Understanding the nature of the human mind via simplification and integration across artificial intelligence and related fields

J Gerard Wolff*

February 1, 2018

Abstract

Towards an understanding of the nature of the human mind, this article summarises the aims and results of an extended programme of research developing the *SP theory of intelligence* and its realisation in the *SP computer model*. The overall aim of the research is simplification and integration of observations and concepts across artificial intelligence, mainstream computing, mathematics, and human learning, perception, and cognition. Perhaps the most significant outcome of this research is the discovery that a concept of *SP-multiple-alignment*, borrowed and adapted from the concept of 'multiple sequence alignment' in bioinformatics, has proved to be a key to the modelling of diverse aspects of human intelligence and the representation of diverse kinds of knowledge. With some additional processing, the SP-multiple-alignment construct is an important part of unsupervised learning in the SP system. Because diverse aspects of intelligence and the representation of diverse kinds of knowledge all flow from one relatively simple framework, there is potential for their seamless integration in any combination. That kind of integration appears to be essential in modelling the fluidity, versatility, and adaptability of the human mind.

*Dr Gerry Wolff, BA (Cantab), PhD (Wales), CEng, MBCS, MIEEE; CognitionResearch.org, Menai Bridge, UK; jgw@cognitionresearch.org; +44 (0) 1248 712962; +44 (0) 7746 290775; *Skype*: gerry.wolff; *Web*: www.cognitionresearch.org.

Introduction

In the Winter 2017 issue of this magazine, several Special Articles, edited by Sergei Niremburg and Micah Clark (2017), provide a 5-year review of progress in the Cognitive Systems Paradigm, as described by Pat Langley (2012).

The orientation of this Cognitive Systems research—understanding the nature of the mind—is very much in keeping with a programme of research on which I have been working since about 1987, with a break between early 2006 and late 2012, developing the *SP theory of intelligence* and its realisation in the *SP computer model*. In view of the convergence, it seems appropriate here to describe the SP programme and the SP system in outline and to summarise the strengths and potential of the SP system.

Background

The overall goal of the SP programme, in accordance with long-established principles in science, has been the simplification and integration of observations and concepts across artificial intelligence, mainstream computing, mathematics, and human learning, perception, and cognition. In its scope, if not in terms of particular topics, this is not far removed from the aim, amongst the Special Articles mentioned above, of developing a common computational framework across artificial intelligence, cognitive science, neuroscience, and robotics, described by John Laird, Christian Lebiere, and Paul Rosenbloom (2017).

The SP programme of research inherits some insights from an earlier programme of research, summarised in Wolff (1988), developing computer models of the learning of a first language by children.

From the beginning, a unifying theme in the SP research, as in the earlier research on language learning, has been that all kinds of processing would be achieved by compression of information via a search for patterns that match each other and via the merging or 'unification' of patterns that are the same.

The main motivation for this theme is research by Fred Attneave (1954), Horace Barlow (1959; 1969), and others, showing the importance of information compression in the workings of brains and nervous systems. Solomonoff's seminal work on the development of *algorithmic probability theory* (Solomonoff, 1964, 1997) is also important.

Since people often ask, the name "SP" stands for *Simplicity* and *Power*, two ideas which, together, mean the same as information compression. This is because information compression may be seen to be a process of maximising 'simplicity' in a body of information, by reducing redundancy in that information, whilst, at the same time, retaining as much as possible of its non-redundant expressive 'power'.

Incidentally, the reason for the emphasis on "a search for patterns that match each other and the merging or 'unification' of patterns that are the same" is that this seems to provide a better handle on possible mechanisms in natural or artificial systems than do the more mathematically-oriented approaches to information compression.

The SP System

The SP system is described in outline in Appendix I of Wolff (2016a), in more detail in Wolff (2013), and in even more detail in Wolff (2006a). Distinctive features and advantages of the SP system are described in Wolff (2016a).

Although the SP programme of research has what I believe are some useful things to say about the nature of the human mind, it does not claim to be comprehensive. Probably the most important omission is any attempt to model human emotions and motivations.

At an early stage, a challenge in the SP programme of research was to discover or create a framework that is more general than the hierarchical-chunking mode of processing which is central in the earlier models of language learning (Wolff, 1988). What appears to be a good answer is the concept of *SP-multiple-alignment*, described below.

In broad terms, the SP system is a brain-like system that takes in *New* information through its senses and stores some or all of it as *Old* information, as shown schematically in Figure 1.

A central idea in the SP system, is the afore-mentioned concept of *SP-multiple-alignment*, borrowed and adapted from the concept of 'multiple sequence alignment' in bioinformatics. Probably the best way to explain the idea is by way of examples, shown in Figures 2 and 3.

Figure 2 shows an example of multiple sequence alignment in bioinformatics. Here, there are five DNA sequences which have been arranged one above the other, and then, by judicious 'stretching' of one or more of the sequences in a computer, symbols that match each other across two or more sequences have been brought into line. A 'good' multiple sequence alignment, like the one shown, is one with a relatively large number of matching symbols from row to row. This process is normally too complex to be done by exhaustive search, so heuristic methods are needed, building multiple sequence alignments in stages and, at each stage, selecting the best partial structures for further processing.

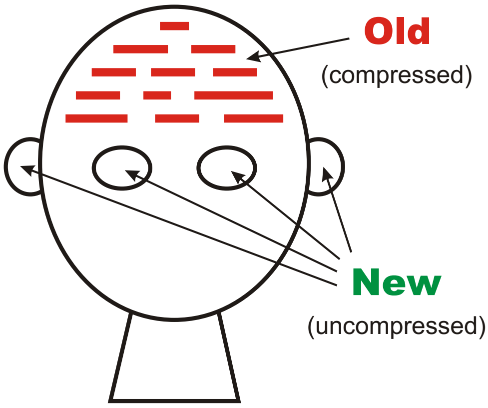

Figure 1: Schematic representation of the SP system from an 'input' perspective. Reproduced, with permission, from Figure 1 in Wolff (2013).

```
  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 2: A 'good' multiple alignment amongst five DNA sequences. Reproduced with permission from Figure 3.1 in Wolff (2006a).

Figure 3 shows an example of an SP-multiple-alignment, superficially similar to the one in Figure 2, except that each sequence, one per row, is called an *SP-pattern* and, more importantly, one of the SP-patterns—sometimes more than one—is a New SP-pattern, normally shown in row 0, and the remaining SP-patterns are Old SP-patterns, normally shown in the remaining rows.

```
0              f o r t u n e                      f a v o u r     s             t h e        b r a v e               0
               | | | | | | |                      | | | | | |     |             | | |        | | | | |
1              | | | | | | |                 Vr 6 f a v o u r #Vr |             | | |        | | | | |               1
               | | | | | | |                 |                 |  |             | | |        | | | | |
2              | | | | | | |             V 7 Vr               #Vr s #V          | | |        | | | | |               2
               | | | | | | |             |                          |           | | |        | | | | |
3              | | | | | | |        VP 3 V                          #V NP       | | |        | | | | |    #NP #VP    3
               | | | | | | |        |                                  |        | | |        | | | | |     |   |
4          N 4 f o r t u n e #N     |                                  |        | | |        | | | | |     |   |     4
           |                 |      |                                  |        | | |        | | | | |     |   |
5     NP 2 N                 #N #NP |                                  |        | | |        | | | | |     |   |     5
      |                          |  |                                  |        | | |        | | | | |     |   |
6 S 0 NP                        #NP VP                                 |        | | |        | | | | |     |  #VP #S 6
                                                                       |        | | |        | | | | |     |
7                                                                      |        | | |    N 5 b r a v e #N  |         7
                                                                       |        | | |    |             |   |
8                                                                      NP 1 D   | | | #D N             #N #NP        8
                                                                            |   | | | |
9                                                                           D 8 t h e #D                             9
```

Figure 3: The best SP-multiple-alignment produced by the SP computer model with a New SP-pattern, '`f o r t u n e f a v o u r s t h e b r a v e`', representing a sentence to be parsed and a repository of user-supplied Old SP-patterns representing grammatical categories, including morphemes and words. Reproduced with permission from Figure 2 in Wolff (2016c).

As can be seen from this example, the building of an SP-multiple-alignment may achieve the effect of parsing a sentence ('`f o r t u n e f a v o u r s t h e b r a v e`') into its grammatical parts and sub-parts. But as we shall see later, the SP system has strengths in several different aspects of intelligence, and in the representation of several different kinds of knowledge—and most of this versatility flows from the building of SP-multiple-alignments.

To create an SP-multiple-alignment like the one shown in Figure 3, the SP system starts with a relatively large repository of Old SP-patterns, each one representing a syntactic structure in English, which may be a morpheme, a word, or a higher-level structure. The Old patterns would ideally be learned by the system, but pending full development of the learning processes, the Old patterns may be supplied to the system by the user.

With a repository of Old patterns in place, the SP system is supplied with the New pattern ('`f o r t u n e f a v o u r s t h e b r a v e`') and the system tries to build one or more SP-multiple-alignments, each of which allows the New pattern to be encoded economically in terms the Old patterns in the SP-multiple-alignment.

The details of how the encoding is done need not detain us here, but it is pertinent to note that the SP-multiple-alignment construct, in conjunction with unsupervised learning in the SP system (outlined below), appears to provide a means of achieving relatively high levels of information compression with many kinds of data.

As with the building of 'good' multiple sequence alignments in bioinformatics, the creation of one or more 'good' SP-multiple-alignments is normally too complex to be done by any exhaustive process. As with multiple sequence alignments in bioinformatics, heuristic search is needed, building the SP-multiple-alignment in stages. With this approach, it is not normally possible to guarantee that the best possible structure has been found, but it is normally possible to create structures that are 'good enough'.

In the SP system, learning is special. Instead of it being a by-product of the building of SP-multiple-alignments it is a process of creating *grammars*, where each grammar is a collection of Old SP-patterns (many of which would normally be derived from partial matches between SP-patterns within SP-multiple-alignments), and each grammar is scored in terms of its effectiveness via SP-multiple-alignment in the economical encoding of a target set of New SP-patterns. As with the building of SP-multiple-alignments, the process is too complex for exhaustive search so heuristic methods are needed.

In the SP system, learning is normally 'unsupervised', deriving structures from incoming sensory information without the need for any kind of 'teacher' or anything equivalent. But it appears that unsupervised learning is the most general kind of learning and that, within the framework of unsupervised learning in the SP system, it is possible to model other kinds of learning such as 'supervised' learning, 'reinforcement' learning, and more.

A potentially useful feature of the SP system is that it is possible to see how abstract constructs and processes in the system may be realised in terms of neurons and their interconnections. This is the basis for *SP-neural*, a 'neural' version of the SP system, described in an early form in Wolff (2006a, Chapter 11), and in an updated and more detailed form in Wolff (2016c).

In this connection, it is relevant to mention that the SP system, in both its abstract and neural forms, is quite different from deep learning in artificial neural networks (Schmidhuber, 2015) and has substantial advantages compared with such systems, as described in Wolff (2016a, Section V) and in Wolff (2018).

This brief summary of the SP system and how it works may have given the impression that it is intended to work entirely with sequences of symbols, like multiple sequence alignments in bioinformatics. But it is envisaged that, in future development of the system, two-dimensional SP-patterns will be introduced, with potential to represent such things as photographs, diagrams, structures in three dimensions Wolff (2014d, Section 6.1 and 6,2), and procedures that work in parallel Wolff (2014a, Sections V-G, V-H, and V-I, and Appendix C).

Strengths and potential of the SP system are summarised in the three sections that follow: versatility in aspects of intelligence, versatility in the representation of diverse kinds of knowledge, and potential in the SP system for the seamless integration of diverse aspects of intelligence, and diverse kinds of knowledge, in any combination. Further information about the strengths and potential of the SP system may be found in (Wolff (2013, Sections 5 to 12), Wolff (2006a, Chapters 5 to 9)) and in other sources referenced in the sections that follow.

Versatility in Aspects of Intelligence

As mentioned above, the SP system has strengths and potential in 'unsupervised' learning of new knowledge, an aspect of human-like intelligence in the SP system that is different from others because it is not a by-product of the building of multiple alignments but is, instead, achieved via the creation of *grammars*, drawing on information within SP-multiple-alignments.

All other aspects of intelligence exhibited by the SP system are modelled via the building of SP-multiple-alignments. 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 (Wolff, 2014d); best-match and semantic kinds of information retrieval; several kinds of reasoning (next paragraph); planning; and problem solving.

Kinds of reasoning that may be modelled in the SP system 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 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 (Wolff (2006a, Section 3.7), Wolff (2013, Section 4.4)).

There is also potential in the system for spatial reasoning (Wolff, 2014a, Section IV-F.1), and for what-if reasoning (Wolff, 2014a, Section IV-F.2).

It seems unlikely that the features of human-like intelligence mentioned above are the full extent of the SP system's potential to imitate what people can do. The close connection that is known to exist between information compression and concepts of prediction and probability (Solomonoff, 1964, 1997; Li and Vitányi, 2014), the central role of information compression in the SP-multiple-alignment framework, and the versatility of the SP-multiple-alignment framework in aspects of intelligence (this section) and in the representation of diverse forms of knowledge (next section), suggest that the SP system has potential to provide a relatively firm foundation for the development of general, human-like artificial intelligence.

Versatility in the Representation of Knowledge

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 Wolff (2007, 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' (Wolff (2006a, Chapter 10), Wolff (2014b, Section 6.6.1), Wolff (2017b, Section 2)).

As previously noted, the addition of two-dimensional SP patterns to the SP computer model is likely to expand the representational repertoire of the SP system to structures in two-dimensions and three-dimensions, and the representation of procedural knowledge with parallel processing.

As with the SP system's generality in aspects of intelligence, it seems likely that the SP system is not constrained to represent only the forms of knowledge that have been mentioned. 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 people may work with.

Seamless Integration of Diverse Aspects of Intelligence, and Diverse Kinds of Knowledge, in Any Combination

An important third feature of the SP system, alongside its versatility in aspects of intelligence and its versatility in the representation of diverse kinds of knowledge, is that *there is clear potential for the SP system to provide seamless integration of diverse aspects of intelligence and diverse kinds of knowledge, 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: the SP-multiple-alignment framework.

It appears that seamless integration of diverse aspects of intelligence and diverse kinds of knowledge, in any combination, is *essential* in any artificial system that aspires to the fluidity, versatility and adaptability of the human mind.

Figure 4 shows schematically how the SP system, with SP-multiple-alignment centre stage, exhibits versatility and integration.

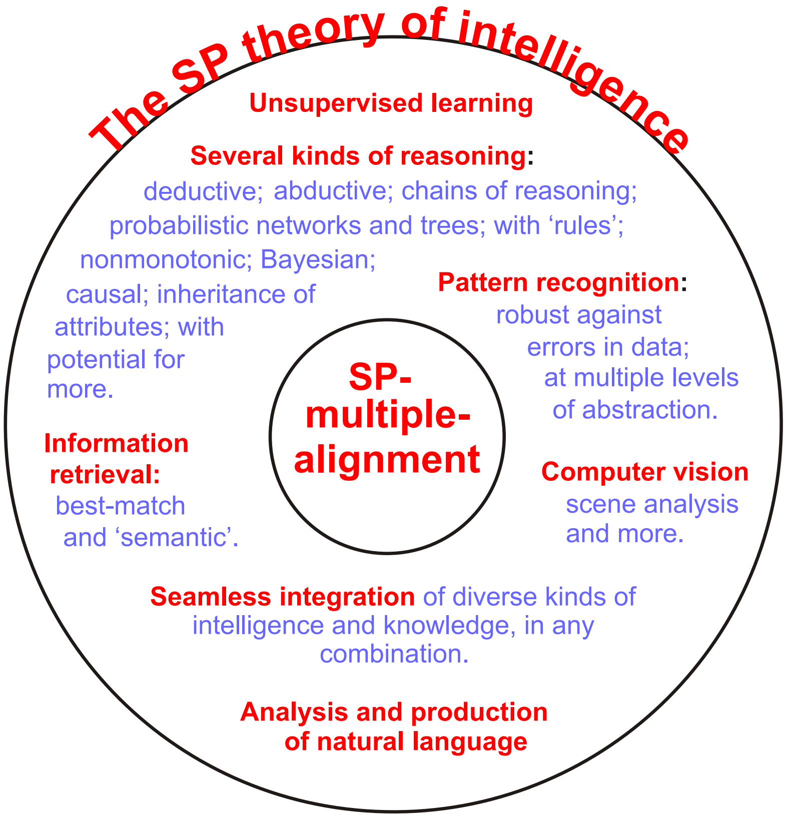

Figure 4: A schematic representation of versatility and integration in the SP system, with SP-multiple-alignment centre stage.

Potential Benefits and Applications of the SP System

Apart from its strengths and potential in modelling aspects of the human mind, it appears that, in more humdrum terms, the SP system has several potential benefits and applications. These include:

- *Big data*. Somewhat unexpectedly, it has been discovered that the SP system has considerable potential to help solve nine significant problems associated with big data (Wolff, 2014c). These are: overcoming the problem of variety in big data; the unsupervised learning of structures and relationships in big data; interpretation of big data via pattern recognition, natural language processing and more; the analysis of streaming data; compression of big data; model-based coding for efficient transmission of big data; potential gains in computational and energy efficiency in the analysis of big data; managing errors and uncertainties in data; and visualisation of structure in big data and providing an audit trail in the processing of big data.

- *Autonomous robots*. The SP system opens up a radically new approach to the development of intelligence in autonomous robots (Wolff, 2014a);

- *An intelligent database system*. The SP system has potential in the development of an intelligent database system with several advantages compared with traditional database systems (Wolff, 2007). In this connection, the SP system has potential to add several kinds of reasoning and other aspects of intelligence to the 'database' represented by the World Wide Web, especially if the SP machine were to be supercharged by replacing the search mechanisms in the foundations of the SP machine with the high-parallel search mechanisms of any of the leading search engines.

- *Medical diagnosis*. The SP system may serve as a vehicle for medical knowledge and to assist practitioners in medical diagnosis, with potential for the automatic or semi-automatic learning of new knowledge (Wolff, 2006b);

- *Computer vision and natural vision*. The SP system opens up a new approach to the development of computer vision and its integration with other aspects of intelligence. It also throws light on several aspects of natural vision (Wolff, 2014d);

- *Neuroscience.* As was mentioned earlier, abstract concepts in the SP theory map quite well into concepts expressed in terms of neurons and their interconnections in a version of the theory called *SP-neural* (Wolff (2016c), Wolff (2006a, Chapter 11)). This has potential to illuminate aspects of neuroscience and to suggest new avenues for investigation.

- *Commonsense reasoning.* In addition to the previously-described strengths of the SP system in several kinds of reasoning, the SP system has strengths in the surprisingly challenging area of "commonsense reasoning", as described by Ernest Davis and Gary Marcus (2015). How the SP system may meet the several challenges in this area is described in Wolff (2016b).

- *Other areas of application.* The SP system has potential in several other areas of application including (Wolff, 2014b): the simplification and integration of computing systems; applications of natural language processing; best-match and semantic forms of information retrieval; software engineering (Wolff, 2017b); the representation of knowledge, reasoning, and the semantic web; information compression; bioinformatics; the detection of computer viruses; and data fusion.

- *Mathematics.* The concept of information compression via the matching and unification of patterns provides an entirely novel interpretation of mathematics (Wolff, 2017a). This interpretation is quite unlike anything described in existing writings about the philosophy of mathematics or its application in science. There are potential benefits in science of this new interpretation of mathematics.

Features of Cognitive Systems Research

It seems that the SP programme of research scores well in terms of the five features of the cognitive systems paradigm described by Langley (2012):

- *Focus on High-Level Cognition.* Although in developing the SP computer model, it has been necessary to pay attention to low-level details, the overall goal has been the modelling of high-level aspects of cognition.

- *Structured Representations.* The SP system is good at modelling such things as natural language grammars, class-inclusion hierarchies, part-whole hierarchies and the like. But since the granularity of representations is not defined, it may in principle model lower-level, 'sub-symbolic', and fuzzier kinds of knowledge.

- *Systems Perspective.* The SP system has what I believe are useful things to say about "How different intellectual abilities interact and fit together; Cognitive architectures that offer unified theories of mind; Integrated intelligent agents that combine capabilities." (Langley, 2012).

- *Influence of Human Cognition.* Right from the beginning, the SP programme of research has drawn heavily on "ideas and inspiration from findings about *human cognition*" (Langley, 2012), including research by Attneave, Barlow, and others mentioned earlier, my research on first language learning by children mentioned earlier, and my own background in experimental and cognitive psychology.

- *Exploratory Research.* The main thrust of the SP programme of research has been exploration to discover a means of unifying ideas across a wide area. The SP-multiple-alignment construct is a "novel approach" to "well-established problems", it has led to "demonstrations of entirely new functionality" with "analyses of challenging cognitive tasks", and it is an "architecture" and "framework" for "integrated intelligence" (Langley, 2012).

Conclusion

It seems that the overarching goal of this research—the simplification and integration of observations and concepts across artificial intelligence, mainstream computing, mathematics, and human learning, perception, and cognition—has, to a large extent, been achieved.

The SP system provides a favourable combination of simplicity and power: the concept of SP-multiple-alignment, together with some relatively simple procedures for unsupervised learning, have proved to be remarkably versatile across diverse aspects of intelligence, in the representation of diverse kinds of knowledge, and in the seamless integration of diverse aspects of intelligence, and diverse kinds of knowledge, in any combination.

That last feature—seamless integration of diverse aspects of intelligence and diverse kinds of knowledge—appears to be essential in any artificial system that aspires to the fluidity, versatility, and adaptability of the human mind.

The SP programme of research appears to score well in terms of the five features of the cognitive systems paradigm described by Langley (2012).

References

F. Attneave. Some informational aspects of visual perception. *Psychological Review*, 61:183–193, 1954.

H. B. Barlow. Sensory mechanisms, the reduction of redundancy, and intelligence. In HMSO, editor, *The Mechanisation of Thought Processes*, pages 535–559. Her Majesty's Stationery Office, London, 1959.

H. B. Barlow. Trigger features, adaptation and economy of impulses. In K. N. Leibovic, editor, *Information Processes in the Nervous System*, pages 209–230. Springer, New York, 1969.

E. Davis and G. Marcus. Commonsense reasoning and commonsense knowledge in artificial intelligence. *Communications of the ACM*, 58(9):92–103, 2015. doi: 10.1145/2701413.

J. E. Laird, C. Lebiere, and P. S Rosenbloom. A standard model of the mind: towards a common computational framework across artificial intelligence, cognitive science, neuroscience, and robotics. *AI Magazine*, 38(4):13–26, 2017.

P. Langley. The cognitive system paradigm. *Advances in Cognitive Systems*, 1:3–13, 2012.

M. Li and P. Vitányi. *An Introduction to Kolmogorov Complexity and Its Applications*. Springer, New York, 3rd edition, 2014.

S. Nirenburg and M. Clark. Guest editors' note. *AI Magazine*, 38(4):3–4, 2017.

J. Schmidhuber. Deep learning in neural networks: an overview. *Neural Networks*, 61:85–117, 2015. doi: 10.1016/j.neunet.2014.09.003.

R. J. Solomonoff. A formal theory of inductive inference. Parts I and II. *Information and Control*, 7:1–22 and 224–254, 1964.

R. J. Solomonoff. The discovery of algorithmic probability. *Journal of Computer and System Sciences*, 55(1):73–88, 1997.

J. G. Wolff. Learning syntax and meanings through optimization and distributional analysis. In Y. Levy, I. M. Schlesinger, and M. D. S. Braine, editors, *Categories and Processes in Language Acquisition*, pages 179–215. Lawrence Erlbaum, Hillsdale, NJ, 1988. bit.ly/ZIGjyc.

J. G. Wolff. *Unifying Computing and Cognition: the SP Theory and Its Applications*. CognitionResearch.org, Menai Bridge, 2006a. ISBNs: 0-9550726-0-3 (ebook edition), 0-9550726-1-1 (print edition). Distributors, including Amazon.com, are detailed on bit.ly/WmB1rs.

J. G. Wolff. Medical diagnosis as pattern recognition in a framework of information compression by multiple alignment, unification and search. *Decision Support Systems*, 42:608–625, 2006b. doi: 10.1016/j.dss.2005.02.005. bit.ly/1F366o7, arXiv:1409.8053 [cs.AI].

J. G. Wolff. Towards an intelligent database system founded on the SP theory of computing and cognition. *Data & Knowledge Engineering*, 60:596–624, 2007. doi: 10.1016/j.datak.2006.04.003. bit.ly/1CUldR6, arXiv:cs/0311031 [cs.DB].

J. G. Wolff. The SP theory of intelligence: an overview. *Information*, 4(3):283–341, 2013. doi: 10.3390/info4030283. bit.ly/1NOMJ6l, arXiv:1306.3888 [cs.AI].

J. G. Wolff. Autonomous robots and the SP theory of intelligence. *IEEE Access*, 2:1629–1651, 2014a. doi: 10.1109/ACCESS.2014.2382753. bit.ly/18DxU5K, arXiv:1409.8027 [cs.AI].

J. G. Wolff. The SP theory of intelligence: benefits and applications. *Information*, 5(1):1–27, 2014b. doi: 10.3390/info5010001. bit.ly/1FRYwew, arXiv:1307.0845 [cs.AI].

J. G. Wolff. Big data and the SP theory of intelligence. *IEEE Access*, 2: 301–315, 2014c. doi: 10.1109/ACCESS.2014.2315297. bit.ly/2qfSR3G, arXiv:1306.3890 [cs.DB]. This paper, with minor revisions, is reproduced in Fei Hu (Ed.), *Big Data: Storage, Sharing, and Security (3S)*, Taylor & Francis LLC, CRC Press, 2016, pp. 143–170.

J. G. Wolff. Application of the SP theory of intelligence to the understanding of natural vision and the development of computer vision. *SpringerPlus*, 3(1):552–570, 2014d. doi: 10.1186/2193-1801-3-552. bit.ly/2oIpZB6, arXiv:1303.2071 [cs.CV].

J. G. Wolff. The SP theory of intelligence: its distinctive features and advantages. *IEEE Access*, 4:216–246, 2016a. doi: 10.1109/ACCESS.2015.2513822. bit.ly/2qgq5QF, arXiv:1508.04087 [cs.AI].

J. G. Wolff. Commonsense reasoning, commonsense knowledge, and the SP theory of intelligence. Technical report, CognitionResearch.org, 2016b. bit.ly/2eBoE9E, arXiv:1609.07772 [cs.AI].

J. G. Wolff. Information compression, multiple alignment, and the representation and processing of knowledge in the brain. *Frontiers in Psychology*, 7:1584, 2016c. ISSN 1664-1078. doi: 10.3389/fpsyg.2016.01584. bit.ly/2esmYyt, arXiv:1604.05535 [cs.AI].

J. G. Wolff. On the "mysterious" effectiveness of mathematics in science. Technical report, CognitionResearch.org, 2017a. bit.ly/2otrHD0, viXra:1706.0004, hal-01534622.

J. G. Wolff. Software engineering and the SP theory of intelligence. Technical report, CognitionResearch.org, 2017b. bit.ly/2w99Wzq, arXiv:1708.06665 [cs.SE].

J. G. Wolff. Solutions to problems with deep learning. Technical report, CognitionResearch.org, 2018. bit.ly/2AJzu4j, arXiv:1801.05457 [cs.LG].