Strengths and potential of the SP theory of intelligence in general, human-like artificial intelligence

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Abstract

This paper first defines *general, human-like artificial intelligence* (GHLAI) in terms of five principles. In the light of the definition, the paper summarises the strengths and potential of the *SP theory of intelligence* and its realisation in the *SP computer model*, outlined in an appendix, in three main areas: the versatility of the SP system in aspects of intelligence; its versatility in the representation of diverse kinds of knowledge; and its potential for the seamless integration of diverse aspects of intelligence and diverse kinds of knowledge, in any combination. There are reasons to believe that a mature version of the SP system may attain full GHLAI in diverse aspects of intelligence and in the representation of diverse kinds of knowledge.

Keywords: artificial intelligence, information compression, SP theory of intelligence;

1 Introduction

The *SP theory of intelligence* and its realisation in the *SP computer model*, outlined in Appendix A, is the product of a programme of research aiming to simplify and integrate observations and concepts across artificial intelligence, mainstream computing, mathematics, and human learning, perception, and cognition.

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Amongst other things, the SP system exhibits features of *general, human-like artificial intelligence* (GHLAI). The purpose of this paper is to describe what GHLAI means, and to summarise the strengths and potential of the SP system in the quest for GHLAI.

The next section describes the concept of GHLAI and how it relates to other concepts in AI and mainstream computing. Then the sections after that describe the strengths and potential of the SP system with respect to five features of GHLAI.

2 GHLAI and related concepts

The idea that something may have GHLAI or be a GHLAI derives from the concept of a *universal framework for the representation and processing of diverse kinds of knowledge* (UFK) [24, Section III] but gives weight to the concept of general, human-like intelligence.

The GHLAI concept is similar to the concepts of 'universal artificial intelligence' (UAI) (see, for example, [5, 4]) and 'artificial general intelligence' (AGI) (see, for example, [2]), but with differences in emphasis, relating to issues that appear to be important.

The concept of GHLAI may at first sight seem to be redundant since it has been recognised for some time that all kinds of computing may be understood in terms of the workings of a UTM or ideas which are recognised as equivalent such as Post's 'canonical system' [15], or Church's 'lambda calculus' [1], or indeed the many conventional computers that are in use today. For the sake of brevity these will be referred to collectively as CCs, short for "conventional computers".

No attempt has been made here to define 'human [-like] intelligence' because it would be difficult or impossible to reach agreement about any such attempt at a general definition. Since, by contrast, there is likely to be a large measure of agreement about specific features of human intelligence, any GHLAI may be assessed in terms of the specific features that it models, concentrating mainly on those that appear to be most challenging. Thus:

1. A GHLAI should demonstrate features of human intelligence without the need for AI-related programming (by contrast with a CC), but see Section 3.3.

2. It should be able to represent any kind of knowledge without the need for additional programming (by contrast with a CC). A qualification here is that new knowledge may be built on top of existing knowledge,

so that the learning of that new knowledge may be facilitated by the existing knowledge (Section **??**).

3. It should facilitate the seamless integration of diverse aspects intelligence and diverse kinds of knowledge, in any combination.

4. It should, like a CC, provide for any kind of processing within the limits set by computational complexity.

5. It should do these things efficiently.

These things are discussed in sections that follow.

3 Versatility in aspects of intelligence via the powerful concept of SP-multiple-alignment

The concept of SP-multiple-alignment provides the key to the versatility of the SP system in aspects of intelligence, as summarised here:

- *Unsupervised learning via the processing of SP-multiple-alignments.* The SP system has strengths and potential in 'unsupervised' learning of new knowledge, meaning learning without the assistance of a 'teacher' or anything equivalent. As outlined in Appendix A.4, unsupervised learning is achieved in the SP system via the processing of SP-multiple-alignments to create Old patterns, directly and indirectly, from New patterns, and to build collections of Old patterns, called *grammars* which are relatively effective in the compression of New patterns ([19, Chapter 9], [21, Section 5]).

  Unsupervised learning appears to be the most fundamental form of learning, with potential as a foundation for other forms of learning such as reinforcement learning, supervised learning, learning by imitation, and learning by being told.

- *How other aspects of intelligence flow from the building of SP-multiple-alignments.* By contrast with the way in which the SP system models unsupervised learning via the processing of already-constructed 'good' SP-multiple-alignments, other aspects of intelligence derive from the building of SP-multiple-alignments (Appendix A.3). These other aspects of intelligence include: the analysis and production of natural language; pattern recognition that is robust in the face of errors in data; pattern recognition at multiple levels of abstraction; computer vision

[22]; best-match and semantic kinds of information retrieval; several kinds of reasoning (more under the next bullet point); planning; and problem solving ([19, Chapters 5 to 8], [21]).

- *How several kinds of reasoning flow from the building of SP-multiple-alignments.* In scientific research and in the applications of science, what is potentially one of the most useful attributes of the SP system is its versatility in reasoning, described in [19, Chapter 7] and [21, Section 10]. Strengths of the SP system in reasoning, derived from the building of SP-multiple-alignments, include: one-step 'deductive' reasoning; chains of reasoning; abductive reasoning; reasoning with probabilistic networks and trees; reasoning with 'rules'; nonmonotonic reasoning and reasoning with default values; Bayesian reasoning with 'explaining away'; causal reasoning; reasoning that is not supported by evidence; the already-mentioned inheritance of attributes in class hierarchies; and inheritance of contexts in part-whole hierarchies. Where it is appropriate, probabilities for inferences may be calculated in a straightforward manner ([19, Section 3.7], [21, Section 4.4]).

  There is also potential for spatial reasoning [23, Section IV-F.1], and for what-if reasoning [23, Section IV-F.2].

- *Versatility in the representation of knowledge.* The SP system also has versatility in the representation of diverse kinds of knowledge, as summarised in Section 4, below.

3.1 Generality in artificial intelligence

Conceivably, the features of human-like intelligence mentioned above are the full extent of the SP system's potential to imitate what people can do. But for reasons given here, it seems likely that the SP system is not constrained in that way: that it provides a relatively firm foundation for the development of GHLAI.

The close connection that is known to exist between information compression and concepts of prediction and probability [16, 17, 9], the central role of information compression in the SP-multiple-alignment framework (Appendix A.3), and the versatility of the SP-multiple-alignment framework in the representation of knowledge (Section 4) and aspects of intelligence (Section 3), suggest that the SP system as it is now will provide a relatively firm foundation for the development of GHLAI.

As noted in Section **??**, the SP system differs in several ways from other AI-related systems and, in its strengths and potential, it has advantages compared with alternatives.

3.2 How the SP system differs from a CC in aspects of intelligence

With regard to the modelling of human-like intelligence, the main attraction of the SP system compared with CCs, is its versatility in diverse aspects of intelligence (Section 3) and its potential for the seamless integration of diverse aspects of intelligence and diverse kinds of knowledge, in any combination (Section 5, below), both these things without the need for ai-related programming.

Unless a CC has been specifically programmed with SP capabilities—in which case it would be an SP system, not a CC—it would be lacking in the above-mentioned capabilities, and, arguably, for that reason, is likely to fall short of general human-like artificial intelligence.

3.3 Existing skills may provide a foundation for new skills

A qualification to the principle that "A GHLAI should demonstrate features of human intelligence without the need for AI-related programming (by contrast with a CC)" (Section 2) is that, in accordance with ordinary experience, existing skills may provide a foundation for new skills. Thus for example, the skills of walking, running, and kicking a ball, are essential pre-requisites for the higher-level skills of playing football at competition level.

Although low-level skills that provide a foundation for higher-level skills may be seen to be equivalent to "AI-related programming" in a CC, there is a difference: low-level skills are concerned with entities and processes that are being learned by the AI, whereas "AI-related programming" is concerned with the creation of 'intelligence' in the AI.

4 Versatility in the representation of knowledge via the powerful concept of SP-multiple-alignment

Although SP-patterns are not very expressive in themselves, they come to life in the SP-multiple-alignment framework. Within that framework, they may serve in the representation of several different kinds of knowledge, including: the syntax of natural languages; class-inclusion hierarchies (with or without cross classification); part-whole hierarchies; discrimination networks and trees; if-then rules; entity-relationship structures [20, Sections 3 and 4]; relational tuples (*ibid.*, Section 3), and concepts in mathematics, logic, and computing, such as 'function', 'variable', 'value', 'set', and 'type definition' ([19, Chapter 10], [25, Section 6.6.1], [28, Section 2]).

With the addition of two-dimensional SP patterns to the SP computer model, there is potential for the SP system to represent such things as: photographs; diagrams; structures in three dimensions [22, Section 6.1 and 6,2]; and procedures that work in parallel [23, Sections V-G, V-H, and V-I, and Appendix C].

4.1 Generality in the representation of knowledge

As with the SP system's generality in aspects of intelligence (Section 3.1), it seems likely that the SP system is not constrained to represent only the forms of knowledge mentioned above: that it provides a relatively firm foundation for the development of human-like versatility in the representation of diverse forms of knowledge.

The generality of information compression as a means of representing knowledge in a succinct manner, the central role of information compression in the SP-multiple-alignment framework, and the versatility of that framework in the representation of knowledge, suggest that the SP system may prove to be a means of representing all the kinds of knowledge that may be processed by a GHLAI.

A qualification here is that, in the same way that people can, if necessary, learn and use some over-complex and obscure forms of knowledge, it seems likely that, because information compression lies at the heart of the SP system, a mature version of the system will, like people, have a preference for forms of representation that are relatively simple and direct, in accordance with the principle of efficiency, outlined in Section 7.

4.2 How the SP system differs from a CC in the representation of knowledge

With regard to the representation of knowledge, attractions of the SP system compared with CCs are:

- The SP system provides for the succinct representation of knowledge via the powerful concept of SP-multiple-alignment. By contrast, SP-multiple-alignments are not part of CCs and are barely recognised as guides or principles for the representation of knowledge in CCs.[1]

- The versatility of the SP system in the representation of knowledge is combined with some constraint—knowledge must be represented with SP patterns and processed via the building and manipulation of SP-multiple-alignments (Section 4)—and that constraint seems to be largely responsible for how the system facilitates the seamless integration of different kinds of knowledge (Section 5).

  By contrast, the representation of knowledge in a CC is a free-for-all: any kind of structure that may be represented with arrays 0s and 1s is accepted. This relative lack of discipline seems to be largely responsible for the excessive number of formats and formalisms in computing today and the many incompatibilities that exist amongst computer applications today.

The need for some discipline in how computing is done is not a new idea. In the early days of computing by machine, there was much 'spaghetti programming' with the infamous "goto" statement, leading to the creation of programs that were difficult to understand and to maintain. This problem was largely solved by the introduction of 'structured programming' (see, for example, [6]). Later, it became apparent that there could be more gains in the comprehensibility and maintainability of software via the introduction of 'object-oriented' programming and design, modelling software on real-world objects and classes of object.

4.3 Existing knowledge may provide a foundation for new knowledge

As with the discussion of skills in Section 3.3, the previously-noted qualification to the principle that "[A GHLAI] should be able to represent any kind of knowledge without the need for additional programming (by contrast with a CC)" (Section 2) is that, in accordance with ordinary experience, existing knowledge may provide a foundation for new knowledge. Thus for example, knowledge of the basics in a given subject is an essential pre-requisite for the learning of more advanced concepts in that subject.

As before, low-level knowledge that provides a foundation for more advanced knowledge may be seen to be equivalent to "AI-related programming" in a CC, but there is a difference: low-level knowledge is concerned with

[1]For example, none of these ideas is mentioned in "Knowledge representation and reasoning", *Wikipedia*, bit.ly/2fmKVtP, retrieved 2017-08-07.

things that are being learned by the AI, whereas "AI-related programming" is concerned with the creation of 'intelligence' in the AI. That difference applies even if the given AI is a student of AI as an academic discipline!

5 Seamless integration of diverse aspects of intelligence and diverse kinds of knowledge

In connection with the potential of the SP system as a GHLAI, an important third feature of the system, alongside its versatility in aspects of intelligence and its versatility in the representation of knowledge, is that *there is clear potential for the SP system to provide seamless integration of diverse kinds of knowledge and diverse aspects of intelligence, in any combination.* This is because diverse aspects of intelligence and diverse kinds of knowledge all flow from a single coherent and relatively simple source: SP patterns within the SP-multiple-alignment framework.

In this respect, there is a sharp contrast between the SP system and the majority of other AI systems, which are either narrowly specialised for one or two functions or, if they aspire to be more general, are collections or kluges of different functions, with little or no integration.[2]

This point is important because it appears that seamless integration of diverse aspects of intelligence and diverse kinds of knowledge, in any combination, are essential pre-requisites for human levels of fluidity, versatility and adaptability in intelligence.

6 Generality in computing

In addition to the potential generality of the SP system in AI, its potential generality appears to extend to computations of all kinds, not merely those with an AI flavour:

- The SP system may model a NAND gate, as described below.
- Within the SP system, the output of any NAND gate may become the input for any other, as described for 'composite functions' in [19, Section 10.4.3].

[2]Although Allen Newell called for the development of *Unified Theories of Cognition* [12, 11], and researchers in 'Artificial General Intelligence' are aiming for a similar kind of integration in AI, it appears that none of the resulting systems are fully integrated: "We have not discovered any one algorithm or approach capable of yielding the emergence of [general intelligence]." [3, p. 1].

- Hence, in principle, NAND gates within the SP system may be connected in any desired combination.
- Since it is widely accepted that, in principle, the computational heart of any general-purpose computer may be constructed entirely from NAND gates [13], it appears that the SP system has the generality of a CC.

With regard to the first point above, Figure 1 (a) shows four SP-patterns which, together, define the input-output relations in a NAND gate. The non-numeric symbols are not essential in this context but they have mnemonic value as explained in the caption to the figure, and those kinds of markers are likely to be needed in other context.

```
ng i1 0 #i1 i2 0 #i2 op 1 #op #ng
ng i1 0 #i1 i2 1 #i2 op 1 #op #ng
ng i1 1 #i1 i2 0 #i2 op 1 #op #ng
ng i1 1 #i1 i2 1 #i2 op 0 #op #ng

(a)

0 ng i1 1 #i1 i2 0 #i2          #ng 0
  |  |  |  |   |  |  |           |
1 ng i1 1 #i1 i2 0 #i2 op 1 #op #ng 1

(b)
```

Figure 1: Structures to illustrate how the SP system may simulate a NAND gate, as described in the text. (a) Four SP-patterns which, together, define the NAND function; *Key:* '`ng`' is mnemonic for 'NAND gate'; '`i`' stands for 'input'; '`op`' stands for 'output'. (b) The best SP-multiple-alignment found by the SP computer model with the New pattern '`ng i1 1 #i1 i2 0 #i2 #ng`' and Old patterns as shown in (a).

When the SP computer model is run with those four SP-patterns in the repository of Old SP-patterns, and with the New SP-pattern '`ng i1 1 #i1 i2 0 #i2 #ng`', the best SP-multiple-alignment found by the model is the one shown in Figure 1 (b), with the New SP-pattern in row 0 and one of the Old SP-patterns in row 1.

Here, the New pattern may be regarded as input to the NAND gate, with the values '`1 0`'. The corresponding output may be read off as '`1`', between the symbols '`op`' and '`#op`' in the Old pattern in row 1. Thus the input '`1 0`' has produced the output '`1`', in accordance with any correctly-working NAND gate.

6.1 What about things that the SP system can't do, except with some kind of 'programming' or 'training'?

In considering the possibility that the SP system might be developed into a GHLAI is that, while the mechanisms for the building and processing of SP-multiple-alignments, yield several different AI-related capabilities, described above, there are lots of things that a newly-created system, without any 'experience', would not be able to do. It would not, for example, have any knowledge of how to hold a pencil, how to climb a ladder, how to negotiate an international treaty, and so on.

Is it reasonable to suggest that such a system might be a GHLAI when there are so many shortcomings in what it can do? The answer, of course, is "Yes, such a system can be 'universal' in exactly the same way that a universal Turing machine, or a newborn baby, is universal". This is because, in all three cases, there is the potential to do a wide variety of different things, provided that it has appropriate knowledge, acquired via learning (babies and AI systems) or via programming (non-AI computers).

Since procedures or processes are forms of knowledge, and since we have reason to believe that the SP system has potential to accommodate any kind of knowledge (Section 4), it seems reasonable to believe that the SP system has potential, in principle and with the right knowledge, do any kind of computation that is not ruled out by over-large computational complexity.

7 Efficiency

The fifth suggested feature of a GHLAI is that it should in some sense be relatively 'efficient' in its ability to support diverse aspects of intelligence, to represent diverse kinds of knowledge, and to provide for seamless integration of diverse kinds of knowledge and diverse aspects of intelligence, in any combination. This section expands on that idea.

It is anticipated that, when the SP system is more fully developed, it is likely to be more 'efficient' than a CC, largely because it contains well-developed mechanisms for compression of information via the matching and unification of patterns (ICMUP), expressed via the powerful concept of SP-multiple-alignment. This provides the key to the SP system's versatility in aspects of intelligence (Section 3), and in the representation of diverse kinds of knowledge (Section 4), and its potential for the seamless integration of diverse aspects of intelligence and diverse kinds of knowledge in any combination (Section 5).

Although the computational 'core' of a CC is likely to be smaller and simpler than in the SP machine, the SP system has potential for relative advantages like these:

- *More intelligence.* A CC is likely to fall short of the SP system in modelling the fluidity, versatility, and adaptability of human intelligence—unless the CC has been programmed with all the features of the SP system, in which case it would be an SP system and not a CC.

- *Economies in software.* Because of the pervasive influence of information compression in the SP system, its 'software' is likely to be relatively compact. By contrast, the absence of well-developed mechanisms for ICMUP in the core of the CC is likely to mean the need for such mechanisms to be repeatedly recreated in different guises and in different applications. This can mean software with a bloating that more than offsets the small size of the central processor.

- *Economies in data.* Unlike a CC, the SP system is designed to compress its data via unsupervised learning. This would normally mean that data for the SP machine would, after compression, be substantially smaller than data for a CC.

- *Dramatic reductions in the variety of formats and formalisms.* An enormous variety of formats and formalisms is associated with conventional systems. The SP machine has potential for dramatic simplifications in this area.

- *Efficiency in processing.* Although CCs, compared with human brains, are extraordinarily effective in such arithmetic tasks as adding up numbers or finding square roots, the advent of big data is creating demands that exceed the capabilities of the most powerful supercomputers [7, p. 9]. But by exploiting statistical information that the SP system gathers as a by-product of how it works, there is potential in the system for substantial gains in the energy efficiency of its computations [24, Sections VIII and IX].

With regard to the second and third bullet points, all knowledge in the SP system reflects the world outside the system. This may include knowledge of entities and their interrelations—the kind of knowledge that would conventionally be called 'data'—and knowledge of real-world processes or procedures—the kind of knowledge that might conventionally be called 'software'.

All such knowledge is stored as SP patterns without any formal distinctions amongst them. But in a CC, stored knowledge may be seen to comprise two components:

- Knowledge of the system's environment, as in the SP machine. This knowledge may be contained in external 'databases' and also in 'software'.

- Knowledge of processes or procedures, contained largely in 'software', needed to overcome the deficiencies of the core model. This kind of knowledge, such as knowledge of how to search for matching patterns, may be recreated many times in many different guises and in many different applications.

8 Conclusion

This paper defines *general, human-like artificial intelligence* (GHLAI) as follows: a GHLAI should demonstrate human-like intelligence without the need for AI-related programming (by contrast with a conventional computer (CC)); it should be able to represent any kind of knowledge without the need for additional programming (by contrast with a CC); it should facilitate the seamless integration of diverse aspects intelligence and diverse kinds of knowledge, in any combination; it should, like a CC, provide for any kind of processing within the limits set by computational complexity; and it should do these things efficiently.

With regard to GHLAI, the strengths and potential of the SP theory of intelligence (and its realisation in the SP computer model), as it is now, are summarised in three main areas: the versatility of the SP system in aspects of intelligence; its versatility in the representation of diverse kinds of knowledge; and its potential for the seamless integration of diverse aspects of intelligence and diverse kinds of knowledge, in any combination.

There are reasons to believe that, with regard to the versatility of the SP system in aspects of intelligence and in the representation of diverse kinds of knowledge, the potential of the system goes beyond its current capabilities, probably extending to the range of AI-related capabilities, and the representation of kinds of knowledge, that are needed for a fully-developed GHLAI.

A Outline of the SP system

To help ensure that this paper is free standing, the SP system is described here in outline with enough detail to make the rest of the paper intelligible.

The *SP theory of intelligence* and its realisation in the *SP computer model* is the product of a unique extended programme of research aiming to simplify and integrate observations and concepts across artificial intelligence, mainstream computing, mathematics, and human learning, perception, and cognition, with information compression as a unifying theme.[3]

The latest version of the SP computer model is SP71. Details of where the source code and associated files may be obtained are here: www.cognitionresearch.org/sp.htm#ARCHIVING.

It is envisaged that the SP computer model will provide the basis for the development of an industrial-strength *SP machine*, described briefly in Appendix A.5, below.

The SP system is described most fully in [19] and quite fully but more briefly in [21]. Other publications from this programme of research are detailed, many with download links, on www.cognitionresearch.org/sp.htm.

A.1 Overview

The SP theory is conceived as a brain-like system which receives *New* information via its senses and stores some or all of it in compressed form as *Old* information, as shown schematically in Figure 2.

Both New and Old information are expressed as arrays of atomic *symbols* in one or two dimensions called *patterns*. To date, the SP computer model works only with one-dimensional patterns but it is envisaged that it will be generalised to work with two-dimensional patterns.

In this context, a 'symbol' is simply a mark that can be matched with any other symbol to determine whether they are the same or different. No other result is permitted. Apart from some distinctions needed for the internal workings of the SP system, SP symbols do not have meanings such as 'plus' ('+'), 'multiply' ('$*$'), and so on. Any meaning associated with an SP symbol derives entirely from other symbols with which it is associated.

[3]This ambitious objective is in keeping with Occam's Razor. And as a means of solving the exceptionally difficult problem of developing general, human-level artificial intelligence, it is in keeping with "If a problem cannot be solved, enlarge it", attributed to President Eisenhower; it chimes with Allen Newell's exhortation that psychologists should work to understand "a genuine slab of human behaviour" [10, p. 303] and his work on *Unified Theories of Cognition* [11]; and it is in keeping with the quest for "Artificial General Intelligence" (*Wikipedia*, bit.ly/1ZxCQPo, retrieved 2017-08-15).

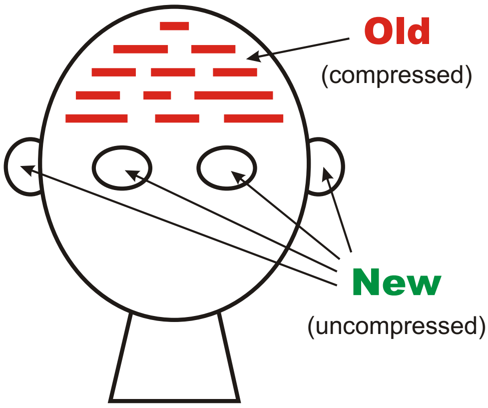

Figure 2: Schematic representation of the SP system from an 'input' perspective. Adapted with permission from Figure 1 in [21].

A.2 Multiple alignments in bioinformatics

At the heart of the SP system is a process of finding patterns that match each other and merging or 'unifying' multiple instances to make one, a process which is referred to here and elsewhere as 'Information Compression via the Matching and Unification of Patterns' (ICMUP). More specifically, a central part of the SP system is a concept of *multiple alignment*, borrowed and adapted from bioinformatics.[4]

The original concept of multiple alignment is an arrangement of two or more DNA sequences or sequences of amino acid residues, in rows or columns, with judicious 'stretching' of selected sequences in a computer to bring matching symbols, as many as possible, into line. An example of such a multiple alignment of five DNA sequences is shown in Figure 3.

A.3 SP-multiple-alignments in the SP system

In the SP system, multiple alignments are sufficiently different from those in bioinformatics for them to be given a different name: *SP-multiple-alignments*.[5] The distinctive features of an SP-multiple-alignment are:

- Normally, one New pattern is shown in row 0. Sometimes there is more than one New pattern in row 0 or column 0.

[4]Six variants of ICMUP and how they may be realised via SP-multiple-alignment are described in Appendix **??**.

[5]This name has been introduced fairly recently to make clear that there are important differences between the two kinds of multiple alignment.

```
  G G A     G     C A G G G A G G A     T G     G   G G A
  | | |     |     | | | | | | | | |     | |     |   | | |
  G G | G   G C C C A G G G A G G A     | G G C G   G G A
  | | |     | | | | | | | | | | | |     | |     |   | | |
A | G A C T G C C C A G G G | G G | G C T G     G A | G A
  | | |           | | | | | | | | |   |   |     |   | | |
  G G A A         | A G G G A G G A   | A G     G   G G A
  | |   |         | | | | | | | |     |   |     |   | | |
  G G C A         C A G G G A G G     C   G     G   G G A
```

Figure 3: A 'good' multiple alignment amongst five DNA sequences. Reproduced with permission from Figure 3.1 in [19].

- The Old patterns are shown in the remaining rows (or columns), one pattern per row (or column).
- As with the original concept of multiple alignment, the aim in building multiple alignments is to bring matching symbols into alignment. More specifically in SP-multiple-alignments, the aim is to create or discover one or more 'good' SP-multiple-alignments that allow the New pattern to be encoded economically in terms of the Old patterns. How this encoding is done is described in [19, Section 2.5] and in [21, Section 4.1].

An example of an SP-multiple-alignment is shown in Figure 4.

```
0                   t w o           k i t t e n     s               p l a y         0
                    | | |           | | | | | |     |               | | | |
1                   | | |       Nr 5 k i t t e n #Nr |               | | | |         1
                    | | |       |               | |                 | | | |
2                   | | |   N Np Nr             #Nr s #N            | | | |         2
                    | | |   | |                     |               | | | |
3             D Dp 4 t w o #D | |                     |               | | | |         3
              |            |  | |                     |               | | | |
4          NP D            #D N |                     #N #NP          | | | |         4
           |                    |                        |            | | | |
5          |                    |                        |      Vr 1 p l a y #Vr      5
           |                    |                        |      |              |
6          |                    |                        |  V Vp Vr          #Vr #V     6
           |                    |                        |  | |                   |
7 S Num    ; NP                 |                      #NP V |                  #V #S 7
    |      |                    |                           |
8   Num PL ;                    Np                          Vp                        8
```

Figure 4: The best SP-multiple-alignment created by the SP computer model with a store of Old patterns like those in rows 1 to 8 (representing grammatical structures, including words) and a New pattern (representing a sentence to be parsed) shown in row 0. Adapted with permission from Figures 1 in [20].

In this SP-multiple-alignment, a sentence is shown as a New pattern in row 0. The remaining rows show Old patterns, one per row, representing grammatical structures including words. The overall effect is to analyse (parse) the sentence into its parts and subparts. The pattern in row 8 shows the association between the plural subject of the sentence, marked with the symbol '`Np`', and the plural main verb, marked with the symbol '`Vp`'.

Because, with most ordinary multiple alignments or with SP-multiple-alignments, there is an astronomically large number of ways in which patterns may be aligned, discovering good multiple alignments means the use of heuristic methods: building each multiple alignment in stages and discarding all but the best few multiple alignment at the end of each stage. With this kind of technique it is normally possible to find multiple alignments that are reasonably good but it is not normally possible to guarantee that the best possible multiple alignment has been found.

The concept of SP-multiple-alignment has proved to be extraordinarily powerful: in the representation of knowledge (Section 4), in aspects of intelligence (Section 3), and in the seamless integration of diverse kinds of knowledge and diverse aspects of intelligence in any combination (Section 5). It could prove to be as significant for an understanding of intelligence as is DNA for biological sciences: it could be the 'double helix' of intelligence.

There is more about the concept of SP-multiple-alignment in Appendix **??**.

A.4 Unsupervised learning

Unsupervised learning in the SP system is described quite fully in [19, Sections 3.9 and 9.2]. The aim with unsupervised learning in the SP system is, for a given set of New patterns, to create one or two *grammars*—meaning collections of Old SP patterns—that are effective at encoding the given set of New patterns in an economical manner.

The building of SP-multiple-alignments is an integral part of unsupervised learning in the SP system. It provides a means of creating Old patterns via the direct assimilation of New patterns into the set of Old patterns, and via the splitting of New patterns and pre-existing Old patterns to create additional Old patterns. And it provides a means of evaluating candidate grammars in terms of their effectiveness at encoding the given set of New patterns in an economical manner.

As with the building of SP-multiple-alignments, the creation of good grammars requires heuristic search through the space of alternative grammars: creating grammars in stages and discarding low-scoring grammars at the end of each stage.

The SP computer model can discover plausible grammars from samples of English-like artificial languages. This includes the discovery of segmental structures, classes of structure, and abstract patterns.

At present, the program has two main weaknesses outlined in [21, Section 3.3]: it does not learn intermediate levels of abstraction or discontinuous dependencies in data. However, it appears that these problems are soluble, and it seems likely that their solution would greatly enhance the performance of the system in the learning of diverse kinds of knowledge.

To ensure that unsupervised learning in the SP system is robust and useful across a wide range of different kinds of data, it will be necessary for the system, including its procedures for unsupervised learning, to have been generalised for two-dimensional patterns as well as one-dimensional patterns (Appendix A.1).

A.5 The SP machine

As mentioned earlier, it is envisaged that an industrial-strength *SP machine* will be developed from the SP theory and the SP computer model [14]. Initially, this will be created as a high-parallel software virtual machine, hosted on an existing high-performance computer. An interesting possibility is to develop the SP machine as a software virtual machine that is driven by the high-parallel search processes in any of the leading internet search engines.

Later, there may be a case for developing new hardware for the SP machine, to take advantage of optimisations that may be achieved by tailoring the hardware to the characteristics of the SP system. In particular, there is potential for substantial gains in efficiency and savings in energy compared with conventional computers by taking advantage of statistical information that is gathered by the SP system as a by-product of how it works ([24, Section IX], [23, Section III], [14, Section 14]).

A.6 Distinctive features and advantages of the SP system

Distinctive features of the SP system and its main advantages compared with AI-related alternatives are described in [27]. In particular, Section V of that paper describes thirteen problems with deep learning in artificial neural networks and how, with the SP system, those problems may be overcome. The SP system also provides a comprehensive solution to a fourteenth problem with deep learning—"catastrophic forgetting"—meaning the way in which new learning in a deep learning system wipes out old memories.[6]

The main strengths of the SP system are in its versatility in the representation of several kinds of knowledge (Section 4), its versatility in several aspects of intelligence (Section 3), and because these things all flow from one relatively simple framework—the SP-multiple-alignment concept—they may work together seamlessly in any combination (Section 5). That kind of seamless integration appears to be essential in any system that aspires to general human-level artificial intelligence.

A.7 Potential benefits and applications of the SP system

Potential benefits and applications of the SP system are described in several peer-reviewed papers, copies of which may be obtained via links from www.cognitionresearch.org/sp.htm: the SP system may help to solve nine problems with big data [24]; it may help in the development of human-like intelligence in autonomous robots [23]; the SP system may help in the understanding of human vision and in the development of computer vision [22]; it may function as a database system with intelligence [20]; it may assist medical practitioners in medical diagnosis [18]; it provides insights into commonsense reasoning [26]; and it has several other potential benefits and applications described in [25].

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