the incorporation of such algorithm-modifying rules in a flexible and readily expanded fashion.

Another important reason for PAP's use of solution trees is that it allows it to "show its work." This ability will be critical for effective interaction with the human user. Finally, in addition to performing essentially algebraic calculations like the one illustrated in Fig. 2, more mature versions of PAP are intended to be able to develop and carry out plans of a more general, not purely algebraic, nature [13,14]. Regarding the present algebraic problem as one instance of a more general problem-solving task will permit the same control structure to deal with the more general classes of problems.

We return to the specific calculation of Appendix A and Fig. 2. The value of the problem node called nd4 is f , that is, the task of that node is to calculate f . From its KB, PAP finds that f is something found by solving the Boltzmann equation. (For this example, PAP uses the variant "boltzeqa" of this equation, already introduced in Section 2 in connection with the features of the KB.) This task is assigned to node nd10, whose value is "SOLVEFOR(boltzeqa,f)." This value is just the function call which is made in order to accomplish the task.

The function call SOLVEFOR(eq,v) attempts to solve equation eq for variable v. For a range of algebraic equations, integral equations, o.d.e. s and p.d.e.s, it will successfully solve eq and return the result:

(C3) a*v^2+b*v+c=0;

(D3) $A V^2 + B V + C = 0$ (5)

(C4) solvefor(d3,v);

solvefor V
algebraic-apply solve

(D4) $V = \frac{-\sqrt{B^2 - 4AC} + B}{2A}, V = \frac{B - \sqrt{B^2 - 4AC}}{2A}$

(C5) a**diff(b**diff(v,y),y)=c;

(D5) $A \left(\frac{d}{dy} \left(B \frac{dV}{dy} \right) \right) = C$

(C6) solvefor(d5,v); (6)

solvefor V
slv1tm

(D6) $V = \text{INT}\left(\frac{\text{INT}(-, Y)}{A}, Y\right)$

In (5), SOLVEFOR notices that the equation is algebraic, and so applies the MACSYMA routine SOLVE, printing a diagnostic message indicating this. In (6), the message "slv1tm" indicates that another routine (of that name) in SOLVEFOR's (currently small) collection of solution methods is used. The range of equations which SOLVEFOR can solve outright is currently quite limited, written to deal with equations of the type of the test problems brought before it thus far. Its development into a more comprehensive library of available solution techniques is a useful task of a MACSYMA variety.

In addition to recognizing those equations it can solve outright (for

which it returns an answer) and those it cannot solve, for some equations, SOLVEFOR recognizes a situation in which a perturbative solution might prove successful:

(C7) boltzeqa;

$$(D7) \quad \frac{dF}{dTH} THDT + \frac{dF}{dR} RDT = \frac{\frac{d}{dY} (AA \frac{dF}{dY}) NUH}{AAP}$$

(C8) solvefor(d7,f);

solvefor F

other de type

(7)

$$\text{consider ordering on } \frac{dF}{dTH} THDT + \frac{dF}{dR} RDT - \frac{\frac{d}{dY} (AA \frac{dF}{dY}) NUH}{AAP} = 0$$

term scalings: [F KPTH THDT, $\frac{F RDT}{A}$, $\frac{2 AA F KPY NUH}{AAP}$, 0]

num ratios [1, $\frac{SIN(TH) VB}{A THDT}$, $\frac{8.4994B-13 AA DENSI}{AAP DL SQRT(MASS) THDT TT}$, 0.0B0]

unevald parms: [A, TH, THDT, VB, AA, AAP, DENSI, DL, MASS, TT]
give values,or continue->usr ordr
[aa=1,th=%pi,aap=1,per(tftr)];

num ratios [1, 0.0B0, $\frac{8.4994B7}{DL SQRT(MASS) THDT TT}$, 0.0B0]

unevald parms: {DL, MASS, THDT, TT}
give values,or continue->usr ordr
continue;

give eplst1
[1,ep1,1,1];

geneqhier

collisionless orbits is small compared with the minor radius of the confinement device. From the mechanized portions of ORDRSUG just described, or some extension of them, it should not be difficult to have PAP generate eplst1, or at least suggest one, but at present this has not been done.

Once given eplst1, the rest of the ordering process is automatic. f is expressed as an expansion to some specified order in $ep1$, this is inserted into boltzeqa, and the appropriate heirarchy ["eqhier=" in (7)] of kinetic equations to solve is generated [in the function GENEQHIER, whose name is announced in (7) and in Appendix A]. The value returned by SOLVEFOR at the end of (7) may be read "The result is $f = f_0 + \epsilon_1 f_1$ (+higher order terms, if needed), IN WHICH the expansion parameter is ϵ_1 , and the newly introduced variables f_0, f_1 are found by solving the corresponding equations given in eqhier." When PAP receives a response of this form from SOLVEFOR, it creates new subtasks (nodes nd16, nd18 in Fig. 2) of the same form as the earlier problem (node nd4) of computing f .

Note that this represents an incremental increase of the KB. Instead of the new knowledge being "taught" to PAP by the user, the possibility for which was indicated in Section 2, here it is PAP itself which has generated the new knowledge increment. The kinetic equations generated by ORDRSUG are associated with the variables f_0 and f_1 created by PAP in the same manner as boltzeqa is associated with the member f of the permanent KB. This uniformity in the representation of newly developed and permanent information will permit PAP to be able to operate on them in a unified fashion, and will facilitate the incorporation of new results into the KB, i.e., "learning" [15-17]. This uniformity is part of the general design philosophy for PAP, and provides constraints on the representation of both information in the KB, as well as output from PAP's routines.

Continuing with the main calculation, at nd20 PAP applies SOLVEFOR to f_0 , and finds that this is an equation it can solve outright. For f_1 (nd19), it instead finds that it must try to induce a second ordering, invoking ORDRSUG as before. This time the ordering is in ϵ_2 , which determines the collisionality regime of interest. Here, an analysis of the type induced by ORDRSUG is inconclusive on whether the collisional (3rd) term in boltzega should be ordered large or small compared with the precessional (1st) term. This is to be expected, because realistic devices can operate in differing collisionality regimes. Indeed, the transport literature can with some validity be viewed as a search through the space of possible relative orderings of the terms in the full kinetic equation consistent with reasonable parameter values, in which conceptually the same calculation is done for each ordering. Here, PAP could be instructed to investigate a particular ordering, or all reasonable ones. In Appendix A, the choice made is to order the collision frequency small. The calculation is thus of the same class of calculations as the tokamak banana regime [18], the precession-dominant banana-drift regime [19], and the superbanana regime in rippled tokamaks [20] and stellarators [21,22], the hallmark of which is a diffusion coefficient linear in the effective collision frequency, here called ν_h (ν_h). The assumption made by PAP in the present calculation, that $\partial f / \partial t$ (∂) is independent of θ and y , makes it most closely analogous to the banana-drift calculation of Ref. 19 (once θ is reinterpreted to mean the ripple phase instead of poloidal azimuth), and that result may be recovered from the result generated by PAP here, with the appropriate expression substituted for ν_h . For all these calculations, however, most of the solution tree of Fig. 2 is valid, giving a more concrete formal meaning to the general statement that all the calculations are "conceptually similar." By using such solution trees

stored in its KB to direct its approach to problems not previously attempted, it is hoped that PAP will be able to apply analogical reasoning [23-25] to apply solution approaches known to be effective for previously treated problems to new problems of similar character.

In (D4) in Appendix A, the answer for gamr is first given formally, leaving the function INT unevaluated. INT is evaluated, where possible, by the application to the formal result of INTEV , in (C5,D5). INTEV expands the multiple-integral notation allowed in INT into the usual single-integral form, looks up the dependencies on the integration variables of the other variables in the integrand, using the KB, and then performs the integration. (The dependencies of the variables f_0 , f_1 , etc. introduced by PAP are known from the inheritance organization of the KB mentioned in Section 2. In this case, the f 's inherit the dependencies of the full f , modified by additional information discovered subsequent to their introduction from, for example, solving the relevant kinetic equation.) Because it takes more trouble to first pull formal quantities which are independent of the integration variable outside the integral, INTEV succeeds in evaluating (D4), when a simple application of INTEGRATE to (the properly expanded version of) (D4) takes a great deal longer, and fails. Of the three terms in the factor multiplying $v_b \sin(\theta)$ in (D4), corresponding to f_{11} , f_{10} , and f_0 , one notes that only the f_{11} -term, the term linear in n_{uh} , contributes in (D5), in agreement with established theory. A closer imitation of the human theorist would be achieved by having PAP apply INTEV to the result of each subtask, and to only proceed, in any expansion it introduces, to the lowest order at which a nonzero result is found (up to some maximum order, say, at which it might ask whether the answer is 0 to all orders). The answer so obtained would be the same as that given here, but would obviate the need to have the user set the

order to which the expansions have to be carried out. The modifications necessary to allow PAP control expansions in this fashion should be straightforward.

A human theorist would usually collect the two terms appearing in the integrand in (D5) into one. Again because of the operation of the MACSYMA functions DIFF and INTEGRATE which it uses, the function INTEV leaves the result in the less than optimal form shown. Improvements in making decisions of this sort in doing formal algebraic manipulations would be useful for MACSYMA and MACSYMA-like facilities.

When the collisional term is ordered large instead of small at nd19, i.e., if $ep1st1=[1,ep2,1,1]$ instead of the value $[1,1,ep2,1]$ is taken in Appendix A, PAP undertakes a calculation of the " $1/\nu$ "-regime variety, also familiar from rippled tokamaks [19,29] and stellarators [30]. PAP recovers the stellarator result, except that it as yet has no ability to reason about the appropriate boundary conditions in y , thus leaving the y -integration indefinite.

In the AI work done on the automated solution of physics problems, a good deal of effort has been devoted to developing rules and procedures by which to select an appropriate equation to use to solve for a given variable [26-28]. For example, in the present context, if the distribution function f is desired, it is insufficient to run through every equation in plasma physics for those containing f , and randomly pick one to solve for f . At present, an adequate amount of additional "pruning" of the solution tree has been achieved in PAP simply by information in the KB about which equation(s) are typically used to solve for which variables. It is as yet unclear whether in the process of making PAP able to deal with a much broader range of plasma problems substantially more sophisticated equation-selection strategies will

become necessary.

Another point at which there lies the danger of a "combinatorial explosion" due to insufficiently constrained search, which has been ignored in the present calculation, is in the choice of the right form of the equations used, that is, in the proper coordinates in terms of which to express the problem, and in some assumptions implicit in the equations used. For example, use of the Lorentz form of the collisional term in boltzega is justified for some problems (e.g., ripple transport), but not for others. Similarly, use of the pitch-angle variable y is convenient for problems where pitch-angle scattering is the crucial feature in determining transport, but might be a poor choice for other problems. Rules enabling PAP to make judicious choices of this sort could be incorporated into the KB, and to the PAP control structure could be added a feature which accesses information of this sort in the KB under appropriate conditions.

4. DISCUSSION

In this section are considered some of the issues raised by my experience with PAP thus far, and some of the possible directions for future development.

A number of desirable extensions for PAP have been mentioned in the discussion of the preceeding sections. A great deal of expansion of the PAP-KB will be needed to enable it to deal with a broad class of plasma physics problems. To a large extent, this will require simply more information, organized along lines already established. The degree to which it will also call for significant conceptual extension is an open and interesting question.

Another type of extension, probably of only slight interest from an AI

standpoint, but quite important in terms of its effect on performance, is enhancing the collection of mathematical tools available. For example, the class of equations with which the SOLVEFOR function can successfully deal is currently rather limited, as is its range of perturbative techniques.

More conceptually interesting is the extension of PAP's heuristic reasoning capabilities, as represented by the function HEURMAP, discussed in Section 2. As noted there, one would like PAP to be able to understand arguments given to it in qualitative terms. The function HEURMAP provides only part of the abilities needed. In the illustrations of HEURMAP given in Section 2, and in its application by PAP in ordering the Boltzmann equation in Section 3, after the relevant equations had been HEURMAPped into something approximate and manageable, some kind of selection of the dominant terms in the mapped equations and balancing of those terms was needed in order to reach the desired heuristic estimate. The reasoning by which a human theorist is able to put definite limits on the y -integration in gamr in Section 3 also involves a recognition that the integrand in a certain range of the integration is dominant.

A related but somewhat different type of qualitative reasoning is exemplified by the following, describing a thermal instability in a fusion reactor: "If the plasma gets a bit hotter, its collisionality decreases. As its collisionality decreases, the energy confinement time increases. An increased confinement time with the same rate of heating implies the plasma will become still hotter, reinforcing the initial tendency, so the process continues in this direction." Here, it is not principally an estimate of the size of the solutions of the governing equations which is desired, but of their qualitative evolution. This kind of "qualitative process theory" has been studied [31-33] by workers in AI, and a version of this reasoning, tuned

to deal with the kinds of phenomena relevant to plasma physics, should not be difficult to implement. Moreover, the same kind of reasoning is useful not only in describing physical phenomena in a terse fashion, but also in describing why some mathematical techniques will or will not work. Thus, it may be feasible to expand not only PAP's knowledge of plasma theory in this more efficient fashion, but also its collection of mathematical tools.

The task of developing the full structure of the theory and associated mathematical tools for plasma physics (or any comparable knowledge domain) is more than can be accomplished by one person, or one small group of archivists. Moreover, the people best able to communicate the best way to deal with any given subspecialty are the experts in that area. Therefore, one very desirable extension would be to equip PAP with mechanisms for knowledge acquisition [9-11], so that it can be distributed for the general use of the plasma community, and its KB can be expanded by new contributions from its human users. Used in this fashion, the PAP-KB could serve as an "electronic journal" [34], a unified, easily updated embodiment of plasma theory, through which one could easily discover what has been done in a given area, its conceptual structure, and historical evolution.

A question which naturally arises when the notion of having a computer do semi-independent physics "research" is discussed is "Can it actually do anything 'new,' or must it effectively be fed all that it needs to know in order to obtain each new result?" As I have tried to indicate in earlier sections, most of what goes into each new physics calculation is not new. Often, "newness" enters a new calculation mainly by stitching together known techniques in a new pattern. Thus, taking the view that a theorist is in large part simply applying a large but finite number of mathematical and conceptual analytic techniques in an infinite variety of combinations, there

is no reason why a mechanized collection of a large portion of these techniques should not be able to do large portions of many "new" calculations. Indeed, the calculation of the previous section shows that, even with a very modest fraction of the plasma theorist's full "toolbox," realistic physics results can be computer-generated, with only a small amount of human consultation.

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APPENDIX A

```
(C4)calc(gamr);
```

```
solvefor F
other de type
```

```

              d      dF
              (--- (AA ---)) NUH
              dY      dY
consider ordering on --- SIN(TH) VB + --- THDT - ----- = 0
              dF      dF
              dR      dTH      AAP
              2
term scalings: [-----, F KPTH THDT, -----, 0]
              F SIN(TH) VB      2 AA F KPY NUH
              A      AAP
              A THDT      8.4994B-13 A AA DENSI
num ratios [1, -----, -----, 0.0B0]
              SIN(TH) VB      AAP DL SQRT(MASS) SIN(TH) TT      VB
              1.5d+0
```

```
unevald parms: [A, TH, THDT, VB, AA, AAP, DENSI, DL, MASS, TT]
give values, or continue->usr order
continue;
```

```
give eplst1
[ep1,1,1,1];
geneqhier
```

```
solvefor FO
homog-f0-type de
```

```
solvefor F1
other de type
```

```

              d      dF1
              (--- (AA ---)) NUH
              dY      dY
consider ordering on --- SIN(TH) VB + --- THDT - ----- = 0
              dFO      dF1
              dR      dTH      AAP
              2
term scalings: [-----, F1 KPTH THDT, -----, 0]
              FO SIN(TH) VB      2 AA F1 KPY NUH
              A      AAP
              A F1 THDT
num ratios [1, -----, -----, 0.0B0]
              FO SIN(TH) VB      AAP DL FO SQRT(MASS) SIN(TH) TT      VB
              8.4994B-13 A AA DENSI F1
              1.5d+0
```

```
unevald parms: [A, FO, F1, TH, THDT, VB, AA, AAP, DENSI, DL, MASS, TT]
```


give values,or continue->usr ordr
continue;

give eplst1
[1,1,ep2,1];

geneqhier

solvefor F10
slv1tm

solvefor F11
slv1tm

(D4) INT(AAP SIN(TH) VB (EP1 (EP2

$$\frac{\text{dF0}}{\text{dR}} \text{SIN(TH) VB}$$

$$\text{NUH} \left(\frac{\text{d}}{\text{dY}} \left(\text{AA} \left(\frac{\text{d}}{\text{dY}} \left(\text{INT} \left(\frac{\text{THDT}}{\text{AAP THDT}}, \text{TH} \right) \right) \right) \right) \right)$$

$$\text{INT} \left(\frac{\text{dF0}}{\text{dR}} \text{SIN(TH) VB} \right)$$

$$+ \text{INT} \left(\frac{\text{THDT}}{\text{AAP THDT}}, \text{TH} \right) + \text{FO}, [\text{TH}, \text{Y}], [0, \text{INDEF}], [2 \pi, \text{INDEF}])$$

$$\text{THDT}$$

(C5)intev(%);

(D5) INT(%PI AA EP1 EP2 $\frac{\text{dF0}}{\text{dR}} \text{NUH VB} \frac{\text{d}^2 \text{VB}}{\text{dY}^2}$

$$+ \%PI \frac{\text{dAA}}{\text{dY}} \text{EP1 EP2} \frac{\text{dF0}}{\text{dR}} \text{NUH VB} \frac{\text{dVB}}{\text{dY}}, \text{Y})/\text{THDT}$$

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FIGURE CAPTIONS

FIG. 1. Depiction of an "inheritance network" for plasma transport results.

- Deeper nodes are more specific instances of the higher nodes. The labels on the connecting arcs describe the nature of the particular specialization.

FIG. 2. Structure of the "solution tree" generated by PAP in doing the transport calculation discussed in Section 3. The main goal [at node (nd1)], the calculation of $gamr$, appears at the top of the tree, and subgoals arising from this main task appear below. The upward directed, dashed lines lead to subgoals already established at the time of the creation of the parent goal from which the lines emanate.

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Fig. 1

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Fig. 2

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