Pāṇini's Grammar and Computer Science

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I Introduction

The enterprise of computer science has two fundamental elements. The first element is to develop techniques that make the elucidation of the computational structure of nature and the mind easier. The second element is the creation of new computing algorithms and machines that have powerful cognitive and computational abilities: this includes development of new techniques of representing and manipulating knowledge, inference and deduction.

The tasks of representing and processing knowledge with a somewhat different emphasis has parallels in many ancient disciplines. Thus grammarians have long considered questions of relating facts about the physical world and cognition to linguistic expressions. Likewise logicians have developed formal structures to relate events and draw inferences from them. This is seen best in the work of ancient Indian logicians and grammarians. It has been argued by Ingalls, Staal, Matilal, Briggs, Kak and others[1] that many contemporary developments in formal logic, linguistics, and computer science are a rediscovery of the work of these ancient masters. But apart from the question of a correct history of ideas it raises the following important question of significance to Sanskritists as well as cognitive and computer scientists: Are there other rules in ancient Indian logic and grammar that may be of use in making further advance in cognitive and computer sciences? A little bit of history shows why this is a valid question. Nineteenth century Western linguists did not see the significance of the context-sensitive rules of Pāṇini's grammar. In fact their fundamental importance was seen only when Pāṇinian style structures were first introduced by Western linguists such as Chomsky about thirty years ago. According to the distinguished linguist Frits Staal: "We can now assert, with the power of hindsight, that Indian linguists in the fifth century B.C. knew and understood more than Western linguists in the nineteenth century A.D. Can one not extend this conclusion and claim that it is probable that Indian linguists are still ahead of their Western colleagues and may continue to be so in the next century? Quite possible; all we can say is that it is difficult to detect something that we have not already discovered ourselves."[2]

Computationally, grammars of natural language are as powerful as any computing machine. But since the setting of a grammar is so different from the typical purpose of a computer, this fact is often obscured. The formal structure of a grammar can be easily adapted so as to perform numerical processing. In this paper we discuss formal aspects of certain rules of Pāṇini's grammar, *Aṣṭādhyāyī (A)*, which is traditionally studied together with the *dhātupāṭha*, which is a list of verbal roots arranged into sublists, and the *gaṇapāṭha*, which is a list of various classes of morphs, one class being the *dhātupāṭha*. It is now becoming clear that *A* does not merely deal with analysis of words (*śabdānuśāsana*) but in fact provides a structure for the analysis of sentences. Due to its algebraic nature and its comprehensiveness, the structure has been described as a machine generating words and sentences of Sanskrit.[3] Composed in the succinct *sūtra* style, *A* consists of nearly 4000 *sūtras* that capture the fundamentals of Sanskrit language in terms of its phonology, morphology and syntax. As in any formal system, the structure consists of definitions, theorems (linguistic facts), and meta-theorems (rules regarding rules). The rules are of different kinds: some are universal and context-sensitive transformations, others operate sequentially or recursively. Generally these rules are expressed in three groups: (i) rules of interpretation or meta-rules – *saṃjñā* and *paribhāṣā* rules, (ii) rules of affixation – rules prescribing affixes after two kinds of basic *dhātu* and *prātipadika* roots, and (iii) rules of transformation for the stems and the suffixes – the morphophonemic rules. Note that a computer program has exactly the same general features of context-sensitive rules, recursion, and sequential rule application. It is not surprising, therefore, that these *sūtras* have been compared to a computer program that generates Sanskrit sentences. Pāṇini's grammar is algebraic where a finite set of rules generates an infinite number of words and sentences.

It is generally agreed that the Pāṇinian system is based on a principle of economy, an Occam's razor. This makes the structure to be of special interest to cognitive scientists. Furthermore, development of logic has been seen as emerging from the background of grammatical categories both in India and Greece. Considering the preeminent position of the Pāṇinian system in the Indian intellectual tradition, its significance for students of logic and history of science becomes clear.

It is also important to place Pāṇini's grammar in the context of a continuing development of mathematics and science in India. Seidenberg has shown[4] that the rise of the earliest mathematics should be seen in the Vedic literature. Furthermore, Kak has established[5] that the Brahmi script of Pāṇini's time is to be derived from the Indus script of the third millennium B.C. This means that Pāṇini himself was heir to a very long and rich tradition of learning.

Grammatical categories serve to express knowledge about the world. Pāṇini's system of knowledge representation is based in the *kāraka* theory. The *kāraka* are deep structure relations that mediate mappings from semantic relations (such as agent, goal, location) to phonological representations (in terms of case-endings tha may express voices) via surface structures (in terms of morphological categories such as nominal cases, prepositions, and verbal voices).[6] On the morphological level the *kārakas* are represented by six triplets of case-endings, each of which *roughly* corresponds with one *kāraka*. The *kāraka* rules are applied with the governing (*adhikāra*) *sūtra* P.2.3.1: *anabhihite*, (add a case-ending after a lexical unit to convey a *kāraka* only) if it is not expressed (already). Two of the *kārakas*, *kartṛ* and *karman* can be expressed by verbal endings, whereas some other *kārakas* can also be expressed by primary and secondary suffixes. The *kāraka* theory is of obvious interest to the computer scientist interested in natural language processing. The reader interested in the details of this theory should see the essays by Joshi[7] and Kiparsky and Staal.[8]

A comprehensive study of A from a computing science perspective should include linguistic, structural, and algorithmic aspects. Such a study must be based on the long tradition of analysis of A that goes back about 2,500 years. Problems of particular interest to the computer scientist include the arrangement of the rules and the smallest set of rules that would be equivalent to A. Rearranged rules, such as those by Bhaṭṭojī Dīkṣita in his *Siddhānta Kaumudī*, would provide an invaluable frame of comparison. But before a comparison can be made from an algorithmic perspective one needs to describe A's rule in a form convenient for analysis by computer. With this in mind, we discuss in this introductory paper certain formal aspects of Pāṇini's grammar. In particular we consider the following two aspects:

1. The *sūtra* style and the nature of rules,
2. The structure of the rule system.

We will show how the rules can be easily cast in familiar algebraic or transformational forms. An explicitly algebraic representation is essential before Pāṇini's rules are expressed on a computer so that their computational and cognitive implications can be properly assessed.

II The sūtra style and the nature of the rules

The *sūtra* style represents a genre of Sanskrit literature. Traditionally, a *sūtra* is defined as the most concise of statements which uses as few letters as possible. Although many books have been written in the *sūtra* style, Pāṇini's grammar or *Pāṇinisūtra*, *(Ps)*, is unanimously regarded by tradition as a model of the *sūtra* style of composition.

Words and sentences constitute the data as well as the rules for grammar. Language is thus both a means and an end. Pāṇini's grammar deals with Sanskrit. But its end language (the object language) and the means language (the metalanguage) are distinctly different from each other. Pāṇini's matalanguage has its own vocabulary, syntax, and grammar although it is basically Sanskrit. An extensive use of abbreviated expressions and other devices has given it an appearance of a code language. It is this feature of the *Pāṇinisūtra* that has inspired comparisons with a computer programme. A few prominent aspects of this code language will be described later. A striking feature of the language of the *sūtra* is the use of abbreviated expressions. Economy of expression is Pāṇini's primary concern and he has achieved it by employing several algebraic devices. Use of technical terms in place of lengthy expressions is one of them. He uses symbols like *ṭi, ghu, gha* and *bha*. Further, a code representation, technically known as *pratyāhāra*, enables him to save words and even letters in a rule. For instance, instead of directly mentioning the letters *y, v, r, l*, Pāṇini makes use of the *pratyāhāra* *yaṇ*; for vowels he uses the term *ac*; for consonants, *hal* and so on.

Following is an example of a rule containing all code words:

P.6.1.74: *iko yaṇ aci*

i, u, ṛ, and *ḷ* are replaced by *y, v, r* and *l* respectively when a vowel follows.

Use of words without adding endings to them traditionally known as *(avibhaktikanirdeśa)* is another striking feature of the language of the *Ps.* However, it will not be described here.

IIA A *Ps* is a single clause proposition consisting of a subject, a predicate, and an environment. It is a statement about grammatical features such as a suffix, an augment, a substitute, accent, reduplication, elision, and compounding. It is usually of the form *A is B in the environment C.* This can be written in the following formula:

$$Ps : A \Rightarrow B\ (C)$$

Here $\Rightarrow$ stands for *is* or *becomes*, and ( ) stands for *when*, A stands for the subject, B represents predicate, and C stands for environment. While A and B are the necessary components of a *sūtra*, C is optional. A unique feature of the *Ps* is the absence of a finite verb predicate. Tradition holds that the finite verb *asti* (is) or *bhavati* (becomes) is taken to be present in each rule. A Pāṇinian rule is thus a statement about something being or becoming something else. Pāṇini's marked predilection for nominalization is clearly reflected in his attempt to reduce all statements to those on being or becoming. Thus for instance, instead of saying, *tat lupyate*,

That (code letter) is dropped,

Pāṇini says: *tasya lopaḥ* (P.1.3.9),

Its (i.e. the code letter's) elision (takes place).

IIB Another interesting feature of the Pāṇinian proposition is the total absence of syllogization or any other kind of logical argumentation. Other *sūtra* works such as the *Nyāyasūtra* and the *Brahmasūtra* often contain, in addition to A, B, and C, a cause *(hetu)* and an illustration *(dṛṣṭanta)*. In his grammar, Pāṇini never poses the question, Why? His *sūtras* are statements of linguistic facts in reply to the question, What? In other words, he describes facts of language without accounting for them. To sum up, the language of the *Ps* consists of three types A, B, and C as shown above.[9]

IIC The relation between A and B on the one hand, and that of C with A and B on the other, is expressed by Pāṇini by the use of certain cases. While the predicate item is always used in the nominative, the case of the subject item is determined by its specific relation with the predicate. For instance, if the predicate is a substitute *(ādeśa)* the subject is used in the genitive. This has been directly stated by Pāṇini in a rule.[10] If, on the other hand, the predicate is a suffix *(pratyaya)*, the subject is put in the ablative.[11] Environment is expressed in the locative if it follows the subject.[12] These statements can be put in the following formula:

For substitute: $A\ (gen) \Rightarrow B\ (nom)\ (C(loc)\ )$

For suffix: $A\ (abl) \Rightarrow B\ (nom)\ (C(loc)\ )$

A few more formulas can be formed on the basis of other observations.[13] The following rule is an illustration of the first formula:

P.6.1.74: *iko yaṇ aci*

yaṇ is substituted in place of *ik* when *ac* follows.

The genitive form *ikaḥ*, the nominative form *yaṇ* and the locative form *aci* are in accordance with the statement made above and the mutual relationship among the three items is conveyed by the case-endings.

IID Science may be viewed as a body of generalizations followed by statements of exception when necessary. Pāṇinian science of grammar also consists of a set of general rules followed by statements of exception. A *Ps* can be thus either a generalized statement or a specific statement which stands as an exception to a generalization. In a generalized as well as particular statement the subject or the predicate can be a multi-member category. A single predicate may be shared by many or all subjects. For instance consider

> P.3.2.1: *(dhātoḥ) karmaṇy aṇ*
>
> The suffix *aṇ* is added to a root in the sense of object.

The word *dhātoh̄*, which is put inside the brackets (the reason will be explained later), is the subject and *aṇ* is the predicate. Here *dhātu* stands for any root in general. The statement of the suffix *aṇ* thus is applicable to all roots in general. The predicate *aṇ* is thus shared by all subjects. Here the subject, which is a multi-member category, is represented by a class term (i.e. *dhātu*). This type of Ps can be represented as:

$A^{1-n} \ \Rightarrow \ B(C)$. On the other hand, sometimes many predicates are linked with one subject. For example,

> P.5.2.32: *ner biḍacbirīsacau*
>
> P.5.3.33: *(ner)inacpiṭaccikaci ca*
>
> The suffixes *biḍac, birīsac, inac* and *piṭac* are added to *ni* (in the sense of flat nose) and in case of the later two suffixes *ni* is replaced by *cika* and *ci*, respectively.

Here as many as four predicates are shared by one single subject, *ni.* This statement could be represented as:

$A \ \Rightarrow \ B^{1-n} \ (C)$

A third type in which both A and B are simultaneously multi-member categories is also occasionally met with. For instance,

> P.3.1.133: *(dhātoḥ) ṇvultṛcau*
>
> The suffixes *ṇvul* and *tṛc* are added to any root.
>
> This statement is of the type
>
> $A^{1-n} \ \Rightarrow \ B^{1-n}(C)$

Just as is true for A and B, C also can be a multi-member category. For instance,

> P.1.3.13: *(dhātoḥ) bhāvakarmaṇoḥ (ātmanepadam)*
>
> *Ātmanepada* endings are added (to a root) in the sense of *bhāva* (state) or *karman* (object).

Bhāvakarmaṇoḥ expresses the environment in terms of meaning. The two meanings *bhāva* and *karman* are mentioned here. This can be represented as
$A \;\Rightarrow\; B(C^{1-n})$

Finally, combination of all the three multi-member categories is also met with in certain *sūtra*. For instance,

> P.3.4.70: *(dhātoḥ) tayoreva kṛtyaktakhalarthāḥ*
>
> The suffixes *kṛtya, kta* and those conveying the same meaning as that of *khal* are added to any root in the sense of *bhāva* (state) or *karman* (object).

The term *tayoḥ* is to be interpretated as *bhāvakarmaṇoḥ*. We thus have a statement of the type
$A^{1-n} \;\Rightarrow\; B^{1-n} \quad (C^{1-n})$. Observations made above hold true of both the general and special rules in Pāṇini's grammar. To sum up, the three categories A, B and C may be either single-member or multi-member categories. They appear in all permutations and combinations in *Ps*.

IIE Now it remains to be seen whether Pāṇini has provided any clarification regarding the application of the multi-member categories. Two questions arise when a statement contains multi-member categories:

1. Are the members in a category linked to each other disjunctively or conjunctively?

2. What are the mutual relations between the members of two multi-member categories?

Question 1:

Pāṇini has employed three linking devices in the *A*, namely, juxtaposition, *dvandva* compound, and the particle *ca*. They link either items or statements. We are at present concerned with linking of items. These devices work in terms of disjunction or conjunction. Disjunction implies application of all the items separately, whereas conjunction implies their application together. Items put together in a *dvandva* compound are disjunctively connected. For instance,

> P.3.1.133: *(dhātoḥ) ṇvultṛcau*
>
> The suffixes *ṇvul* and *tṛc* are added to any root.

Here the compound *ṇvultṛcau* is a multimember predicate. The items *ṇvul* and *tṛc* are disjunctively connected with each other. Therefore, they are separately and not simultaneously added to a root. Thus we can derive two separate forms such as *pācaka* and *paktṛ* from root *pac*. On the contrary, if the items are put in juxtaposition they are conjunctively connected with each other and are, therefore, simultaneously applicable. For instance,

> P.7.4.49: *saḥ syārdhadhātuke (taḥ)*
>
> *s* is replaced by *t* when an *ārdhadhātuka* ending beginning with *s* follows.

Here two items, *si* and *ārdhadhātuke*, which belong to the category C are not put together in a compound, but are mentioned separately in juxtaposition. Therefore they are conjunctively connected. In other words *si* and *ārdhadhātuke* are co-referential. Whenever items belonging to one category are put in juxtaposition in a rule they hold a head-modifier (or adjective-substantive) relationship. Two or more items belonging to the same category and yet not connected by a head-modifier relation never occur in juxtaposition in a single *sūtra*. Juxtaposed occurrence of two heads or modifiers always indicates the existence of separate *sūtra*. The particle *ca* is never used to link two or more items as it does in ordinary language.[14] Items belonging to the same category in a rule are either put in a compound or are juxtaposed according to their relation with each other.[15]

Question 2:

Pāṇini accepts the principle of numerical correspondence for linking items in two multi-member categories. He states the rule as follows:

P.1.3.10: *yathāsankhyam anudeśaḥ samānām*
Items (in two categories) having the same (number) are connected (with each other) in their respective number (i.e. order).

Take, for instance, P.4.3.94: *tūdīśalāturavarmmatīkūcavārāḍ ḍhakchaṇḍhañyakaḥ*

The suffixes *ḍhak, chaṇ, dhañ, yak* are respectively added to (the stems) *tūdī*, *śalātura*, *varmmatī*, and *kūcavāra* (in the sense 'it is the place where his ancestors lived').

Here both A and B consist of four members each and the members of A are connected with the members of B in the same order in which they are put in the compound.

III Arrangement of the Rules

As stated earlier, a Pāṇinian rule consists of three elements: A, B, and C, the last being optional. All these elements are not always explicitly present in the wording of a *sūtra*. Just as a finite verb form is implicit, a certain element is understood to be present in a *sūtra* from the context. While interpreting certain rules, commentators actually borrow the missing term from the preceding rule. This borrowing or continuation of a word or words is technically called *anuvṛtti*. The procedure of *anuvṛtti* is nothing but ellipsis which is a regular feature of ordinary language. While ellipsis is optional and has an *ad hoc* character in ordinary language, *anuvṛtti* is a systematic and mechanical device in *A*. The *sūtra* in *A* are arranged in such a manner that a rule borrows an item or items from the preceding context. By putting together such rules which share an item or items in common Pāṇini has been able to achieve economy of expression to a large extent. A few examples of *anuvṛtti* will show the working of this device:

P.1.4.14: *suptinantaṃ padam*

That which ends in *sup* or *tin* endings is called *pada.*

P.1.4.15: *naḥ kye (padam)*

That which ends in *n* (is called *pada* when the suffix *kya* follows.)

The predicate item *padam* which is missing in P 1.4.15 is continued from P.1.4.14. (The missing item when borrowed from the preceding rule is put into brackets).

> P.3.3.114: *napuṃsake bhāve ktaḥ (dhātoḥ)*
> The suffix *kta* is added (to the root in the sense of *bhāva*, state, and the form is used in neuter).
> P.3.3.115: *lyuṭ ca (napuṃsake bhāve ktaḥ dhātoḥ)*
> And suffix *lyuṭ* (is added to a root in the sense of *bhāva* and the form is used in the neuter).

The environment expressed by the terms *napuṃsake* and *bhāve* is carried forward in P.3.3.115 from P.3.3.114. The subject item *dhātoḥ*, which is carried forward in P.3.3.114, is also continued in a number of rules. For example, the term *dhātoḥ* which is mentioned in P.3.1.92 is continued throughout the following third chapter, nearly in 500 rules. Through the device of *anuvṛtti* Pāṇini has been thus able to avoid repetition of the word *dhātoḥ* in more than 500 rules. *Anuvṛtti* is thus intrinsic with the style of the *Ps*. Although Pāṇini has arranged rules in his grammar mainly on thematic basis, the arrangement of rules within different sections is totally governed by the dictates of *anuvṛtti*. A very important difference between *anuvṛtti* and ellipsis in ordinary language consists in the fact that while the latter is dependent upon expectancy and the listener's (or rather receiver's) intention, the former is obligatory. Items in the previous rules *must* continue in the subsequent rules. Expectancy is not just sufficient ground for continuing an item. An item is found to be continued even when there is no expectancy. For example

> P.1.2.4.: *sārvadhātukampit*
> A *sārvadhātuka* suffix, other than the one which is *pit* is *ṅit*.

> P.1.2.5.: *asaṃyogālliṭ kit (apit)*
> A *liṭ* suffix other than the one which is *pit* added to (a root) not ending in a conjunct consonant is *kit*.

All the three elements, namely subject (*liṭ*), predicate (*kit*) and environment (*asaṃyogat*) are present in P.1.2.5. It presents no expectancy for any item in order to complete its meaning. Yet the item *apit* is continued in the rule.

There are, however, some constraints on this flow of *anuvṛtti*. The major constraint is that an item is carried forward in the subsequent rules until it is blocked by an incompatible item. Thus compatibility and incompatibility play a major role in deciding *anuvṛtti* of words. For instance, in the example given above the item *nit* which is continued in P.1.2.4. is not further continued in P.1.2.5 because it contains the item *kit* which is incompatible with *nit*. Two incompatible items do not exist in a rule except under some special circumstances. The fundamental rule of *anuvṛtti* can thus be stated as follows:

> An item is continued in the subsequent rules unless it is blocked by an incompatible item.
> Two items are incompatible if they belong to the same category (i.e. subject, predicate, or environment).

Again in the same example quoted above the items *sārvadhātuka* and *liṭ* are incompatible with each other. Therefore, the former is not continued in P.1.2.5 as it is blocked by the latter.

Items which are incompatible with each other usually appear in the same case-ending. However, appearance in the same case-ending is not the only identification mark of incompatible items. Their relative syntactic position has also to be taken into consideration. Turning back again to the above example, the two items *sārvadhātukam* and *apit* together form the subject category in P.1.2.4. While *sārvadhātukam* is the head item, *apit* is its modifier (adjective). There is obviously no incompatibility between a head and a modifier. This is true not only when they belong to one and the same rule as in the above case, but also when they are mentioned in two different rules. Thus modifier item *apit* mentioned in P.1.2.4 is compatible with the head item in the subsequent rule. Therefore, although the head item *liṭ* in P.1.2.5 blocks the incompatible item *sārvadhātukam* in the preceding rule, it does not block the modifier item *apit*, which is therefore, continued in P.1.2.5. Another rule of *anuvṛtti* may be laid down on the basis of this observation as follows:

> A head item blocks an incompatible head item, but it does not block a modifier if it is not incompatible.
> A modifier blocks an incompatible modifier, but it does not block a head item if it is not incompatible.

There are, however, cases when a head or a modifier is not continued since it is incompatible not on syntactic, but on semantic grounds. (These cases will not be discussed here as they have no direct bearing on the present topic.)

Arrangement of the *sūtra* in the *A* is initially topic wise. Thus the *Ps* begins with definitions of various technical terms and rules of interpretation and treats various types of derivations such as compounds, primary derivatives and secondary derivatives in separate sections. The last part of the *A* is devoted to morphophonemics including euphonic combination, accent and tone. Within a thematic group the *sūtra* are arranged on the basis of the principles of *anuvṛtti*. Although, a generalization is followed by specific or individual rules, this order is often violated due to exigencies of *anuvṛtti*. *Anuvṛtti* is thus a key-word for the arrangement of the *Ps*.[16]

IV Techniques of Description

In addition to *anuvṛtti* and artificial technical terminology including *pratyāhāras* Pāṇini employs the device called *anubandha*. An *anubandha* is a code-letter which indicates a grammatical function like elision and reduplication. Pāṇini has made use of almost all vowels and consonants as symbols for various functions. *Anubandhas* are added to various grammatical units such as suffix, an augment and a root. For example, the suffix *a* is mentioned as *aṇ* where the code letter *ṇ* suggests that the vowel (either initial or final depending upon the type of derivation) of the stem to which the affix is added is lengthened.[17] The *anubandha k* attached to an augment indicates that it is added at the end of an element.[18] Thus the augment *t* which is mentioned as *tuk* in the rule *hrasvasya piti kṛti tuk* (P.6.1.69) is added after an element, e.g. in the form *ādṛtya* it appears after root *dṛ* which ends in a short vowel. The *anubandha ṅ* attached to a verbal root indicates that the root is conjugated in the middle voice. *Anubandha* is thus a powerful device.

IVA A major aspect of Pāṇini's descriptive technique is the law of *utsarga* and *apavāda* that relates exceptions and individual rules. Although Pāṇini never explicitly states the law of *utsarga* and *apavāda* it is part of the interpretative apparatus used with the *Ps*.[19] The law of *utsarga* and *apavāda* states that an *apavāda* 'exception' is more powerful than an *utsarga* 'general rule'. Therefore before applying the *utsarga* one has to give check for its *apavāda(s)*. The *utsarga* thus occupies the area not occupied by its exceptions. Further, once an *utsarga* is barred from entering in to the area of its exception, it can never enter the area again. For example:

> P.4.1.92: *tasyāpatyam (aṇ)*
> (The suffix *an* is added to a noun in the sense) 'his offspring.'
>
> P.4.1.95: *ata iñ tasyāpatyam*

The suffix *iñ* is added to a noun ending in *a* (in the sense 'his offspring'). P.4.1.95 is an exception to P.4.1.92. Therefore, the suffix *aṇ* taught by P.4.1.92 is barred from being applied to stems ending in *a*. Thus from the stem *dakṣa* is derived the patronymic *dākṣi (dakṣa + iñ)* and not *dakṣa + aṇ)*.

Sometimes application of the *utsarga*, even in the domain of *apavāda*, is desired. In such cases, Pāṇini announces that the *apavāda* operates optionally. For instance,

> P.4.1.121: *dvyacaḥ (ḍhak striyāḥ)*
> (The suffix *ḍhak* is added to a feminine noun) consisting of two vowels (in sense 'his offspring')
> P.4.1.118: *pīlāyā vā (aṇ striyāḥ)*
> (The suffix *aṇ* is added) optionally to *pīlā* (in the sense 'his offspring').

The option marker *vā* in P.4.1.118 suggests that the exceptional suffix *aṇ* operates optionally. Therefore, the *utsarga* suffix *ḍhak* taught by P.4.1.121 is also applied and two alternate forms, *paileya (pīla + ḍhak*) and *paila (pīla + aṇ*) are derived.

IVB An extremely important principle is the *siddha* principle. Even though Pāṇini does not directly mention it, his statement of the *asiddha* principle (P.8.2.1) implies it. Traditionally, the whole *A* is divided into two parts on the basis of P.8.2.1: (1) the *siddhakāṇḍa* (P.1.1.1. to the end of the first section of the eight Chapter) and (2) the *asiddhakāṇḍa* or *tripādī* (P.8.2.1 to the end of the fourth section of the eighth Chapter). *Tripādī* begins with the *adhikāra*, 'chapter heading', 8.2.1: *pūrvatrāsiddham* '(From now on every rule is regarded as) not having taken effect with reference to preceding ones'.

The term *siddhakāṇḍa* implies that any rule in this part of *A* is *siddha* 'having taken effect' for any other rule in the whole of *A*. In other words, before being effective, a rule takes into consideration possibility of application of other rules. The sequence of rules in the book does not matter in the derivational process. What matters is the *siddha* relation among the rules. The finite verb form *bhavati* is, for instance, derived as follows:

bhu + *laṭ* P.3.2.123

bhu + *tip* P.3.4.78

bhu + *śap* + *ti* P.3.1.68

bho + *a* + *ti* P.7.2.115; P.6.1.78

bhavati

It will be clear from the derivational stages given above that the rule in the first section of the third Chapter applies after the rule in the fourth section of the same chapter and the rule in the sixth Chapter applies after the rule in the seventh Chapter. These rules are *siddha* for each other so that they can feed each other (the application of P.6.1.78 is dependent on the application of P.7.2.115 in the present example.) This free movement of rules in all directions is implied by the *siddha* principle. Yet this arbitrary application of rules within 1.1-8.1 is restricted somewhat by a category of rules that are ordered pairs. In each pair, the rule that is applied first is called *antaranga* and the rule that is applied next is called *bahiranga*.

> On the contrary the rules in the *asiddhakāṇḍa* are operative only
> in one direction.
> P.8.2.1. *pūrvatrāsiddham*

states that all the rules stated subsequently are *asiddha*, not effective for the rules stated earlier, that is for the rules in the *siddhakāṇḍa*. Similarly for each rule in the *asiddhakāṇḍa*, all subsequent rules are *asiddha*. In other words, rules in the *asiddhakāṇḍa* operate in the same order in which they are arranged. For example, the form *pakva* is derived from root *pac* as follows:

pac + *ta* P.3.2.102

pak + *ta* P.8.2.30

pak + *va* P.8.2.52

pakva

It is clear from the procedure given above that P.8.2.30 precedes the application of P.8.2.52. In fact, if P.8.2.52 is applied first P.8.2.30 cannot be applied since the environment favorable for its application does not exist. The rules in the *asiddhakāṇḍa* must therefore apply in the same sequence in which they are stated by Pāṇini.

Both the *siddha* and *asiddha* principles have been recently studied carefully, leading to important new insights.[20]

V Concluding Remarks

Our analysis was meant to highlight several formal features of Pāṇini's grammar that have direct parallels in computer science. What might be other features of the grammar that have not yet been rediscovered in computer science remains to be seen. But the very success of A suggests that aspects of its structure will have implications for further advance in computer science, knowledge representation, and linguistics. In particular we can hope for significant applications in natural language processing. The ongoing analysis of the structures of Pāṇini and those of the later grammarians and logicians will be aided by the development of software to implement A on a digital computer.

The specific issues of immediate interest to the computer scientist include analysis of the arrangement of the rules and search for other arrangements that are equivalent in terms of their generative power. The formal aspects of these arrangements and their relationships is likely to help define the notion of distance between grammars. Such a notion is of immediate relevance for machine translation. Given two languages with grammars that are close in structure, as in the Indo-Aryan family of languages, one would expect the translation across the languages to be relatively easy. A formaliztion of the notion of closeness is also likely to give pointers regarding how an automatic translation might proceed.

One great virtue of the Pāṇinian system is that it operates at the level of roots and suffixes defining a deeper level of analysis than afforded by recent approaches like generalized phrase structure grammars[21] that have been inspired by development of computer parsing techniques. This allows for one to include parts of the lexicon in the definition of the grammatical structure. Closeness between languages that share a great deal of a lexicon will thus be represented better using a Pāṇinian structure.

These fundamental investigations that have bearing on linguistics, knowledge representation, and natural language processing by computer require collaboration between computer scientists and Sanskritists. Computer oriented studies on A would also help to introduce AI (artificial intelligence), logic, and cognitive science as additional areas of study in the Sanskrit departments of universities. This would allow the Sanskrit departments to complement the programme of the computer science departments. With the incorporation of these additional areas, a graduate of Sanskrit could hope to make useful contributions to the computer software industry as well, particularly in the fields of natural language processing and artificial intelligence.

Notes

1. D.H.H. Ingalls, *Materials for the Study of Navya-Nyāya Logic*. Cambridge: Harvard University Press, 1951.
   Frits Staal, *Universals, Studies in Indian Logic and Linguistics*. Chicago: University of Chicago Press, 1988.
   B.K. Matilal, *The Navya-Nyāya Doctrine of Negation*. Cambridge: Harvard University Press, 1968.
   R. Briggs, "Knowledge representation in Sanskrit and artificial intelligence", *AI Magazine*, vol. 6, 1985, pp. 22-38.
   S. Kak, "The Pāṇinian approach to natural language processing", *International Journal of Approximate Reasoning*, vol. 1, 1987, pp. 117-130.

2. F. Staal, *op. cit.*, page 47.

3. S.D. Joshi, "Sentence structure according to Pāṇini", in *Glimpses of Veda and Vyākaraṇa*, edited by G.V. Devasthali. Bombay: Popular

Prakashan, 1985.
S. Kak, *op. cit.*

4. A. Seidenberg, "The ritual origin of geometry," *Archive for History of Exact Science*, vol. 1, 1962, pp. 488-527.
A. Seidenberg, "The origin of mathematics," *Archive for History of Exact Science*, vol. 18, 1978, pp. 301-342.

5. S. Kak, "A frequency analysis of the Indus script", *Cryptologia*, vol. 12, 1988, pp. 129-143.
S. Kak, "Indus writing", *Mankind Quarterly*, vol. 30, 1989, pp. 113-118.

6. P. Kiparsky and J.F. Staal in Staal, *op. cit.*

7. S.D. Joshi, *op. cit.*

8. P. Kiparsky and F. Staal, *op. cit.*

9. It must be borne in mind that exceptions to such a structure for *Ps* do exist. But these exceptions do not define the general structure of the rules.

10. P.1.1.49.

11. P.1.1.67.

12. P.1.1.66.

13. For details, see Saroja Bhate, "Some aspects of Pāṇini's sūtra style of composition," *B.R. Modak Felicitation Volume,* March 1989, pp. 37-46.

14. For example, *rāmaśca kṛṣṇaśca gacchataḥ*. Here *ca* links two items disjunctively. The particle *ca* can also link two or more items conjunctively in ordinary language: for example 'He eats curds and honey'.

15. For details see S.D. Joshi and Saroja Bhate. *The Role of the particle ca in the interpretation of the Aṣṭādhyāyī.* Publication of the Centre of Advanced Study of Sanskrit, University of Poona, 1983.

16. For a discussion of the principles of *anuvṛtti*, see S.D. Joshi and Saroja Bhate, *The Fundamentals of Anuvṛtti*, Publication of the Centre of Advanced Study of Sanskrit, University of Poona, 1984.

17. P.7.2.115 to 117.

18. P.1.1.46.

19. For example, the rules of interpretation (*paribhāṣā*) 57, 58, 59, 60, 62, 64, and 65 in the *Paribhāṣenduśekhara* of Nāgojibhaṭṭa edited by K.G. Abhayankar, Bhandarkar Oriental Research Institute, Pune, 1962.

20. S.D. Joshi and Paul Kiparsky, "*Siddha* and *asiddha* in Pāṇinian phonology," in *Current Approaches to Phonological Theory*, edited by D. Dinneen. Bloomington, 1979.

21. G. Gazdar, E. Klien, G. Pullum, I. Sag, *Generalized Phrase Structure Grammar*. Cambridge: Harvard University Press, 1985.
    Gazdar *et al.* claim that context-sensitive rules can be replaced by a larger set of context-free rules for all natural languages, excepting Bambara (Mande family, West Africa) and a certain Swiss dialect of German. Centext-free rules make parsing by computer easier.