In Memory of Steffen Hölldobler: From Logic to Formal and Cognitive Reasoning

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With this article, the two authors would like to pay tribute to the memory of their dear friend and colleague Steffen Hölldobler, who left us far too early in 2023. Ulrich (UF), in his time as a postdoc at the University of the Bundeswehr Munich, mentored Steffen as a student in his first logic lectures. Meghna (MB) is Steffen's last PhD student. Although there is so much more to the wonderful man Steffen was, this article strives to briefly touch upon some of the various hats he donned during his lifetime — as a student, a researcher, a professor and a friend.

1. The PhD Student

After pursuing a Diploma in Computer Science, Steffen happened to quit the Army and start as a research and teaching assistant at the University of the Bundeswehr Munich with Prof. Niegel, where UF was working as a postdoc. During his time as a PhD student Steffen started as a visiting research associate at Alan Robinson's Logic Programming Research Group at the Syracuse University, USA in 1983. During this visit he became interested in the combination of logic and functional programming — a topic that paved the way for a very fruitful collaboration between UF and Steffen (e.g. [1]). Figure 1 shows an example: there is a logic program PYTHAGORAS which uses a function $*$ for multiplication. During execution of the program it might happen that the arguments of the function are not yet instantiated, such that the function cannot be evaluated; in such a case the unification algorithm uses an equivalent logic program, in our example the clauses for MULT, to further evaluate the function call.

Steffen and UF published together on this topic and because they were reasonably successful, both were able to take a lot of liberties — they were kind of *enfants terrible* and enjoyed rebelling against the rigidity of academic administration.

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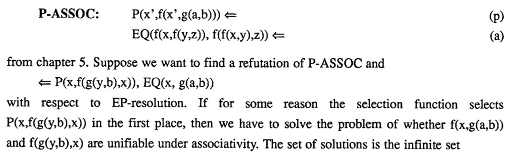
$$
\begin{aligned}
S = \{ & \mathrm{PYTHAGORAS}(a, b, c) \leftarrow \mathrm{SQUARE}(c, a*a+b*b) \\
& \mathrm{SQUARE}(v, v*v) \leftarrow \\
& \mathrm{MULT}(x, 0, 0) \leftarrow \\
& \mathrm{MULT}(0, y, 0) \leftarrow \\
& \mathrm{MULT}(x+1, y+1, y+1+z) \leftarrow \mathrm{MULT}(x, y+1, z) \}.
\end{aligned}
$$

Figure 1: Functional and Horn Clause Logic Language (FHCL) for the Combination of Horn Clauses with Functions. Example taken from [1].


P-ASSOC: P(x',f(x',g(a,b))) ⇐ (p)
EQ(f(x,f(y,z)), f(f(x,y),z)) ⇐ (a)

from chapter 5. Suppose we want to find a refutation of P-ASSOC and
⇐ P(x,f(g(y,b),x)), EQ(x, g(a,b))
with respect to EP-resolution. If for some reason the selection function selects P(x,f(g(y,b),x)) in the first place, then we have to solve the problem of whether f(x,g(a,b)) and f(g(y,b),x) are unifiable under associativity. The set of solutions is the infinite set

Figure 2: Equational Logic Programming. Example taken from [2].

For his PhD-Thesis Steffen concentrated on Equational Logic Programming and his Dissertation was published in the prestigious Springer series Lecture Notes in AI [2]. Figure 2 shows an example from his thesis. It is a logic program which contains Horn clauses together with Horn equality theories and has to be evaluated by EP-resolution based on EP-unification.

2. The Postdoc

In 1988 Steffen joined Wolgang Bibel's Intellectics Group at TU Darmstadt in Germany and shortly thereafter, in 1989, he was offered a one-year fellowship as a postdoc at the International Computer Science Institute (ICSI) at Berkeley, USA. During this period he still remained true to his theme of equational logic programming. There he was introduced to connectionism by Jerry Feldman and he immediately realised that this method could be used excellently for calculating unifiers. Steffen managed to find a clever representation of terms and the unification problem in order to efficiently use networks for computation. Figure 3 shows an example of the representation of two terms from [3].

UF very well remembers the discussion whether this

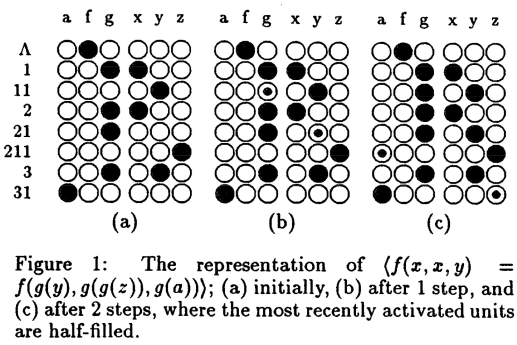
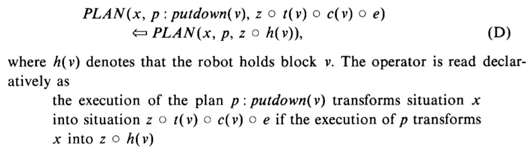


Figure 3: Computing a Unifier by a Neural Network. Example taken from [3].

approach could be regarded as cognitively motivated or whether it was just a clever 'hardware trick'. Anyhow, this research at the ICSI finally led to a postdoctoral thesis (Habilitation) on Automated Inferencing and Connectionist Models in 1993. Steffen received this academic degree from TU Darmstadt with Wolfgang Bibel and Larry Feldman as supervisors. Later on in a series of papers beginning in 2000 he started discussing the problem of combining connectionist-based approaches with symbolic reasoning. In [4] he discussed questions like "how can first-order rules be extracted from a connectionist network?" or "how can established learning algorithms such as backpropagation be combined with symbolic knowledge representation?" — and yes, these are exactly the topics which are nowadays discussed in order to find a way towards explainable AI! All of this can certainly be viewed as Steffen's first turn towards the field of cognitive science. In later years this aspect becomes much clearer and even more prominent in his work.

Another continuation of Steffen's earlier work on unification theory can be traced in his work on planning — shortly after joining Wolfgang Bibel's Intellectics group in 1988 Steffen came across various planning approaches. Together with Josef Schneeberger, he developed a new calculus for deductive planning [5]. The basis for this approach are equational logic programs [2], where situations, which depict states of the world, and plans, which are sequences of actions that transform one situation to another, are represented by terms. Reasoning about situations and plans are performed at the object level and a generated plan precisely corresponds to the well-known concept of a computed answer substitution via SLDE-resolution [6, 2].

As a small example let us consider a situation, where a robot is holding a block v, denoted by $h(v)$, and it is required to perform the action of putting v down on a table



$$PLAN(x, p : putdown(v), z \circ t(v) \circ c(v) \circ e) \Leftarrow PLAN(x, p, z \circ h(v)), \qquad \text{(D)}$$

where $h(v)$ denotes that the robot holds block v. The operator is read declaratively as

the execution of the plan $p : putdown(v)$ transforms situation x into situation $z \circ t(v) \circ c(v) \circ e$ if the execution of p transforms x into $z \circ h(v)$

Figure 4: A Definition of $putdown$ from [5].

surface t, denoted by $putdown(v)$. Figure 4 shows the definition of the $putdown$-operator. If there is a plan or a sequence of actions whose execution leads to a situation where the robot is holding a block v, then we execute a plan involving the action $putdown$, which results in the block v being on the table with its top clear and the robot's hands empty. Analogously, $z \circ t(v) \circ c(v) \circ e$ is a term representing a situation where $t(v)$ denotes that the block v is on the table t, $c(v)$ denotes that the top of v is clear, and e denotes that the robot's hands are empty. And p : $putdown(v)$ is a term denoting a plan p with the additional action of putting v down.

This approach was further developed by Steffen and other members of the Darmstadt Intellectics Group [7, 8, 9, 10]. In particular, Steffen's cooperation with Michael Thielscher was most successful. The work addresses fundamental AI problems like the frame and the ramification problem. It also considers different types of logic, e.g. linear logic, and alternative proof procedures. Today the approach is known as the *fluent calculus* [11, 12] and is considered to be one of the most important approaches in the field of reasoning about situations, actions, and causality.

During his time with Wolfgang Bibel's Intellectics group Steffen was extremely productive. He published in several different areas of AI, e.g. [13, 14], and certainly contributed significantly to the high international reputation of the field of Intellectics at TU Darmstadt.

3. The European Master's Program in Computational Logic

Steffen became a Professor for Knowledge Representation and Reasoning in the Computer Science Department at the Technische Universität Dresden in 1993. In 1997 he established the "International Master's programme in Computational Logic (MCL)", which was one of the first English-language Master's programmes at a computer science faculty in Germany and thus garnered a lot of attention for computer science at TU Dresden.

The "European Master's Program in Computational Logic", established under his leadership in 2004, expanded the previous programme concept [15]. Besides Dresden as a coordinating university the following partners participated: Free University of Bozen-Bolzano, Italy, Universidade Nova de Lisboa, Portugal, Technische Universität Wien, Austria and NICTA, Australia. In 2003, Steffen founded the International Center for Computational Logic (ICCL) as an international competence centre for research and teaching in the field of computational logic. He was also committed to the faculty as Dean of Studies for international degree programmes. He was the coordinator of both programmes until 2019 and raised a large number of Erasmus scholarships. In the period between 2010 and 2014, the two programmes were supplemented by the DAAD-funded "International PhD Program in Computational Logic" through his initiative.

Steffen organised numerous international summer schools for students both at TU Dresden and in Vietnam, Indonesia, Thailand and Mongolia, among others. These Asian summer schools lasted 2 weeks each, during which a group of German colleagues taught students. During this time Steffen's many talents became apparent. Organisation in an Asian country was certainly not always easy but Steffen managed to organise everything with remarkable ease. Not only did he enjoy organising the course, but he was also enthusiastic to teach and got the participants excited about Computational Logic. Whenever possible, the lecturers also attended the courses of their colleagues and this helped develop a special relationship among them during the time spent at the summer schools. The many weeks UF was able to spend during these occasions are certainly among his fondest memories.

During the Mongolian summer school MB accompanied the team as a student assistant. At that time she was pursuing a master's degree in Computational Logic at TU Dresden and met Steffen through his formidable logic lectures. The trip to Mongolia left a lasting impression in MB's mind and she looks back at them with immense fondness and gratitude to this day. Steffen had been her friend, philosopher and guide ever since and played a very important role in her life.

4. Cognitive Science and Logic

As mentioned earlier, Steffen already had points of contact with Cognitive Science through his involvement with Connectionism. Also the discussions in the Darmstadt Intellectics group about Johnson Laird's work on deduction, after the publication of [16], made him familiar with the subject area.

However, he finally stumbled into the field of Cognitive Science in the year 2007, when he presented an idea of computing semantic operators associated with logic programs by feed-forward connectionist networks at a lecture in the summer school of the International Center of Computational Logic at TU Dresden. He put forward the proposal of recursively propagating (logical) interpretations with respect to the logic programs through the connectionist networks until they converged to stable states — which were the least models of the programs. After his talk Steffen apprehensively asked the audience whether these aforementioned stable states have something in common with *mental models*. Researcher Michiel van Lambalgen, who was in the audience, raised his arm and answered: these are mental models.

How humans reason has been a long standing question in psychology and cognitive science, with many paradigms attempting to explain and put together pieces of the extraordinary puzzle. Following psychologist Philip Johnson Laird in [17], Steffen too began considering the question, *"are there general ways of thinking that humans follow when they make deductions?"*. Given Steffen's background in mathematics and computational logic, his preliminary attempt was to consider classical two-valued logic. After all it has been considered a normative theory for many accounts of human reasoning. However, as many studies have hence indicated, it is perhaps safe to say that classical two-valued logic is no longer considered as the doctrine for the same [18]. To that end, Steffen and his colleagues began exploring the three-valued non-monotonic logic paradigm and thus began the development of the *Weak Completion Semantics*.

Steffen's broad long term research goal was to develop a *computational* and *comprehensive* (cognitive) theory for adequately modelling human reasoning tasks. He envisioned the theory to be computational such that human responses to a reasoning task may be computed, and comprehensive such that the theory may be able to encompass a wide variety of tasks. The Weak Completion Semantics is based on ideas initially proposed by Keith Stenning and Michiel van Lambalgen in [19]. It is mathematically sound [20], has been applied to various human reasoning tasks such as the suppression task [21], the selection task [22], the belief-bias effect [23], ethical decision-making [24] etc. It has outperformed the twelve cognitive theories considered by Philip Johnson-Laird and Sangeet Khemlani [25] in syllogistic reasoning [26] and is implementable in a connectionist setting [27].

The Weak Completion Semantics: An Example

As a brief demonstrative example of how the Weak Completion Semantics (WCS) can be used to model human reasoning scenarios, let us consider an excerpt from an experiment, dubbed as the suppression task, which was conducted by psychologist Ruth Byrne [28] following [29, 30, 31], in order to study if and under what circumstances humans suppress classically valid responses such as *modus ponens* and *modus tollens*.

Let us begin with the given premises, *if she has an essay to write, then she will study late in the library* and *she has an essay to write.* For any reasoning episode the first step within the WCS framework is to construct a representative logic program. In line with the above premises we thus construct the following program, $\mathcal{P}$:

$$\{l \leftarrow e \wedge \neg ab_e,\ ab_e \leftarrow \bot,\ e \leftarrow \top\},$$

where e and l represent that she has an essay to write and that she will study late in the library, respectively. The *abnormality predicate* ab_e is assumed to be false. The abnormality predicate serves the purpose of the (default) assumption that nothing is abnormal with regards to a given context — something humans seem to assume when reasoning with limited information, as was suggested in [19]. Weakly completing $\mathcal{P}$ results in $wc(\mathcal{P})$:

$$\{l \leftrightarrow e \wedge \neg ab_e,\ ab_e \leftrightarrow \bot,\ e \leftrightarrow \top\},$$

whose least model (the step by step computation of which is excluded from the current discussion for simplification purposes) is $\langle\{e, l\}, \{ab_e\}\rangle$. Here, the atoms e and l are true while ab_e is false. Anything outside the scope of this model is unknown in this context. In other words, the reasoner concludes that *she will study late in the library*, which forms the majority consensus in the experiments reported by Byrne.

Now, if the above premises were to be supplemented with an additional premise: *if the library stays open, then she will study late in the library*, the set would be represented by the following program $\mathcal{P}'$:

$$\begin{aligned}\{l &\leftarrow e \wedge \neg ab_e,\ ab_e \leftarrow \bot,\\ l &\leftarrow o \wedge \neg ab_o,\ ab_o \leftarrow \bot,\\ ab_e &\leftarrow \neg o,\ ab_o \leftarrow \neg e,\\ e &\leftarrow \top\},\end{aligned}$$

where the meanings of the previously mentioned atoms remain the same, o denotes the library stays open and ab_o denotes any abnormality with respect to the library staying open. The two definitions of ab_e semantically mean that either there is nothing abnormal with respect to having an essay to write (the default assumption) or as suggested by the addition of the above premise, there may be something abnormal namely that the library might be closed. Similarly the definitions of ab_o semantically mean that either there is no abnormality with regards to the library staying open or there is no essay to write.

Now, weakly completing $\mathcal{P}'$ results in $wc(\mathcal{P}')$:

$$\begin{aligned}\{l &\leftrightarrow (e \wedge \neg ab_e) \vee (o \wedge \neg ab_o),\\ ab_e &\leftrightarrow \bot \vee \neg o,\\ ab_o &\leftrightarrow \bot \vee \neg e,\\ e &\leftrightarrow \top\},\end{aligned}$$

whose least model is $\langle\{e\}, \{ab_o\}\rangle$, where e is true and ab_o is false. As l is unknown with respect to this model, the previously drawn conclusion, *she will study late in the library*, is now suppressed and the reasoner concludes that *she may or may not study late in the library.* This phenomenon is the so-called suppression effect reflected in the experiments reported by Byrne. In the demonstrated case, even when the antecedent is affirmed i.e. a person has an essay to write, reasoners may not automatically conclude that the person will study late in the library (i.e. draw an MP conclusion) because there is a possibility of the library being closed which may disable the person from doing so. Analogously in the context of the least model of $wc(\mathcal{P}')$, it is unknown whether the library stays open (o) or not hence the atom ab_e is unknown. And this means l is (also) unknown in the least model.

Closing

Until his untimely demise in 2023, Steffen had authored four monographs, more than 100 scientific articles and edited more than 30 publications. Aside his own research, Steffen had moreover been very active in his academic community, organising workshops and conferences and serving for many years on the selection committee for the GI Doctoral Award. He also held a honorary professorship from Stavropol university, but at the same time was horrified by the recent Russian war of aggression in Ukraine. One of his last activities before he fell ill was the attempt to organise a scientific event in parallel to the 17th annual G20 summit in November 2022 in Bali in order to demonstrate peaceful and friendly coexistence among scientists across all borders.

In this article the authors have tried to focus on the various aspects of Steffen's work. However, the limited scope of this article does not and cannot assimilate the essence of the man Steffen was. And this commemoration would indeed be incomplete without emphasising that while a good scientist, Steffen was also a people person — his presence in a room could hardly go unnoticed. He was a family man and a loving father. As MB fondly recollects, he would often advise her to not stress about "small" things and reminded her time and again that happiness is the most important thing in life. As he would often say, *das Leben ist schön — life is beautiful.*

Indeed, the authors will terribly miss their dear friend and bid him a very fond farewell.

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