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In order to investigate the possibility of synthesizing new knowledge at a cognitive level more advanced than that which unaided human experts can reach, an ultra-complex chess endgame (King and two Bishops against King and Knight) was chosen as an experimental testbed. As a preparation for investigating this possibility, support was provided by the chess scholar and specialist in the endgame, A.J. Roycroft, and by a complete tabulation of factual knowledge of the domain completed by Kenneth Thompson.

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20. Abstract (continued

It turned out that no reasonable amount of practice, nor access to a database of 200 million chess facts, could enable Roycroft to master the endgame (thus the endgame is authentically "ultra-complex"). The next step is to try and instill articulate mastery into a machine system by the "rules from examples" method of computer induction.

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IDEAS ON KNOWLEDGE SYNTHESIS STEMMING FROM THE KBBKN ENDGAME

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1. The goal and experimental domain

In order to investigate the possibility of synthesising new knowledge at a cognitive level beyond that which unaided human experts can reach, we have chosen an ultra-complex chess endgame (King and two Bishops against King and Knight) as the experimental test bed. As a preparation for investigating this possibility we had the support of (1) the endgame scholar A.J. Roycroft and (2) a complete tabulation of factual knowledge of this domain computed by Kenneth Thompson. It turned out that no reasonable amount of practice (e.g. one year), including access to a database of 200 million facts, could render Roycroft capable of mastering this endgame (i.e., it is authentically "ultra-complex"). The next step is to try and instil articulate mastery into a machine system by the "rules-from-examples" method of computer induction.

By an *ultra-complex* domain we mean one which is currently beyond the range not only of human comprehensibility but also of human mastery, except in an *ad hoc*, partial and approximate fashion. Such domains include many industrial problems, e.g., sufficiently-large Travelling-Salesman problems, or circuit-board design for optimal placement or dynamical control and are also found in the more complex chess endgames. These latter offer more economical and controllable test beds than the factory floor. The end-product when finished will instruct its users so that they will be able to understand the previously ill-understood problems and to master them. We seek to construct such a system to the level of a reasoning knowledge-based tutor. When complete, such a tutor expert system would operate in a more challenging intellectual area than any previous system, human or machine. Although studied and validated in the test bed of a chess ending, the search, inference and example-processing of this system would transfer to other complex domains. We are investigating how the rule-induction approach can be extended by building on Stephen Muggleton's (1987) current experiments to automate "structuring" of problem domains, which at present can only be done by human experts.

2. Look-up strategies embodying superhuman skill

In tasks of the highest complexity, the skill of correct decision-taking is simply not accessible to human cognition. Such skills exist in principle, but are not acquirable by man through any amount of unaided effort. A study of an expert's battle with what we have termed an ultra-complex domain formed part of a previous series of experiments in the Turing Institute (Michie and Hayes-Michie, 1986). A.J. Roycroft

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(AJR) is one of the world's leading scholars of the chess endgame, often regarded as an intellectually deeper specialism than the tournament play of the unrestricted game of chess itself. Through the combined good offices of a number of institutions, Roycroft was available for an eighteen-month collaborative study (Michie and Hayes-Michie, 1986). He identified the endgame King and two Bishops versus King and Knight (KBBKN) as having the desired property of inaccessibility to unaided human expertise. The problem space comprises of the order of 10^8 legal positions and had wrongly been believed by chess-endgame specialists to be, in general, a draw. At Roycroft's instigation, Kenneth Thompson computed by an exhaustive method a complete look-up table in which the following information is retrievable for every legal position: (1) whether the position is won for White or not won, (2) if the former, then which subset of the moves legally available from the given position are optimal moves and (3) the distance-to-win.

This computation provided the first in what has become a series of surprises. With the exception of a few freak positions, the KBBKN game, regarded by masters as a draw, was shown to be won by White against any defence from any starting position within the problem space. The worst case requires a total of 66 moves by White, which when put together with Black's 65 replies, amounts to 131 plies. Alen Shapiro subsequently augmented Thompson's work with the addition of an interactive user interface. A player can now engage in the play of either side against a move-perfect look-up-driven opponent. This facility was reserved for the second phase of an experiment planned in four phases. [In all phases we ignored the stipulation derivable from the official Laws of Chess that for a win to be valid in a pawnless ending it must not comprise more than 50 successive non-capture moves.]

Figure 1 shows the distribution of legal White-to-move positions plotted against distance from the goal along the optimal path. A curious feature is the presence in the distribution of two "pinches" of which the more extreme (containing no more than 100,000 positions per move) occupies the interval 38-44 moves from the end, which is defined as checkmate or safe Knight capture. This latter "pinch" is associated with a celebrated family of positions named after Kling and Horwitz (1851) (see Diagram 1). Roycroft's conjecture was that these positions are "unavoidable" in the sense that optimal play starting sufficiently far from the goal is obliged to pass through a member of this family, exiting via one of only four essentially different positions of the critical cluster. For this reason they are called *compulsory exits*. Figure 2 shows these four Kling and Horwitz exit positions.

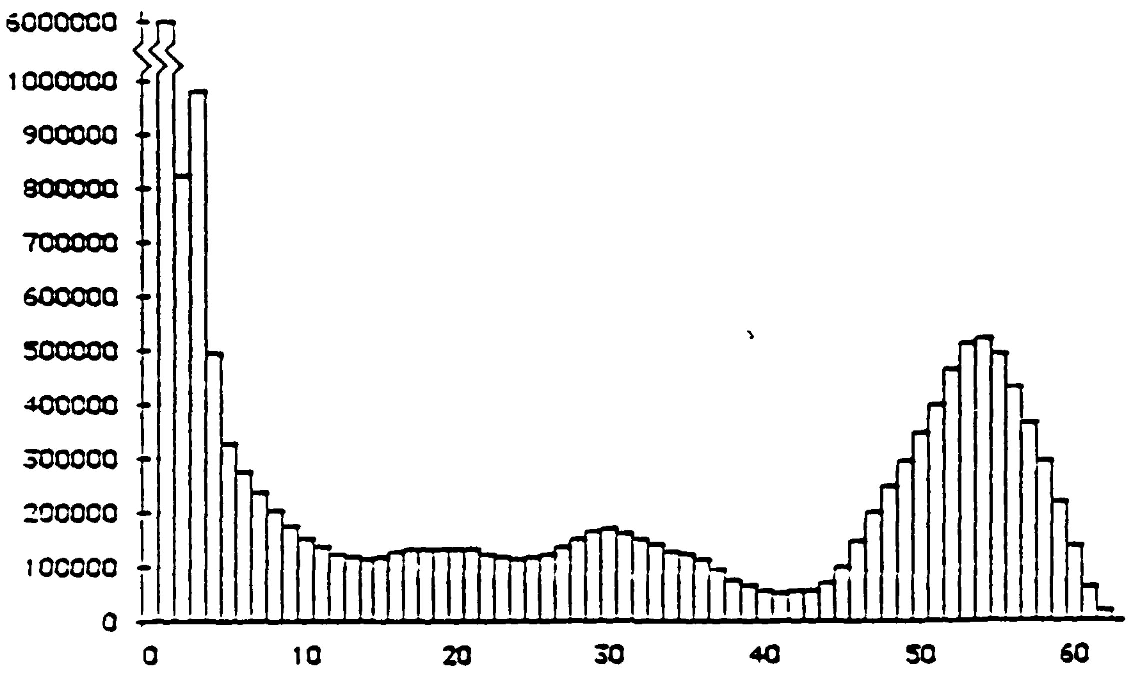


Figure 1: Depth (horizontal axis) of legal KBBKN White-to-move positions plotted against frequency (vertical axis).

J. Kling and B. Horwitz, 1851

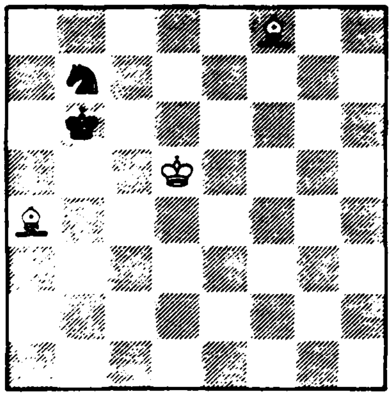
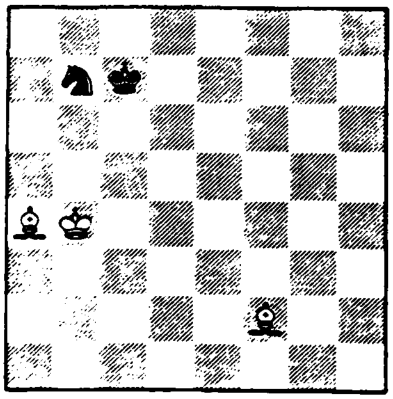
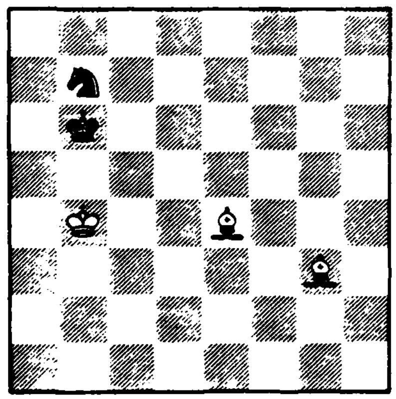


Diagram 1

The starting position of the Kling and Horwitz study, which they stated to be drawn. In quotation: "Two Bishops against a Knight cannot win, if the weaker party can obtain a position similar to the above [our diagram 1]; but they win in most cases."



No. 1



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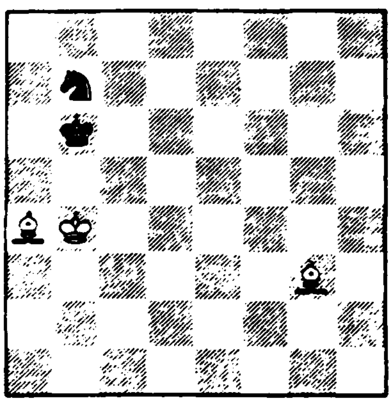

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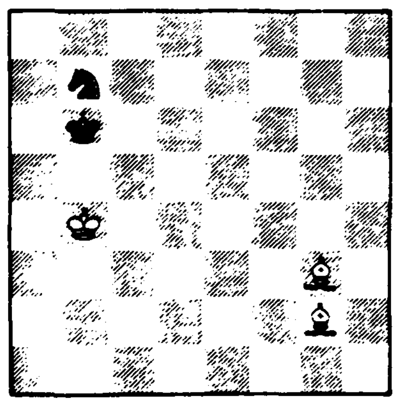

No. 4

Figure 2: The four known BTM *compulsory exits* from a Kling and Horwitz position. In No. 1 Black loses in 39, in Nos. 2 and 3 in 38, but in No. 4 Black loses in 40 moves. Nos. 1, 2 and 3 occurred in twelve machine-generated optimal paths supplied by Ken Thompson in 1985, but No. 4 did not.

3. The four-phase research plan

The research described here was conceived as consisting of four consecutive phases, for the first two of which results are available as of this writing.

Phase 1. During the first phase Roycroft was not allowed access to Thompson's database or Shapiro's interactive user interface. His task was to see how far he could climb up this rock-face, so to speak, by intensive study using his own resources. These were supplemented by the statement that move-perfect winning play was theoretically attainable. He also possessed a further small piece of machine-generated knowledge : out of the positions most distant from the kill, he had been given one. For this one position, he had twelve machine-generated optimal paths to the goal.
After three months of uninterrupted study of the KBBKN endgame, Roycroft announced the end of the first phase, stating that he had gained all the mastery of the endgame that he felt was in his unaided power to gain. Testing his performance as White against the table-driven machine defence confirmed his subjective prediction that his mastery would be shown to be lacunary. In two of the ten test games he "offered a draw" after much inconclusive skirmishing. The average path efficiency (Doran and Michie, 1966) of his play was 38%.

Phase 2. Roycroft was allowed free access to the database and its interactive user interface, from which he could obtain an instant answer to any factual question he cared to put. He thus had unlimited access to facts, but not to concepts, not unnaturally, since the machine did not possess them either. We were in a sense testing Roycroft's brain as a device for turning facts into concepts. This phase ran for two months, at the end of which he felt that he had identified several illuminating concepts, but failed to see how they could be discovered by any programmed method. Systematic tests partially confirmed Roycroft's impression of lack of progress. Again, two out of ten tests were failed, but the average path efficiency stood somewhat higher, at 50%. Table 1 summarises the results obtained from the two sets of tests.

No.	Position					Optimal depth	AJR's Estimate	AJR's Solution	Path efficiency
	WK	WB	WB	BK	BN				
1.	c2	d5	f2	f4	h7	54	55	68	79%
2.	d2	c1	g8	a8	a5	19	52	52	37%
3.	c1	c8	f8	a4	d8	51	--	122	42%
4.	b1	d6	e8	e6	h5	58	57	abandoned after 75	0%
5.	b2	e1	b3	e2	g1	60	54	109	55%
6.	c1	c3	a2	e7	a3†	51	--	abandoned after 69	0%
7.	d2	h7	c1	h2	d7	20	18	34	59%
8.	c2	d2	c8	g2	h1	15	15	32	47%
9.	c1	a3	a4	f1	f2	17	19	53	32%
10.	d2	g5	e8	h8	f8	18	20	66	27%
11.	c2	c1	a6	f2	b6	20	16	114	18%
12.	d4	g5	f3	f2	h6	16	20	111	14%
13.	c2	f6	h5	h2	d5	17	16	18	94%
14.	c2	e6	h8	b4	e1	18	19	20	90%
15.	d4	b2	g8	f4	d6	49	34	abandoned after 60	0%
16.	a1	g1	e8	g7	d2	56	40	74	76%
17.	a1	h7	a3	d2	h5	53	36	74	72%
18.	b1	c5	g4	d5	b3	60	57	abandoned after 92	0%
19.	c1	c8	c7	e2	g6	54	46	85	64%
20.	a1	c7	a4	d2	f6	59	49	68	87%

Table 1: The upper ten test positions were administered to the subject (AJR) at the end of Phase 1, and the lower ten at the end of Phase 2. Path efficiency is (optimal depth / solution depth) × 100%.

† Since 1. Bb4+ wins at once, there is plainly a clerical error here [Information from AJR — Ed.].

Whether a professional cryptanalyst or a trained methodologist placed under identical conditions would find himself equally at a loss is not known. These professions uniquely aim to inculcate a developed craft of converting raw facts to concepts. Until results are to hand we cannot be sure how far the Roycroft result should be generalized. Part of the new work plan proposed here is to study the success of specifically trained people on the same problem.

Phase 3. Instead of interactive access to all atomic facts, Roycroft will be provided with a small number of specimen sequences of optimal play, variations analogous to those available to him for study during phase 1, but carefully pre-selected to represent sparsely scattered sub-spaces in the total problem space. We have suggestive evidence that facts structured into such molecular (as opposed to atomic) form constitute assimilable and potentially instructive material whereas even a superabundance of individual facts does not. This phase lies in the future.

Phase 4. Others associated with the project, Stephen Muggleton and Alen Shapiro, have laid the groundwork for the long-term task of building an expert system that is to have complete mastery, not in the purely operational sense of the present table-driven program, but as a concept-structured program which can thereby codify and explain its skill along the lines already shown feasible in small domains (Shapiro, 1983; Shapiro and Michie, 1986) and documented in Appendix 1. The method is the inductive inference of concept-structured rules from (database-stored) examples. This is the 'superarticulacy' phenomenon (Michie, 1985).

After a succesful conclusion of phase 4, it may be possible for Roycroft to assimilate the machine's tactical conceptualisation of the task so that he may acquire the mental mastery too. The aimed-for transformation is thus:

$$\textit{Human Expert} + \textit{Expert System} \rightarrow \textit{Human Superexpert}$$

In summary, the machine system now would act, upon completion of phase 4, as a tutor, coaching the human expert interactively through the medium of structured and annotated examples.

4. A proposed design outline for a KBBKN expert system

4.1. Functions of the expert system

Functions required of the expert system (in estimated increasing order of implementational difficulty) include:

- Optimal play (the KBBKN database suffices)

- Classification of positions into classes, where a class can be:

  -- depth of position (i.e., distance in number of moves from winning the Knight; the KBBKN database suffices)

  -- 'phase of play' (assuming that play progresses through a sequence of stages that are explicitable in terms meaningful to a human player; the KBBKN database probably suffices in most cases for this, but a possible further elaboration is outlined in the next section)

- Explanation of correct moves (not necessarily optimal moves; 'correct' in the sense of some relatively simple conceptual framework for playing this ending). Explanation should be in terms of the current phase of play, a current subgoal and possibly tactical constraints.

- Explanations of why some given move is incorrect (where 'correct' is with respect to the system's conceptual view on KBBKN).

- Explanation of the reasons for classifying a position as being of a certain 'phase of play'. Normally, this will be in terms of attributes, though occassionally short variations may have to be exhibited.

4.2. Resources and tools available

Existing tools for building the expert system include:

1- The KBBKN database (Thompson, 1986) of the complete set of more then 100 million positions and their depths, together with software for endowing the user with facilities for retrieval, display, generation of variations, etc., already developed for this project by Shapiro. These facilities urgently need supplementing with interactive-graphics extensions to enable the domain-specialist to interact directly with the kind of images and dynamic effects which he is accustomed mentally to manipulate during problem-solving and analysis.

2- Inductive-learning tools: ACLS (e.g. embedded in RuleMaster) (Petterson and Niblett, 1982) and ASSISTANT (Bratko and Kononinko, 1986) are two efficient inductive-learning programs (derived from Quinlan's (1979) ID3 program) for constructing classification rules in the form of decision trees from examples.

3- The Prolog-based description-building program MARVIN first developed by Claude Sammut (Sammut and Banerji, 1986) and recently re-implemented and installed at the Turing Institute by Bijan Arbab. Relational descriptions after the manner of Patrick Winston's early work (1979) are developed by the system on the basis of guided prompts to the user for specific examples and counter-examples of the concept and its sub-concepts.

4- Advice- and plan-driven algorithms for knowledge-based game playing, AL1 (Bratko and Michie, 1982) and AL3 (Bratko, 1982). These combine game-specific knowledge (in the form of 'advice' and rules for reasoning about plans) with game-tree searching.

5- A system for symbolic derivation of chess patterns SYMCOM (Bratko, 1985) which can be used for automatic generation of meaningful patterns as an alternative to inductive learning. Instead of inducing rules from examples, SYMCOM derives rules from 'first principles', i.e., the rules of the game, by symbolic manipulation.

4.3. A proposed plan for assembling the expert system using the above tools, assumed available by then

These tools can be used in two ways:

- as functional modules of the expert system's knowledge base (e.g., classification rules):

- as functional modules of the expert system (e.g., knowledge-driven planning and search)

In particular, these tools could be used to accomplish the following tasks in building the expert system:

- To implement some functions of an expert system, the KBBKN database lookup suffices (e.g., optimal play, required unless this would clash with "transparency" goals in the sense of explanations as referred to earlier in this section).

- Inductive-learning tools can be used for constructing position-classification rules (a 'phase-of-play' recogniser as referred to before). Since, for the human user, these rules have to be transparent, and for the computer relatively compact, the techniques of structured induction and tree-pruning are suggested.

- Inductive learning can also aid the construction of planning knowledge. In AL3, this knowledge is represented as a set of rules of the form:

if
given pattern matches the current knowledge about the game being played
then
consider an action of either generating a new plan, verifying a plan, modifying a plan, or combining two existing plans.

Inductive-learning programs can help to specify the left-hand-side patterns of rules; similarly, goal predicates may be useful as primitives in which to express the right-hand sides of rules.

- As a concession to the tutoring and explanation power required, the expert system need not play optimally, but may merely perform 'correctly'. That is, the system will have to find a win (typically not the shortest) by using a neat and economical conceptualisation of KBBKN, if such can be found. Subject to this condition such knowledge might be used by an AL3-type program performing reasoning about plans, constrained game-tree search, and calls to a decision-rule interpreter (Bratko, 1982).

- Explanation generation: the position classification can be explained by showing in an appropriate form a path in the decision tree; occasionally, this explanation will also include variations from a shallow search necessary for classification, viz. whenever a position calls for 'search'.

- Textual explanation of play may well be based on AL3 execution trace and the main variation according to AL3's 'current understanding' of the game in progress.

5. Discussion

If the objectives of the KBBKN experiment are reached, then we will know that machine synthesis of conceptualised codifications of knowledge far beyond what already exists in books or brains, constitutes a practical possibility. Meanwhile, indications that this might be so have already been reported in two other problem domains. One domain concerns the interpretation of electrocardiogram records (Bratko, Mozetic and Lavrac, 1986). The other is Shapiro's (1983) work on a subset of the chess endgame King and Pawn versus King and Rook (KPKR).

Is it perhaps an exaggerated response to see a technological revolution in laboratory demonstrations? Perhaps; but we should at the same time not lose sight of the seriousness of the technical poison to which superarticulacy is offered as an antidote. The dangers of software opacity in socially critical areas have been documented elsewhere (Kopec and Michie, 1983). Throughout the advanced nations, a widening sector of the installed base of mechanical and electronic equipment has already become unmaintainable. Correspondingly, the role played by traditional documentation — maintenance manuals, inspection guides, test procedures, codes of practice and the like — is insensibly changing from that of a practical guide to that of mere compliance with legislation. Moreover, as each generation of technicians retires, e.g. from the engine-testing sheds of the aircraft industry, the new generation hangs back from absorbing their precious know-how, relating as it does to designs seen as obsolescent. In summary, combinatorial problems, escalating beyond human comprehension, abound not only in industrial and military affairs but throughout modern society as a whole. The possibility of mass manufacture of usable "how-to-do-it" codifications we now believe to be sufficiently established. The time-scale remains unclear in which these techniques may progress from the laboratory to large-scale field trials.

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Appendix 1.

Machine-generated "how-to-do-it" text from a complete and correct rule-base synthesised by machine within an expert-supplied hierarchical framework. The list of primitives given to the inductive synthesiser is given in Appendix 2 (from Michie, 1986).

- Machine-generated advice text for PA7, top-level rule
  to decide whether or not this position is won for White.

  The position is won for White (PA7 top-level rule):
  iff the BR can be captured safely (rimmx)
  or *none* of the following is true
  a black piece controls the queening square (bxqsq)
  or there is a simple delay to White's queening the Pawn (DQ level 2.1)
  or the WK is in stalemate (stlmt)
  or there is a good delayed skewer (DS level 2.2)

- Machine-generated advice text for DQ, level 2.1
  to decide whether or not there is a simple delay to White's queening the Pawn.

  There is a simple delay to White's queening the Pawn (DQ level 2.1):
  iff *any* of the following is true
  there is a good delay from a mate threat (THRMT level 3.1)
  or there is a good delay due to the white King being on a8 (WKA8D level 3.2)
  or there is a good delay due to the white King being in check (WKCHK level 3.3)
  or there is a good delay due to a double attack threat (DBLAT level 3.4)
  or there is a good delay because of a hidden check (hdchk)

- Machine-generated advice text for DS, level 2.2
  to decide whether or not there is a good delayed skewer.

  There is a good delayed skewer (DS level 2.2):
  iff there is a special opposition pattern present (spcop)
  or *all* of the following are true
  the WK is one away from the relevant edge (wtoeg)
  and the Kings are in normal opposition (dsopp)
  and the WK distance to intersect point is too great (dwipd)
  and there is a potential skewer as opposed to a fork (skewr)
  and the BK is not attacked in some way by the promoted WP (bkxbq)

- Machine-generated advice text for THRMT, level 3.1
  to decide whether or not there is a good delay from a mate threat.

  There is a good delay from a mate threat (THRMT level 3.1):
  iff the BR attacks a mating square safely (rxmsq)
  and the BK can attack the WP (bkxwp)
  or *none* of the following is true
  the BK is attacked in some way by the promoted WP (bkxbq)
  or the mating square is attacked in some way by the promoted WP (qxmsq)
  or the BR does not have safe access to file a or rank 8 (r2ar8)

- Machine-generated advice text for WKA8D, level 3.2
to decide whether or not there is a good delay due to the white King being on a8

There is a good delay due to the white King being on a8 (WKA8D level 3.2):
iff the WK is on square a8 (wkna8)
  and *any* of the following is true
    the BR has safe access to file a or rank 8 (r2ar8)
    or B attacks the WP (BR in direction $x = -1$ only) (blxwp)
    or a very simple pattern applies (simpl)

- Machine-generated advice text for WKCHK, level 3.3
to decide whether or not there is a good delay due to the white King being in check.

There is a good delay due to the white King being in check (WKCHK level 3.3):
iff *all* of the following are true
  the WK is in check (wknck)
  and the BR cannot be captured safely (rimmx)
  and *any* of the following is true
    Black can attack the queening square (BTOQS level 4.2)
    or the BK can attack the critical square (b7) (bkxcr)
    or the BR bears on the WP (direction $x = -1$ only) (rkxwp)
    or there is a skewer threat lurking (thrsk)
    or B can renew the check to good advantage (mulch)

- Machine-generated advice text for OKSKR, level 4.1
to decide whether or not the potential skewer is good.

the potential skewer is good (OKSKR level 4.1):
iff *any* of the following is true
  the BR has safe access to file a or rank 8 (r2ar8)
  or the WK cannot control the intersect point (wkcti)
  or the BK can support the BR (bkspr)
  or the BR alone can renew the skewer threat (reskr)
  or the WK can be skewered after one or more checks (skach)
  or the WK can be reskewered via a delayed skewer (reskd)

- Machine-generated advice text for BTOQS, level 4.2
to decide whether or not Black can attack the queening square.

Black can attack the queening square (BTOQS level 4.2):
iff the BK is not in the BR's way (bknwy)
  and *any* of the following is true
    the BR can achieve a skewer or the BK can attack the WP (skrxp)
    or the BK is on file a in a position to aid the BR (bkona)
    or the BK is on rank 8 in a position to aid the BR (bkon8)
    or the WK is overloaded (wkovl)

[No machine-generated text for DBLAT (level 3.4) was produced because it contains a 3-valued attribute which the text-producing system cannot parse.]

Appendix 2.

List of unique primitive attributes invoked in the text of Appendix 1 (those marked † are specific to DBLAT - not included above).

bkblk †	is the BK in the way?
bkon8	is the BK on rank 8 in a position to aid the BR?
bkona	is the BK on file a in a position to aid the BR?
bkspr	can the BK support the BR?
bkxbq	is the BK attacked in some way by the promoted WP?
bkxcr	can the BK attack the critical square (b7)?
bkxwp	can the BK attack the WP?
blxwp	does B attacks the WP (BR in direction $x = -1$ only)?
bxqsq	do one or more B pieces control the queening square?
cntxt †	is the WK on an edge and not on a8?
dsopp	are the kings in normal opposition?
dwipd	is the WK distance to intersect point too great?
hdchk	is there a good delay because there is a hidden check?
katri †	does any king control intersect point; if so, which?
mutch	can B renew the check to good advantage?
qxmsq	is the mating sq attacked in some way by the promoted WP?
r2ar8	does the BR have safe access to file a or rank 8?
reskd	can the WK be reskewered via a delayed skewer?
reskr	can the BR alone renew the skewer threat?
rimmx	can the BR be captured safely?
rkxwp	does the BR bear on the WP (direction $x = -1$ only)?
rxmsq	does the BR attack a mating square safely?
simpl	does a very simple pattern apply?
skach	can the WK be skewered after one or more checks?
skewr	is there a potential skewer as opposed to fork?
skewr	can the BR achieve a skewer or BK attack the WP?
spcop	is there a special opposition pattern present?
stlmt	is the WK in stalemate?
thrsk	is there a skewer threat lurking?
wkcti	can the WK control the intersect point?
wkna8	is the WK on square a8?
wknck	is the WK in check?
wkovl	is the WK overloaded?
wkpos †	is the WK in a potential skewer position?
wtoeg	is the WK one away from the relevant edge?