Proposal: An empirical investigation of the extent to which human belief change is consistent with AGM belief revision and KM belief update

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CCS CONCEPTS

• **Computing methodologies → Nonmonotonic, default reasoning and belief revision**; *Reasoning about belief and knowledge*; • **Theory of computation** → Logic.

KEYWORDS

non-monotonic reasoning, belief revision, belief update, belief change, propositional logic, survey, Mechanical Turk

1 PROJECT DESCRIPTION

In previous work, empirical investigations have been performed to find patterns of non-monotonic inference. Non-monotonic inferences are made by reasoners when the inferences have the potential to change in light of new information. In particular, an investigation was conducted by Da Silva Neves *et al.* [30] on French students to determine whether human reasoning was consistent with defeasible reasoning, a form of non-monotonic reasoning. We aim to extend this work by investigating the relationship between human reasoning and two forms of belief change. Part of this work will include a comprehensive investigation of three important forms of non-monotonic reasoning: defeasible reasoning, belief revision and belief update.

Belief change is necessary when a reasoning agent is confronted with inconsistent or outdated information. In AI, inconsistent information is revised, whilst outdated information is updated. In AI, these operations are formally different and have distinct axioms which determine how these operations are performed. Whilst in the literature experiments have shown that human reasoning exhibits non-monotonicity, it remains open to determine whether there exists a set of rules which accurately describes how humans make non-monotonic inferences. This project aims to contribute to this open question. This problem is important because human reasoners often make decisions which are efficient and flexible. We want AI systems to be efficient and flexible too. By investigating human belief change, we have a framework on which to compare the performance of belief change systems in AI.

2 PROBLEM STATEMENT

Non-monotonic reasoning and belief change have been described as two approaches to the same problem. In [30], an empirical investigation is conducted to determine if human reasoning conforms to the properties of System P, a class of non-monotonic reasoning defined for preferential consequence relations. We will extend this work by investigating empirically whether human reasoning conforms to two forms of belief change. In particular, we will investigate the conformance of human reasoning with belief revision and belief update.

2.1 Aims

The AGM approach to belief revision provides rationality postulates for which belief revision must hold. Similarly, the KM approach to belief update provides rationality postulates for which belief update must hold. We aim to identify the postulates of belief revision and the postulates of belief update which are consistent with human reasoning. In order to do this, we aim to develop a set of concrete examples which model reasoning situations in which a reasoner might have to revise or update their beliefs. We wish to investigate for each postulate, the degree to which the reasoner believes the premises and the conclusion. By comparing the degree of belief for both the premises and conclusion for each postulate, we want to calculate which postulates are consistent with human reasoners.

2.2 Research questions

RQ 1. To what extent is human reasoning consistent with the postulates of AGM belief revision?
In this research question, we ask whether human reasoning tends to follow the patterns observed in AGM belief revision. First we separate each pattern into its component premises and conclusion. As the patterns (postulates) of AGM belief revision are formulated in propositional logic, it is then required that these patterns are translated to a concrete human-readable form. Once this is done, the degree of belief for the premises and the degree of belief for the conclusion will be measured for each postulate. We will use this information together to make an assessment of which postulates are consistent with human reasoning.
RQ 2. To what extent is human reasoning consistent with the postulates of KM belief update?
In this research question, we ask whether human reasoning tends to follow the patterns observed in KM belief update. First we separate each pattern into its component premises and conclusion. Similar to AGM belief revision, the patterns (postulates) of KM belief update are formulated in propositional logic and need to translated to a concrete human-readable form. Once this is done, the degree of belief for the premises and the degree of belief for the conclusion will be measured for each postulate. We will use this information together to make an assessment of which postulates are consistent with human reasoning.

2.3 Requirements

The requirements for this study includes an empirical investigation conducted on human subjects. The focus of the investigation is to test empirically the postulates of belief revision and belief update. We will pose a set of questions for each of belief revision and belief update in the form of surveys. In these surveys, we want to ask our participants to indicate the degree of their beliefs of the premises of each postulate and to indicate the degree of their beliefs of the conclusion of each postulate. For the experiment investigating belief revision, we require concrete representations of the AGM postulates to develop belief revision reasoning examples. Similarly, we require concrete representations of the KM postulates to develop belief update reasoning examples. In addition, each postulate must be separated into a set of premises and a conclusion. Another requirement is to determine how a postulate is corroborated by a human reasoner.

2.3.1 Patterns for non-monotonic inference. We refer to the language of propositional logic and adopt the following notational conventions. For belief revision, we use $*$ to denote a revision operator. The revision of a belief set K with new consistent information p is denoted by the formula $K * p$. For belief update, we use $\diamond$ to denote an update operator. The update of a belief set ψ with new belief μ is denoted by the formula $\psi \diamond \mu$. AGM belief revision (refer to Table 1) consists of the following patterns: *Closure*, *Inclusion*, *Vacuity*, *Success*, *Extensionality*, *Consistency*, *Super-expansion* and *Sub-expansion*. KM belief update (refer to Table 2) consists of the following patterns: *U1*, *U2*, *U3*, *U4*, *U5*, *U6*, *U7*, *U8* and *U9*.

Table 1: AGM Postulates

Basic revision postulates	
1. Closure	$K * p = C_n(K * p)$
2. Inclusion	$K * p \subseteq K + p$
3. Vacuity	If $K \nvdash \neg p$
	then $K + p \subseteq K * p$
4. Success	$p \in K * p$
5. Extensionality	If $\vdash p \leftrightarrow q$
	then $K * p = K * q$
6. Consistency	If $p \nvdash \bot$
	then $K * p \nvdash \bot$
Supplementary postulates	
7. Super-expansion	$K * (p \wedge q) \subseteq (K * p) + q$
8. Sub-expansion	If $K * p \nvdash \neg q$
	then $(K * p) + q \subseteq K * (p \wedge q)$

Table 2: KM Postulates

Basic update postulates	
(U1)	$\psi \diamond \mu \models \mu$
(U2)	If $\psi \models \mu$
	then $\psi \diamond \mu \leftrightarrow \psi$
(U3)	If both ψ and μ are satisfiable
	then $\psi \diamond \mu$ is satisfiable
(U4)	If $\psi_1 \leftrightarrow \psi_2$ and $\mu_1 \leftrightarrow \mu_2$
	then $\psi_1 \diamond \mu_1 \leftrightarrow \psi_2 \diamond \mu_2$
(U5)	$(\psi \diamond \mu) \wedge \phi \models \psi \diamond (\mu \wedge \phi)$
(U6)	If $\psi \diamond \mu_1 \models \mu_2$ and $\psi \diamond \mu_2 \models \mu_1$
	then $\psi \diamond \mu_1 \leftrightarrow \psi \diamond \mu_2$
(U7)	If ψ is complete
	then $(\psi \diamond \mu_1) \wedge (\psi \diamond \mu_2) \models \psi \diamond (\mu_1 \vee \mu_2)$
(U8)	$(\psi_1 \vee \psi_2) \diamond \mu \leftrightarrow (\psi_1 \diamond \mu) \vee (\psi_2 \diamond \mu)$
(U9)	If ψ is complete and $(\psi \diamond \mu) \wedge \phi$ is satisfiable
	then $\psi \diamond (\mu \wedge \phi) \models (\psi \diamond \mu) \wedge \phi$

2.3.2 Our approach for the empirical test of AGM belief revision. As an example, we consider the AGM postulate of *Vacuity*: If $K \nvdash \neg p$ then $K + p \subseteq K * p$. We will refer to the premises of an argument or postulate as LP, and refer to the conclusion as RP. In this example, let the "If" part be denoted by LP and let the "then" part be denoted by RP. Then, it can be said that *Vacuity* is not corroborated when reasoners endorse the belief $K \nvdash \neg p$, that the negation of p cannot be proven from K, but do not endorse $K + p \subseteq K * p$, the implication that $K + p$ is a subset of or equal to the revision of their beliefs with p, K. In other words, *Vacuity* is not corroborated when reasoners endorse LP, but do not endorse RP. We follow the approach of Da Silva Neves *et al.* [30] by assuming that human inference is constrained by knowledge organisation in memory and that its formal properties emerge from a spreading activation process operating directly on knowledge structures. We hypothesise that this spreading activation process is consistent with the AGM postulates for belief revision. We outline the test of consistence of the spreading activation process with AGM belief revision in the following:

(1) For each postulate of AGM belief revision, we first decompose them into its LP and RP components.
(2) We will choose a set of concrete rules that matches the LP and RP components involved in the postulate. Each rule must be such that some people endorse it as plausible and some other people do not. By assuming that these postulates are not target properties of belief revision, but rather that they are emergent ones, we do not include the symbolic representations and use concrete material to implant the information into memory. In addition, we assume that a single concrete instance should suffice in order to test a given postulate if "the concrete material is such that no implicit knowledge is available or if the instances of the rule refer explicitly to the most typical one". It is important the the influence of material on endorsement of the postulates be tested.

(3) Participants then independently rate the degrees of possibility for $LP \wedge RP$ and $LP \wedge \neg RP$. It allows to evaluate the plausibility of every rule involved in the postulates of AGM belief revision, for each participant, according to the semantics of possibilistic inference. A simple semantics for plausible rules has been proposed by Benferhat, Dubois and Prade [2] and Dubois and Prade [11] within the framework of Possibility theory. According to this semantics, a conditional assertion $\alpha \mid\sim \beta$ can be viewed as a constraint expressing that a situation where α and β are both true has a greater possibility (Π) than a situation where α is true and β is false. Formally, $\alpha \mid\sim \beta$ is a plausible rule if $\Pi(\alpha \wedge \beta) \geq \Pi(\alpha \wedge \neg\beta)$.

(4) For each postulate, (i) a contingency table is constructed and (ii) the coefficient of association between the variables "endorsement of LP"and "endorsement of RP", and the differences between cells A and B, cells A and C, and cells B and C are computed. The contingency table for step (i) is partitioned into four cells A, B, C and D. Cell A refers to those who endorse LP and RP, Cell B refers to those who endorse LP but not RP, Cell C refers to those who do not endorse LP but endorse RP and Cell D refers to those who endorse neither LP nor RP.

(5) The consistency of human inference with an AGM postulate is checked according to a set of decision rules (refer to Appendix A).

We apply this same approach for testing KM belief update.

3 PROCEDURES AND METHODS

In the requirements that we have defined in the previous section, we have identified a set of rules to investigate for each postulate. The rules that we will select are such that some participants will them plausible and some will not. In the following we first describe the experiment required for the selection of these rules. Then, we describe the details of the participants, material, design, procedure, predictions and expected results for the experiments testing belief revision and belief update.

3.1 Experimental protocol for preselection of rules

We will design on an intuitive basis, and following the syntax of the rules involved in the LP and RP components of the postulates, a large set of rules that could potentially be interpreted as plausible beliefs by a sample drawn from the online workforce of Amazon's Mechanical Turk.

Participants. We will recruit 30 native English speakers, an generous approximation of half of our final participant sample, to conduct this experiment. No participant should have formal training in logic. This sample should be representative of general reasoners.

Material. The material for this experiment will consist of 25 pairs of questions related to 25 rules of the form "People who are gluten-intolerant do not enjoy bread-baking programmes on television". Each question will involve an unknown character. Participants will be asked to imagine that these characters were selected randomly by drawing names from an address book. Participants will answer questions like "To which degree do you believe that it possible that George S is gluten-intolerant and does enjoy bread-baking programmes on television?" and "To which degree do you believe it is possible that George S is gluten-intolerant and does not enjoy bread-baking programmes on television?" Participants will be invited to indicate their beliefs of possibility on a Likert-scale, with gradings from 1=strongly disagree to 5=strongly agree.

Design and procedure. Questions will be presented in the form of a survey. The survey will be designed on Google Forms and the experiment will be conducted on Mechanical Turk. The questions in the survey will appear in random order for all participants. Participants will be informed that they could answer by checking the point on the scale that best matched their beliefs, or checking the point 3=neutral if they had an imprecise idea of their beliefs.

Results. We are interested in two outcomes for each rule: *agree* and *disagree*. We will encode the responses from participants in the experiment as follows. An answer of 1 (strongly disagree) or 2 (disagree) will be encoded as *agree*. An answer of 4 (agree) and 5 (strongly agree) will be encoded as *disagree*. A answer of 3 (neutral) will be taken as the average answer for that rule. For each rule, we will then compute the percentages of participants who interpreted the rule as:

(i) a plausible belief (Π(LP $\wedge$ RP) $>$ Π(LP $\wedge$ $\neg$ RP)),
(ii) a non-plausible belief (Π(LP $\wedge$ RP) $\leq$ Π(LP $\wedge$ $\neg$ RP)),
(iii) a material implication (Π(LP $\wedge$ $\neg$ RP) $=$ 0), and
(iv) a material equivalence (Π(LP$\wedge\neg$ RP) $=$ 0 and Π($\neg$LP$\wedge$ RP) $=$ 0)

On the basis of these results, we will select some pairs of rules so that the product of the rates of their endorsement will be close to 0.5.

3.2 Experimental testing of AGM belief revision

Participants. We will recruit 50 native English speakers as participants through Mechanical Turk. No participant should have formal training in logic. Participants in this experiment should not have taken part in the pre-experiment.

Material. AGM belief revision includes eight postulates: *Closure*, *Inclusion*, *Vacuity*, *Success*, *Extensionality*, *Consistency*, *Super-expansion* and *Sub-expansion*. Each of the eight postulates have two rules: one rule in LP and one rule in RP. The eight LP rules will be derived from the experiment. The eight RP rules will be derived according to target properties. The status these sixteen rules have for each participant will be checked by means of two questions.

Design and procedure. The design and procedure will be the same as in the pre-experiment. The thirty-two questions will be presented to participants in the form of a survey. To control the effect of the presentation of questions, each participant will receive a randomised version of the questions.

Predictions. The encoding of answers wlll be the same as in the pre-experiment. In our results, we also want to determine whether the endorsement of LP (ELP) was preferentially associated with the endorsement of RP (ERP). The degree of association will be computed by means of the Phi-coefficient (ϕ) and statistically tested by means of a Chi-square ($\mathcal{X}^2$). The coefficient ϕ for a 2 x 2 table is defined as:

$$\phi = \frac{|AD - BC|}{((A+B)(C+D)(A+C)(B+D))^{\frac{1}{2}}} \tag{1}$$

For each postulate, we propose the statistical hypothesis H_0 (null hypothesis) to be "there was no association between ELP and ERP". The alternate hypothesis, H_1, will be "there is a significant positive association between ELP and ERP". H_0 will be rejected if the probability of obtaining a value as large as the observed ($\mathcal{X}^2$) was not greater than 0.05, as it is usual in experimental psychology. Under the general hypothesis that participants' inference tends to corroborate *Closure*, *Inclusion*, *Vacuity*, *Success*, *Extensionality*, *Consistency*, *Super-expansion* and *Sub-expansion*, we expect that H_0 will be predicted for each property. The computed ($\mathcal{X}^2$) coefficient will also be used to test the differences between cells A and B, cells A and C and cells B and C. Da Silva Neves *et al.* [30] argue that given the independence of statististical tests for each property, each single property could be statistically corroborated while being rejected by a non-negligible number of participants. Under the hypothesis that participant beliefs are consistent with AGM belief revision, we predict that a high proportion of participants would not commit a violation.

Results. We will compute ELP and ERP rates for each postulate of AGM belief revision and produce contingency tables for each postulate, in the style of the pre-experiment.

3.3 Experimental testing of KM belief update

Using a similar methodology to the experiment testing AGM belief revision, we will conduct an experiment testing KM belief update. We briefly mention some important details below, but refer to Section 3.2 for the complete procedure.

Participants. We will recruit 50 native English speakers as participants through Mechanical Turk. No participant should have formal training in logic. Participants in this experiment should not have taken part in the pre-experiment nor the experiment testing AGM belief revision.

Material. KM belief update includes nine postulates: *U1*, *U2*, *U3*, *U4*, *U5*, *U6*, *U7*, *U8* and *U9*. Three of the postulates (*U1*, *U5* and *U8*) have two rules: one rule in LP and one rule in RP. Two of the postulates (*U3* and *U4*) have three rules: two rules in LP and one rule in RP. Two of the postulates (*U2* and *U7*) have four rules: two rules in LP and two rules in RP. One of the postulates (*6*) have six rules: three rules in LP and three rules in RP. One of the postulates (*U9*) has five rules: three rules in RP and two rules in LP. In total there are thirty-one rules, consisting of seventeen in LP and fourteen in RP. The seventeen LP rules will be derived from the experiment. The fourteen RP rules will be derived according to target postulates. The status these thirty-one rules have for each participant will be checked by means of two questions.

Design and Procedure. The sixty-two questions will be presented in random order in the style of a survey, as before.

Predictions. The encoding of answers will be the same as in the pre-experiment. We follow a similar approach to AGM belief revision in terms of the hypothesis predictions and testing.

Results. We will compute ELP and ERP rates for each postulate of KM belief update and produce contingency tables for each postulate, in the style of the pre-experiment.

3.4 Theoretical contributions

This work will provide a comprehensive investigation of the literature on non-monotonic defeasible reasoning, belief revision and belief update. The results from our experiment will substantiate the use of the postulates for AGM belief revision and the postulates as KM belief update, as the formal properties for the systems which they intend to model. This work will also provide a framework on which to compare human belief change with belief revision and belief update, respectively, used in non-monotonic AI systems. As humans are efficient and flexible reasoners, the ability to mimic their reasoning behaviour in AI systems is critical for smarter, more intelligent and more efficient AI.

4 ETHICAL, PROFESSIONAL AND LEGAL ISSUES

The ethical issues for this project relate to the involvement of human subjects in the proposed reasoning experiments. We acknowledge and have read the UCT Code for Research Involving Human Subjects. In order to comply with this code, we need to obtain ethics clearance from the Faculty of Science Human Research Ethics Committee. An application to obtain ethical clearance along with an appended informed consent form, will be submitted prior to performing any research involving human subjects. Part of our ethical clearance application includes whether and how much our participants will be remunerated for taking part in our experiments. For tasks on Mechanical Turk, two costs are involved: the Worker Reward and the Mechanical Turk Fee. The Worker Reward is an amount that we decide to pay Workers for each assignment. The Mechanical Turk Fee is 20% on the reward and bonus amount (if any) which we pay to Workers. Tasks with 10 or more participants will be charged an additional 20% fee on the reward we pay Workers. The minimum fee is $0.01 per assignment or bonus payment. We have decided on a reward amount by considering the minimum wage in the United States of America and considering the minimum wage in South Africa. We will use an exchange rate of R17 = \$1. The minimum wage in the USA is \$7,25/hour (R123,25/hour). The South African minimum wage is R15,57/hour. We use the average minimum wage per hour calculated as follows:

$$\frac{R123,25 + R15,57}{2} = R69,40 \tag{2}$$

We will use the amount in Equation (2) as the reward paid to our participants because we expect that our survey will be completed within an hour. To avoid paying further costs, we will conduct the surveys on Mechanical Turk in batches of no more than 9 participants. At 20% of R69,40, the fee owed to Mechanical Turk for an individual task is R13,88. The cost of an individual survey on Mechanical Turk thus comprises the sum of the reward paid to Workers and the fee owed to Mechanical Turk:

$$R69,40 + R13,88 = R83,23 \tag{3}$$

The pre-experiment requires 30 participants and both experiments 1 and 2 require 50 participants. The total cost for the remuneration of participants in our experiments is calculated as follows:

$$(30 \text{ x } R83,28) + (50 \text{ x } R83,28) + (50 \text{ x } R83,28) = R10826,40 \tag{4}$$

After considering the issue of remuneration, we discuss further ethical issues for our experiments. As part of our experiment, participants will first be presented with instructions, a description of the survey, a digitised consent form and the contact details of the researcher. Upon accepting the conditions set out in the consent form, participants will be authenticated through a digital bot-checker in the style of a *captcha*. Once participants have been authenticated, they will be allowed to answer the survey questions. The personal information that will be collected in each experiment will be limited to the participant's Amazon Turk Worker ID. This personal identifier is unique to Amazon Turk and is used to identify registered members without revealing personal characteristics such as their names, cellphone number, email number or age. Once the responses have been collected and before data-handling, all survey responses shall be anonymised, excluding factors specified on Mechanical Turk which indicate the respondent's membership of our experiment's desired population e.g. their age group or their percentage of HITs completed successfully on Turk. We will specify a window of 1 to 5 days for reviewing completed assignments on Turk before releasing payment. In the case of rejecting a completed assignment, the participant will be contacted via Mechanical Turk with an explanation for the rejection.

In addition to our ethics application, we will submit a Data Management Plan in fulfilment of the requirements as set of by the University of Cape Town prior to collecting, storing, describing or analysing data.

The legal issues faced in the work relate to intellectual property. We acknowledge that the potential IP resulting from this work has not been assigned to any funder and belongs fully to the University of Cape Town. Should any IP materials be developed in the course of this work, we will disclose the necessary information to the Research Contracts and Innovation department at the University of Cape Town within 90 days of discovery, by completion of an Invention Disclosure Form. As stated by the UCT IP Policy, we recognise that copyright in publications is automatically assigned by UCT to the author, and in particular, a student owns the copyright in their thesis or dissertation.

In terms of professional issues, we refer and adhere to the guidelines and polices set out in the UCT Computer Science Graduate Handbook 2020.

5 RELATED WORK

5.1 Forms of non-monotonic reasoning

We discuss the state-of-the-art of three prominent forms of non-monotonic reasoning and belief change in the literature, including their origin, properties and applications.

5.1.1 *Defeasible reasoning.*

In the seminal work by Kraus, Lehmann and Magidor (KLM) [24], they studied general patterns of non-monotonic reasoning and attempted to isolate properties which map non-monotonic reasoning to positive properties, rather than negatively describing non-monotonic reasoning by the property it does not enjoy, monotonicity. They define five families of non-monotonic consequence relations (Systems C, CL, P, CM and M) and provide representation theorems for each. An outcome of this paper is the defacto standard in non-monotonic reasoning, System P, which computes a preferential consequence relation based on the KLM properties Reflexivity, Left Logical Equivalence, Right Weakening, Cautious Monotonicity, CUT and Or. Gärdenfors and Makinson [17] give an elegant interpretation of non-monotonic inferences in terms of underlying *expectations*. They provide two ways of modelling expectations: by expectation sets equipped with selection functions, and by expectation relations. They provide representation theorems and establish relations with preferential models. Using the notion of an *expectation*, Gärdenfors and Makinson argue that belief revision and non-monotonic inference relations can be treated uniformly by viewing the relation of epistemic entrenchment used in Gärdenfors [15] and Gärdenfors and Makinson [16] as a kind of expectation ordering. Lehmann [26] provides a logic of normal defaults, different to the one proposed by Reiter [34], which is rich enough not to require the consideration of non-normal defaults. In his work, Lehmann defines the lexographic closure of any given finite set $\mathcal{D}$ of defaults, and provides examples to show that the lexicographic closure defined corresponds to the basic intuition behind Reiter's defaults. In a subsequent work, Lehmann [27] studies stereotypical reasoning as a basic form of non-monotonic reasoning. Lehmann proposes a formal model for stereotypical reasoning and examines its logical properties. Under weak assumptions, Lehmann finds that stereotypical reasoning is cumulative. Lin and Chen [28] proposed a restricted semantics of four-valued logic for default reasoning to resolve the problems of inconsistency and incoherence whilst retaining the classical extensions in the presence of consistency and coherency. Their results prove that the restricted semantics can maintain both the expressiveness and reasoning ability of default logic and an approach is provided to compute the restricted extensions by reducing them to classical ones. Britz and Varzinczak [6] investigated defeasible modes of reasoning and introduce new modal operators with which to formalise the notion of defeasible necessity and distinct possibility. In their work, Britz and Varzinczak [6] demonstrate how KLM-style conditionals can smoothly be integrated with their richer language.

Britz *et al.* [5] present an approach to defeasible reasoning for the description logic $\mathcal{ALC}$. Their results are based on the work done by Kraus, Lehmann and Magidor (KLM) on defeasible conditionals in the propositional case. Britz *et al.* [5] study versions of a preferential semantics of two forms of defeasible subsumption, and link these constructions formally to KLM-style syntactic properties via representation results. Additionally, Britz *et al.* [5] investigated an appropriate form of *defeasible entailment* for the enriched version of $\mathcal{ALC}$ and their results include an algorithm for the computation of a form of defeasible entailment known as *rational closure* in the propositional case. Governatori *et al.* [18] investigated how to change a preference relation in a non-monotonic logic in order to change the conclusions of the theory itself. The main result of their work is the proof that the problem of revising a non-monotonic theory by changing only the superiority order between conflicting rules is generally computationally hard.

5.1.2 Belief revision. In the seminal work by Alchourrón, Gärdenfors and Makinson [1], the authors studied the processes of contracting a theory to eliminate a proposition and revising a theory to introduce a proposition. They investigate partial meet contraction functions and define the basic postulates of these functions. Alchourrón, Gärdenfors and Makinson [1] have shown that the properties of partial meet contraction functions satisfy the Gärdenfors rationality postulates and that they are are sufficiently general to provide a representation theorem for those postulates. An important outcome for this work is the properties and representation theorem for contraction functions, which has been extended to revision functions in later work. Katsuno and Mendelzon [22] analysed model-theoretically the semantics of revising knowledge bases by sets of propositional sentences, They provide a characterisation of all revision schemes that satisfy the Gärdenfors rationality postulates, in terms of minimal change with respect to an ordering among interpretations. Kern-Isberner [23] discussed the nature of belief change operations and introduced universal inference operators as a proper counterpart in non-monotonic reasoning to iterated belief change. Kern-Isberner [23] investigated belief change in an abstract framework of epistemic states and conditionals. Furthermore, he proposed general postulates for revision and update which also apply to iterated belief change. A critical feature in this framework was the distinction between background knowledge and evidential information. Fermé and Hansson [14] summarised the development of belief revision for the first 25 years since the seminal work by AGM [1]. Fermé and Hansson discussed, amongst others, equivalent characterisations of AGM operations, extended representations of the belief states, change operators not included in the original framework, iterated change, applications of the model, its connections with other formal frameworks, computatibility of AGM operations, and criticism of the model. Boella, Pigozzi and Van Der Torre [3] studied AGM contraction and revision of rules using input/output logical theories. They replace propositional formulas in the AGM framework of theory change by pairs of propositional formulas, representing the rule based character of theories, and they replace the classical consequence operator *Cn* by an input/output logic. The results in their paper suggest that, in general, results from belief base dynamics can be transferred to rule base dynamics, but that a similar transfer of AGM theory change to rule change is much more problematic. Casini and Meyer [8] showed that the standard AGM approach to belief change can be adapted to a preferential non-monotonic framework, with the definition of expansion, contraction and revision operators, and corresponding representation results. Casini and Meyer [8] argue that the adaptation of AGM belief change to a preferential non-monotonic framework depends on the identification of the *monotonic core* of the non-monotonic framework. Their results include that preferential AGM belief change can be obtained in terms of classical AGM belief change. In later work, Casini *et al.* [7] showed that the standard AGM approach to belief change can be transferred to a preferential non-monotonic framework in the sense that change operations can be defined on *conditional* knowledge bases. The results from [8] are extended with characterisations based on semantics and entrenchment relations, showing how some of the constructions defined for propositional logic can be lifted to their preferential non-monotonic framework.

5.1.3 Belief update. Katsuno and Mendelzon [21] argued that there is no set of rationality postulates, a set of rules which every belief revision operator must satisfy, which will be adequate for every application. They distinguish between two kinds of changes that can be made to a knowledge base, an update and a revision. Importantly, they define the rationality postulates for update and provide an axiomatisation of update obtained from the AGM framework. Herzig and Rifi [20] have studied ten concrete propositional update operations of the literature by first characterising their relative strength and their computational complexity. They evaluate these competing update operations with respect to the postulates proposed by Katsuno and Mendelzon [21]. Lang [25] investigated the scope of belief update and showed that it is a specific case of feedback-free action progression. Following this investigation, Lang also explored new issues such as reverse update. Herzig *et al.* [19] studied a family of belief update operators based on formula/literal dependence rather than formula/variable dependence. According to this scheme, Herzig *et al.* [19] explain that updating a belief base by an input formula consists of first forgetting in the base every literal on which the input formula has a negative influence and then conjoining the resulting base with the input formula. They evaluate the update operators in two dimensions: the logical dimension, by checking the status of KM postulates and the computational dimension, by identifying the complexity of a number of decision problems. Miller and Muise [29] present a belief update mechanism for Proper Epistemic Knowledge Bases (PEKBs) that ensures the knowledge base remains consistent when new beliefs are added. They achieved this by first erasing any formulae that contradict these new beliefs and show that this update can be computed in polynomial time. Furthermore, the update mechanism for PEKBs is assessed against the KM postulates for belief update. Creignou *et al.* [10] argue that belief update within fragments of classical logic has not been addressed thus far. They investigate the behavour of refined update operators with respect to the satisfaction of the KM postulates and, in this context, highlight the differences between revision and update. In further work, Creignou *et al.* [9] study belief update in the Horn fragment. They have contributed a representation result which shows that the class of update operators captured by Horn compliant partial (resp. total) preorders over possible worlds is precisely that given by the adapted and augmented Horn update postulates. They also provide concrete Horn update operators and explain Horn revision operators based on partial preorders. Ribeiro *et al.* [35] study belief update when the underlying logic is not necessarily finitary. They demonstrate that in this case the classical construction for KM update does not capture all the rationality postulates for KM belief update and provide evidence as to why their non-finitary construction is weaker.

5.2 Links between human reasoning and non-monotonic reasoning

Elio and Pelletier [12] conducted a study investigating how people update and revise semantically equivalent but syntactically distinct belief sets, both in symbolic-logic problems and in quasi-real-world problems. In their results, it shows that syntactic form affects belief revision choices. Additionally, for symbolic problems, subjects update and revise semantically-equivalent belief sets identically, whereas for quasi-real-world problems they both update and revise problems differently. Contrary to previous studies, their results indicated that subjects on occasion are reluctant to accept a sentence that changes from false to true, but are willing to accept it would it change from true to false. In later work, Elio and Pelletier [13] investigated experimentally the problem of deciding which of several initially accepted sentences to disbelieve, when new information presents a logical inconsistency with the initial set. This problem was that of belief revision. Their results showed that conditional sentences were more readily abandoned than ground sentences, even when either choice would lead to a consistent belief state, and that this preference was more pronounced when problems used natural language cover stories rather than symbols. Da Silva Neves *et al.* [30] conducted an experiment to investigate whether human inference tends to be consistent with the rationality postulates of non-monotonic reasoning (System P plus Rational Monotony). Their results are consistent with all the studied properties, except CUT and Left Logical Equivalence. They support the working hypothesis in AI that System P plus Rational Monotony offer a plausible basic set of properties for non-monotonic logics. Pelletier and Elio [31] reason that people ingeniously use default reasoning to solve complex cognitive tasks which paved the way for non-monotonic formalisms in AI. They make the case that this is a form of a psychologism and discuss results from empirical investigations which they argue should be included in non-monotonic formalisms. Bonnefon *et al.* [4] define a model that predicts an agent's ascriptions of causality between two events in a chain, based on background knowledge about the normal course of the world. Importantly, the background knowledge is represented by non-monotonic consequence relations. Their results include empirical data to support the psychological plausibility of their basic definitions. Ragni *et al.* [33] argue that "approaches other than classical logic might be better suited to capture human inference processes". They analyse inferences from selected formal approaches (System P, Logic Programming, Reiter's Default Logic and OCF based systems) and compare them by their capacity to cover human inference observed in the Suppression Task. In later work, Ragni *et al.* [32] have analysed from both a formal and an empirical perspective the power of non-monotonic systems to model (i) possible explicit defeaters and (ii) more implicit conditional rules that trigger non-monotonic reasoning by the keywords in such rules. Their results indicated that the classical evaluation of inferences has to be extended in the three major aspect (i) regarding the inference system, (ii) the knowledge base and (iii) possible assumed exceptions for the rule.

6 ANTICIPATED OUTCOMES

6.1 Survey

The main outcome for this project are the surveys testing AGM belief revision and belief update. Each survey will be comprised of several components: a survey description, a digitised consent form, an authentication barrier and the actual survey questions. The description will inform participants of the nature of the survey and its duration. The digitised consent form will inform participants about their rights, how their data will be used as well as what remuneration they will receive. Upon completing the digitised consent form and agreeing to its terms, participants will have to pass an authentication barrier. This barrier will take on the form of a *captcha* whereby participants need to prove that they are not a robot. Upon successful authentication, participants will proceed to answer the survey questions. For each survey, we will produce a codebook in which we process, refine and analyse our collected data. The findings in the codebook will inform our discussion and conclusions for this project. We anticipate that designing appropriate questions, to test AGM belief revision and KM belief update, will not be straightforward. In particular, each formalism consists of particular postulates defined in propositional logic. Each postulate needs to be separated into its component premises and conclusion. Each of these postulates need to be made concrete in our survey in order for human reasoners to make sense of them. AGM belief revision consists of 8 postulates while KM belief update consists of 9 postulates. For each reasoning pattern, each postulate will be made concrete by means of an example. Participants must then indicate , the degree of their belief of the premises involved and the degree of their belief of the conclusion. Another challenge that we anticipate is that participants will be tempted to take the survey repeatedly to take advantage of the remuneration. We account for this as shown in our Risks and Risk Management Strategies Table in B. We expect that our online survey distribution platform, Mechanical Turk, will provide us with access to at least 50 participants for each survey. We will rely on the Mechanical Turk server and network infrastructure to be fully operational during our project time-span.

6.2 Expected impact

In the non-monotonic reasoning community, there is currently an emerging research project to test whether the normative properties of formal systems of non-monotonic reasoning are appropriate for modelling human reasoning. The major impact of the work done in this project will thus be to contribute towards this nascent research paradigm. This work will provide a basis for comparing human belief change with AI belief change. We extend the approach of Da Silva Neves *et al.* [30] of testing human defeasible reasoning to testing AGM belief revision and KM belief update. We hypothesise that human reasoning is consistent with AGM belief revision and KM belief update, and aim to find evidence in support of the postulates, considered mainly as plausible rules, to be used as the formal properties for the systems in question. As far as we are aware, the postulates underpinning the formalisms of belief revision and belief update have not been tested using a single methodology. As our methodology for examining AGM belief revision and KM belief update is the same as the methodology used by Da Silva Neves *et al.* [30] for examining defeasible reasoning, another impact of the work will be to perform a comparison of the human defeasible reasoning findings with the findings from our work as there are close formal parallels between the postulates for belief revision and defeasible reasoning such that that they may be seen as "basically the same process, albeit used for two different purposes" [17]. Finally, the results of the project will contribute towards the greater goal of understanding human cognition.

6.3 Key success factors

The project comprises a theoretical and an experimental component. The theoretical component involves a discussion on the formalisms of defeasible reasoning, AGM belief revision and KM belief update; it informs the experimental component. The experimental component consists of an empirical investigation for the extent of correspondence with human reasoning and each of AGM belief revisiona and KM belief update.

Success factors for the surveys:

- The reasoning examples in the pre-experiment reflect plausible situations an ordinary reasoner might encounter
- The questions for experiments 1 and 2 model precisely the logic of the postulates they intend to test
- Survey participants provide clear, personal responses for each question: they do not provide mainly neutral answers to speed through the survey in order to obtain the remuneration

Success factors for the project as a whole:

- Experiments are conducted within and do not exceed the time-frame specified in the project plan
- Patterns of human belief change are identified from the collected data
- The data collected from our project support our hypotheses that human reasoning is consistent with AGM belief revision and KM belief update
- A system-level comparison of our findings with the human defeasible reasoning findings of [30] is possible
- A Master's thesis is submitted upon completion of this project

7 PROJECT PLAN

7.1 Risks

The risks and risk management strategies for this project can be found in Appendix B. Overall, the project is of relatively low-to-moderate risk, and all risks we are aware of can be mitigated.

7.2 Timeline

This project runs over a period of 2 years from 01 February 2020 to 31 January 2022. The timeline for this project can be seen in our Gantt chart (refer to Appendix C) and in our Deliverables and Milestones table (refer to Appendix D.

7.3 Resources required

The resources required for this project are mainly related to the design of the survey and the data collection. We have chosen to develop our survey on Google Forms for several reasons: it is a free platform, it offers an unlimited number of questions and it offers a variety of question types (short-answer text, paragraph text, multiple choice, checkboxes, linear grid, date-time and many others). We will extend the functionality of our surveys on Google Forms with a *captcha* plug-in for user authentication. We will further extend the functionality of our surveys with programming scripts to randomise the order of questions in the survey and to provide each participant with a unique survey code. The programming aspect will be implemented with Java as the high-level programming language. An important requirement is thus to have a fast, reliable internet connection and a computer loaded with a java compiler. For our data collection, we will use Mechanical Turk. The total amount of money required for the data collection is R10 826,40 (see details in Equations (2) - (4)). Another requirement is to have access to document and spreadsheet processing software in which to view our collected data and in which to produce the codebooks for each survey. We intend to make use of the Microsoft 365 suite for this purpose, in particular, we will require the use of Microsoft Excel, Word and PowerPoint. Finally, the thesis that will be produced at the end of this project must be typed and appropriately formatted. For this, we will make use of the Overleaf platform, an online editor and compiler for LaTex documents.

7.4 Deliverables

The main deliverables for this project are the surveys designed and developed to test AGM belief revision and KM belief update respectively. Other deliverables, in no particular order, include:

- First version of project proposal
- A presentation of the project proposal
- Revised project proposal
- An outline of the MSc thesis
- Three iterations of the survey for the pre-experiment
- Three iterations of the survey testing AGM belief revision
- Three iterations of the survey testing KM belief update
- A codebook for the pre-experiment
- A codebook for the experiment testing AGM belief revision
- A codebook for the experiment testing KM belief update
- First version of MSc thesis
- Final camera-ready MSc thesis
- A project website
- A project poster

7.5 Milestones

The milestones for this project are listed in our Gantt chart (refer to Appendix C) and in our Deliverables and Milestones table (refer to Appendix D. The milestones in the Gantt chart include deliverables relating to the submission of an MSc dissertation as well as milestones we set out for the design and execution our experiments.

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Appendices

A DECISION RULES FOR TESTING AGM BELIEF REVISION

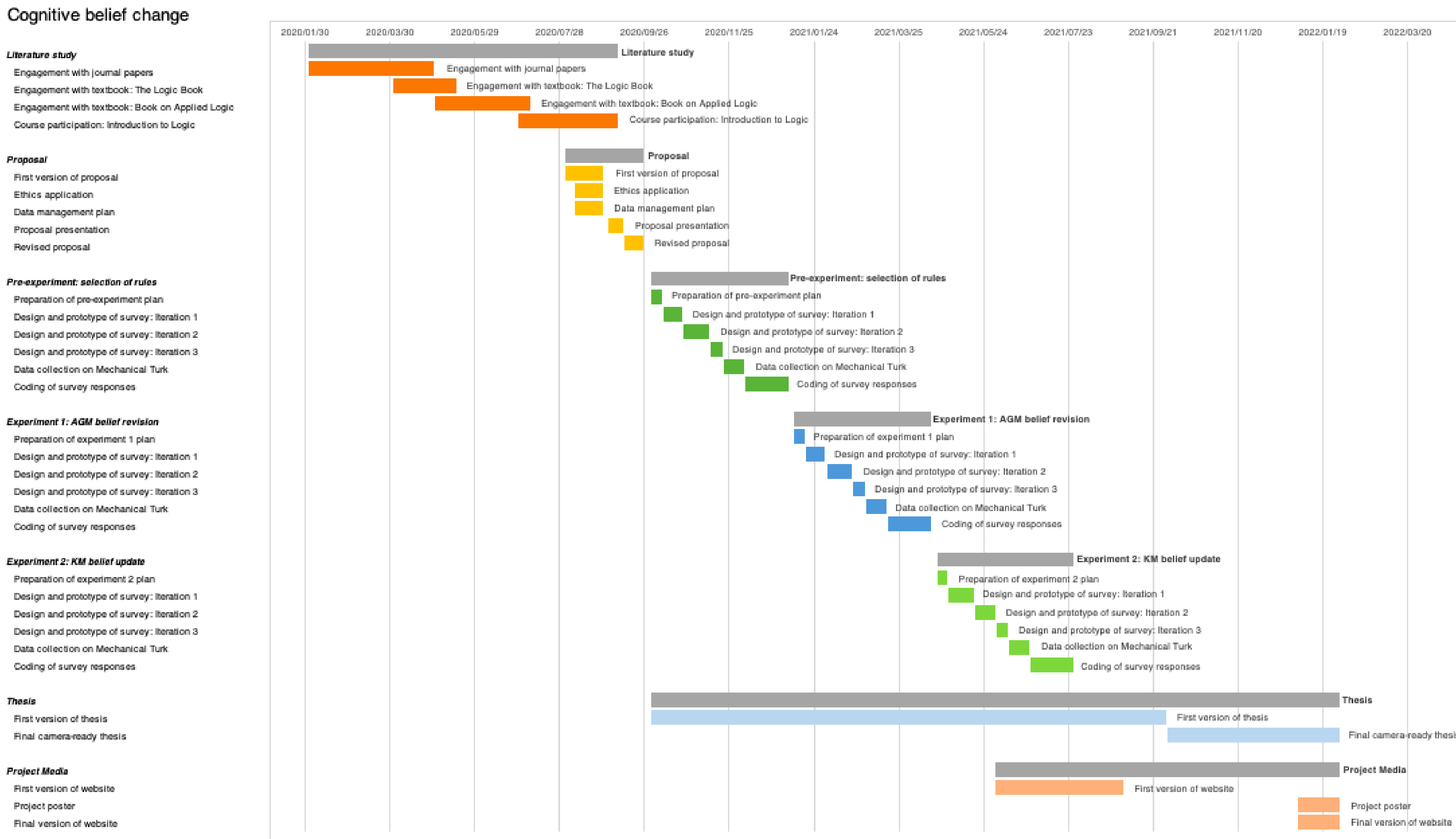
Rule no.	Rule description
1.	If (LP and RP are not significantly associated) or (A is not significantly greater than B, with B close to 0) then (the property under consideration is not corroborated)
2.	If (LP and RP are significantly positively associated) and (A is significantly greater than B, with B close to 0) and (A is not significantly different from C) then (the property under consideration is corroborated)
3*.	If (LP and RP are significantly positively associated) and (A is significantly greater than B, with B close to 0) and (A is significantly different from C) (C is significantly different from B) then (the property under consideration is corroborated)

In the case of decision rule 3*, the inference "RP $\longrightarrow$ LP" contributes also to the association degree but less than the "LP $\longrightarrow$ RP" inference.

B RISKS AND RISK MANAGEMENT STRATEGIES

Risk no.	Risk description	Impact	Probability	Management/Mitigation Strategy
1	The research is of a poor quality	Moderate	Unlikely	Regular engagement with the supervisor, literature and departmental guidelines is necessary to ensure the quality of research is to standard.
2	Logic of experiment questions do not model precisely the logic of the postulates the intend to test	High	Possible	Survey questions must be evaluated by logic experts before the survey goes live. There should be a clear mapping which shows how a selected rule, from the pre-experiment, is transformed to model a particular postulate.
3	Experiment participants are unsatified with data collection procedures	High	Very unlikely	Data collection will only proceed once ethics approval is obtained. Participants will be authenticated through a captcha (bot-check). No personal information is required from participants. Participants will, however, be required to provide their unique Mechanical Turk identifier, their WorkerID, which we will use to check for duplicate responses.
4	Dependence between experiments and high volume of collected data leads to scope creep	High	Likely	The pre-experiment and experiments 1 and 2 involve the design and prototype of a survey as well as the collection and analysis of large volumes of data (e.g. 25-35 pax for pre-experiment and 50 pax for both experiments 1 and 2.) There is also a dependence between the pre-experiment and experiments 1 and between the pre-experiment and experiment 2. In the event that the scope of the work becomes too much, we intend to focus on experiment 2. This means that we will proceed to complete the survey design, data collection and analysis for the pre-experiment and experiment 1. We aim to provide the survey design for experiment 2 as a minimum.
5	A project member falls ill or is incapacitated	Moderate	Likely	As there is only one project member, they must resume work on this project as soon as possible. In the case of short-to-medium-term incapacitation, the project will be postponed by a few months. In the case of long-term incapacitation, a meeting with the supervisor must be held to determine the options for going forward.
6	Access to campus resources will be limited by Covid-19 pandemic for duration of project	Low	Likely	As the project member has access to a good internet connection and has a standard laptop, there is no immediate need to access campus resources. Supervisor meetings continue online and via email. Campus resources are mostly accessible through a VPN.
7	Mechanical Turk platform failure	Moderate	Possible	Alternative platforms for the data collection include virtual focus groups using students from the University of Cape Town and, if the Covid-19 pandemic allows, physical focus groups.

C GANTT CHART



D DELIVERABLES AND MILESTONES

Deliverable/Milestone	Start Date	End Date
Literature study	**2020/02/01**	**2020/09/07**
Engagement with journal papers	2020/02/01	2020/04/30
Engagement with textbook: The Logic Book	2020/04/01	2020/05/16
Engagement with textbook: Book on Applied Logic	2020/05/01	2020/07/07
Course participation: Introduction to Logic	2020/06/29	2020/09/07
Proposal	**2020/08/01**	**2020/09/25**
First version of proposal	2020/08/01	2020/08/28
Ethics application	2020/08/08	2020/08/28
Data management plan	2020/08/08	2020/08/28
Proposal presentation	2020/08/31	2020/09/11
Revised proposal	2020/09/12	2020/09/25
Pre-experiment: selection of rules	**2020/10/01**	**2021/01/06**
Preparation of pre-experiment plan	2020/10/01	2020/10/08
Design and prototype of survey: Iteration 1	2020/10/09	2020/10/23
Design and prototype of survey: Iteration 2	2020/10/24	2020/11/11
Design and prototype of survey: Iteration 3	2020/11/12	2020/11/20
Data collection on Mechanical Turk	2020/11/21	2020/12/05
Coding of survey responses	2020/12/06	2021/01/06
Experiment 1: AGM belief revision	**2021/01/10**	**2021/04/17**
Preparation of pre-experiment plan	2021/01/10	2021/01/17
Design and prototype of survey: Iteration 1	2021/01/18	2021/02/01
Design and prototype of survey: Iteration 2	2021/02/02	2021/02/20
Design and prototype of survey: Iteration 3	2021/02/21	2021/03/01
Data collection on Mechanical Turk	2021/03/02	2021/03/16
Coding of survey responses	2021/03/17	2021/04/17
Experiment 2: KM belief update	**2021/04/17**	**2021/07/27**
Preparation of pre-experiment plan	2021/04/17	2021/04/28
Design and prototype of survey: Iteration 1	2021/04/29	2021/05/17
Design and prototype of survey: Iteration 2	2021/05/18	2021/06/01
Design and prototype of survey: Iteration 3	2021/06/02	2021/06/10
Data collection on Mechanical Turk	2021/06/11	2021/06/25
Coding of survey responses	2021/06/26	2021/07/27
Thesis	**2020/10/01**	**2022/01/31**
First version of thesis	2020/10/01	2021/09/30
Final camera-ready thesis	2021/10/01	2022/01/31
Project Media	**2021/06/01**	**2022/01/31**
First version of website	2021/06/01	2021/08/31
Project poster	2022/01/01	2022/01/31
Final version of website	2022/01/01	2022/01/31