Changing Minds About Climate Change: Belief Revision, Coherence, and Emotion

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Thagard, P., & Findlay, S. (forthcoming). Changing minds about climate change: Belief revision, coherence, and emotion. In E. Olsson (Ed.), *Science in flux: Belief revision in the context of scientific inquiry*. Berlin: Springer.

SCIENTIFIC BELIEF REVISION

Scientists sometimes change their minds. A 2008 survey on the Edge Web site presented more than 100 self-reports of thinkers changing their minds about scientific and methodological issues (http://www.edge.org/q2008/q08_index.html). For example, Stephen Schneider, a Stanford biologist and climatologist, reported how new evidence in the 1970s led him to abandon his previously published belief that human atmospheric emissions would likely have a cooling rather than a warming effect. Instead, he came to believe – what is now widely accepted – that greenhouse gases such as carbon dioxide are contributing to the dramatic trend of global warming. Similarly, Laurence Smith, a UCLA geographer, reported how in 2007 he came to believe that major changes resulting from global warming will come much sooner than he had previously thought. Observations such as the major sea-ice collapse in Canada's Northwest Passage had not been predicted to occur so soon by available computational models, but indicated that climate change is happening much faster than expected. Evidence accumulated over the past three decades is widely taken to show that global warming will have major impacts on human life, and that policy changes such as reducing the production of greenhouse gases are urgently needed. However, such scientific and policy conclusions have received considerable resistance, for example from former American president George W. Bush and Canadian Prime Minister Stephen Harper.

A philosophical theory of belief revision should apply to the issue of global warming by explaining how most scientists have come to accept the following conclusions:

1. The earth is warming.
2. Warming will have devastating impacts on human society.
3. Greenhouse gas emissions are the main causes of warming.
4. Reduction in emissions is the best way to reduce the negative impacts of climate change.

In addition, the theory should provide insight not only into how scientists have come to adopt these beliefs, but also into why a few scientists and a larger number of leaders in business and politics have failed to adopt them.

We will show that belief revision about global warming can be modeled by a theory of explanatory coherence that has previously been applied to many cases of scientific belief change, including the major scientific revolutions (Thagard 1992). We will present a computer simulation of how current evidence supports acceptance of important conclusions about global warming on the basis of explanatory coherence. In addition, we will explain resistance to these conclusions using a computational model of emotional coherence, which shows how political and economic goals can bias the evaluation of evidence and produce irrational rejection of claims about global warming.

Theory evaluation in philosophy, as in science, is comparative, and we will argue that explanatory coherence gives a better account of belief revision than major alternatives. The main competitors are Bayesian theories based on probability theory and logicist theories that use formal logic to characterize the expansion and contraction of belief sets. We will argue that the theory of explanatory coherence is superior to these approaches on a number of major dimensions. Coherence theory provides a detailed account of the rational adoption of claims about climate change, and can also explain irrational resistance to these claims. Moreover, we will show that it is superior to alternatives with respect to computational complexity. This paper reviews the controversy about climate change, shows how explanatory coherence can model the acceptance of important hypotheses, and how emotional coherence can model resistance to belief revision. Finally, we will contrast the coherence account with Bayesian and logicist ones.

CLIMATE CHANGE

The modern history of beliefs about climate change began in 1896, when the Swedish scientist Svante Arrhenius discussed quantitatively the warming potential of carbon dioxide in the atmosphere (Arrhenius 1896, Weart 2003; see also http://www.aip.org/history/climate/index.html). The qualitative idea behind his calculations, now called the greenhouse effect, had been proposed by Joseph Fourier in 1824: the atmosphere lets through the light rays of the Sun but retains the heat from the ground. Arrhenius calculated that if carbon dioxide emissions doubled from their 1896 levels, the planet could face warming of 5-6°C. But such warming was thought to be far off and even beneficial.

In the 1960s, after Charles Keeling found that carbon dioxide levels in the atmosphere were rising annually, Syukuro Manabe and Richard Wetherland calculated that doubling the carbon dioxide in the atmosphere would raise global temperatures a couple of degrees. By 1977, scientific opinion was coming to accept global warming as the primary climate risk for the next century. Unusual weather patterns and devastating droughts in the 1970s and 1980s set the stage for Congressional testimony by James Hansen, head of the NASA Goddard Institute for Space Studies. He warned that storms, floods, and fatal heat waves would result from the long-term warming trend that humans were causing. In 1988, the Intergovernmental Panel on Climate Change (IPCC) was established and began to produce a series of influential reports (http://www.ipcc.ch/). They concluded on the basis of substantial evidence that humans are causing a greenhouse effect warming, and that serious warming is likely in the coming century. In 2006, former Congressman and presidential candidate Al Gore produced the influential documentary *An Inconvenient Truth*. This film, Gore's accompanying book, and the 2007 IPCC report helped solidify the view that major political action is needed to deal with the climate crisis (Gore 2006, IPCC 2007).

Nevertheless, there remains substantial resistance to the IPCC's conclusions, in three major forms. Some scientists claim that observed warming can be explained by natural fluctuations in energy output by the Sun, the Earth's orbital pattern, and natural aerosols from volcanoes. Others are skeptical that human-emitted carbon dioxide can actually enhance the greenhouse effect. However, the most popular opposition today accepts most of the scientific claims but contends that there is no imminent crisis and necessity of costly actions.

Corporations and special interest groups fund research skeptical of a human-caused global warming crisis. Such works usually appear in non-scientific publications such as the *Wall Street Journal*, often with the financial backing of the petroleum or automotive industries and links to political conservatism. Corporations such as

ExxonMobil spend millions of dollars funding right-wing think tanks and supporting skeptical scientists. For example, the Competitive Enterprise Institute (CEI) is a libertarian think tank that received $2.2 million between 1998 and 2006 from ExxonMobil. CEI sponsors the website globalwarming.org which proclaims that policies being proposed to address global warming are not justified by current science and are a dangerous threat to freedom and prosperity.

The administration of U.S. President George W. Bush has been highly influenced by the oil and energy industries consisting of corporations like ExxonMobil. The energy industry gave $48 million to Bush's 2000 campaign to become President, and has contributed $58 million in donations since then. Critics of the global warming crisis claim that there is a great deal of uncertainty associated with the findings of the IPCC: humans may not be the cause of recent warming. Moreover, government should play a very small role in any emission regulation, as property rights and the free market will foster environmental responsibility. The power of technology will naturally provide solutions to global warming, and any emission cuts would be harmful to the economy of the United States, which is not obligated to lead any fight against global warming. Values that serve as the backbone to these beliefs include: small government, individual liberty and property rights, global equality, technology, and economic stability.

In contrast, global warming activists such as Al Gore believe that scientific predictions of global warming are sound and that the planet faces an undeniable crisis. Evidence shows that humans are the cause of warming, and the world's major governments must play a crucial leadership role in the changes necessary to save the planet. Some individuals have been convinced by a combination of evidence and moral motivations to switch views from the skeptics' to the environmentalists' camp. For example, the Australian global warming activist Tim Flannery was once skeptical of the case scientists had made for action against global warming. Influenced by evidence collected in the form of the ice cap record, he gradually revised his beliefs to become a prominent proponent of drastic actions to fight global warming (Flannery 2006). Gore himself had to reject his childhood belief that the Earth is so vast and nature so powerful that nothing we do can have any major or lasting effect on the normal functioning of its natural systems. From the other direction, skeptics such as Bjørn Lomborg (2007) argue against the need for strong political actions to restrict carbon dioxide emissions. Let us now analyze the debate about global warming.

COHERENCE AND REVISION

The structure of the inferences that the Earth is warming because of production of greenhouse gases can be analyzed using the theory of explanatory coherence and the computer model ECHO. The theory and model have already been applied to a great many examples of inference in science, law, and everyday life (see Thagard, 1989, 1992, 2000, and other references). The theory of explanatory coherence consists of the following principles:

Principle 1. Symmetry. Explanatory coherence is a symmetric relation, unlike, say, conditional probability. That is, two propositions *p* and *q* cohere with each other equally.

Principle 2. Explanation. (a) A hypothesis coheres with what it explains, which can either be evidence or another hypothesis; (b) hypotheses that together explain some other proposition cohere with each other; and (c) the more hypotheses it takes to explain something, the lower the degree of coherence.

Principle 3. Analogy. Similar hypotheses that explain similar pieces of evidence cohere.

Principle 4. Data priority. Propositions that describe the results of observations have a degree of acceptability on their own.

Principle 5. Contradiction. Contradictory propositions are incoherent with each other.

Principle 6. Competition. If *P* and *Q* both explain a proposition, and if *P* and *Q* are not explanatorily connected, then *P* and *Q* are incoherent with each other. (*P* and *Q* are explanatorily connected if one explains the other or if together they explain something.)

Principle 7. Acceptance. The acceptability of a proposition in a system of propositions depends on its coherence with them.

These principles do not fully specify how to determine coherence-based acceptance, but algorithms are available that can compute acceptance and rejection of propositions on the basis of coherence relations. The most psychologically natural algorithms use artificial neural networks that represent propositions by artificial neurons or *units* and represent coherence and incoherence relations by excitatory and inhibitory links between the units that represent the propositions. Acceptance or rejection of a proposition is represented by the degree of activation of the unit. The program ECHO spreads activation among all units in a network until some units are activated and others are inactivated, in a way that maximizes the coherence of all the propositions represented by the units. I will not present the technical details here, as they are available elsewhere

(Thagard, 1992, 2000). Several different algorithms for computing coherence are analyzed in Thagard and Verbeurgt (1998).

The problem of scientific belief revision concerns how to deal with situations where new evidence or hypotheses generate the need to consider rejecting beliefs that have previously been accepted. According to the theory of explanatory coherence, belief revision should and often does proceed by evaluating all the relevant hypotheses with respect to all the evidence. A scientific data base consists primarily of a set of propositions describing evidence and hypotheses that explain them. There are coherence relations between pairs of propositions in accord with principle 1: when a hypothesis explains a piece of evidence, they cohere. There are also incoherence relations between pairs in accord with principles 5 and 6. When a new proposition comes along, representing either newly discovered evidence or a newly generated explanatory hypothesis, then this proposition is added to the overall set, along with positive and negative constraints based on the relations of coherence and incoherence that the new proposition has with the old ones. Then an assessment of coherence is performed in accord with principle 7, with the results telling you what to accept and what to reject. Belief revision takes place when a new proposition has sufficient coherence with the entire set of propositions that it becomes accepted and some proposition previously accepted becomes rejected.

Because a variety of algorithms are available for computing coherence, belief revision can be modeled in a highly effective and computationally efficient manner, involving substantial numbers of propositions. For example, Nowak and Thagard (1992a) simulated the acceptance of Copernicus' theory of the solar system and the rejection of Ptolemy's, with a total belief set of over 100 propositions. The LISP code for ECHO and various simulations is available on the Web at: http://cogsci.uwaterloo.ca/Index.html. This site also makes available a partial JAVA version of ECHO.

Explanatory coherence is not intended to be a logically complete theory of belief revision, because it does not take into account a full range of operators such as conjunction and disjunction. Most emphatically, when a new proposition is added to a belief system, no attempt is made to add all its logical consequences, an infinitely large set beyond the power of any human or computer. Nevertheless, explanatory coherence gives a good account of what Gärdenfors (1988, 1992) describes as the three main kinds of belief change: expansion, revision, and contraction. Expansion takes place when a new proposition is introduced into a belief system, becoming accepted if and only if doing so maximizes coherence. Revision occurs when a new proposition is introduced into a belief system and leads other previously accepted propositions to be rejected because maximizing coherence requires accepting the new proposition and rejecting one or more old ones. Contraction occurs when some proposition becomes rejected because it no longer helps to maximize coherence. Simulations of these processes are described in the next section.

We do not use "maximize coherence" as a vague metaphor like most coherentist epistemologists, but rather as a computationally precise notion whose details are available elsewhere (e.g. Thagard 1992, 2000). Logicist theories view belief revision as the result of expansion followed by contraction, but explanatory coherence computes expansion and contraction as happening at the same time in parallel.

Scientific belief revision comes in various degrees. A new proposition describing recently collected evidence may become accepted easily unless it does not fit well with accepted views. Such acceptance would be a simple case of expansion. However, if the new evidence is not easily explained by existing hypotheses, scientists may generate a new hypothesis to explain it. If the new hypothesis conflicts with existing hypotheses, either because it contradicts them or competes as an alternative hypothesis for other evidence, then major belief revision is required. Such revision may lead to theory change, in which one set of hypotheses is replaced by another set, as happens in scientific revolutions. The development of new ideas about climate change has not been revolutionary, since no major scientific theories have had to be rejected. But let us now look in more detail at how explanatory coherence can model the acceptance of global warming.

SIMULATING BELIEF REVISION ABOUT CLIMATE CHANGE

To show how explanatory coherence can be used to simulate belief revision, we begin with a series of simple examples shown in figure 1. Simulation A shows the simplest possible case where there is just one piece of evidence and one hypothesis that explains it. In accord with principle 4 of explanatory coherence, evidence propositions have a degree of acceptability on their own, which in the program ECHO is implemented by their being a positive constraint between each of them and a special unit EVIDENCE that is always accepted. Hence in simulation A, the acceptance of E1 leads to the acceptance of H1 as well.

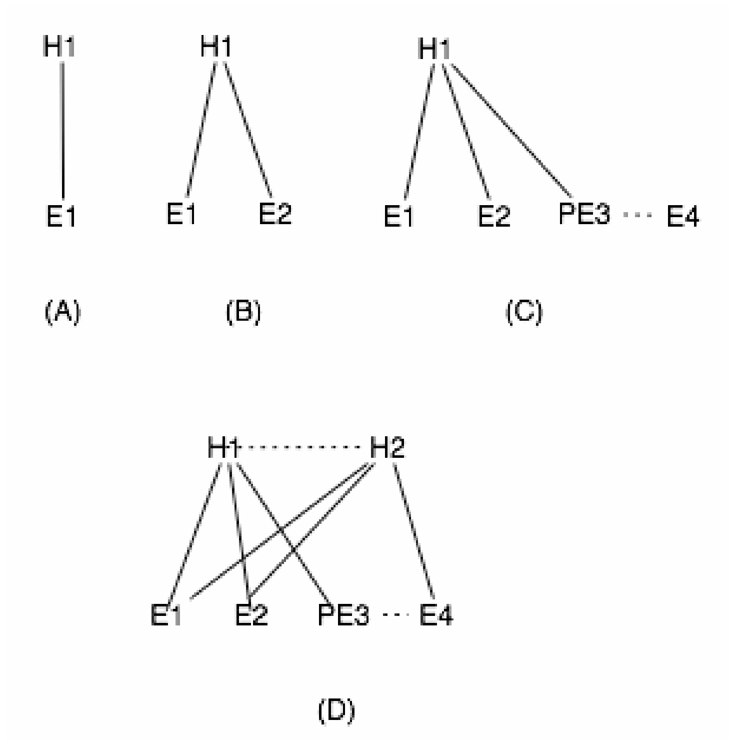

Figure 1. The straight lines indicate coherence relations (positive constraints) established because a hypothesis explains a piece of evidence. The dotted lines indicate incoherence relations (negative constraints). Coherence relations between an evidence unit and E1, E2, and E4 are not shown.

Simulation B depicts a simple case of expansion beyond simulation A, in which a new piece of evidence is added and accepted. The situation gets more interesting in simulation C, where the hypothesis explains a predicted evidence proposition PE3, which however contradicts the actually observed evidence E4. A Popperian would say that H1 has now been refuted and therefore should be rejected, but one failed prediction rarely leads to the rejection of a theory, for good reasons: perhaps the experiment that produced E4 was flawed, or there were other intervening factors that made the prediction of PE3 incorrect. Hence ECHO retains H1 while accepting E4 and rejecting PE3. Refutation of H1 requires the availability of an alternative hypothesis, as shown in simulation D. Here the addition of H2 provides an alternative explanation of the evidence, leading to its acceptance by virtue of its explanation of E4 as well as E1 and E2. This is a classic case of inference to the best explanation, where belief revision is accomplished through simultaneous expansion (the addition of H2) and retraction (the deletion of H1).

Belief revision about climate change can naturally be understood as a case of inference to the best explanation based on explanatory coherence. Figure 2 displays a drastically simplified simulation of the conflict between proponents of the view that climate change is caused by human activities and their critics. The hypothesis that is most important because it has major policy implications is that humans cause global warming. This hypothesis explains many observed phenomena, but figure 2 shows only two crucial generalizations from evidence: global temperatures are rising and the recent rise has been rapid. The main current alternative explanation is that rising temperatures are just the result of natural fluctuations in temperature that have frequently occurred throughout the history of the Earth. Figure 2 also shows the favored explanation of how humans have caused global warming, through the greenhouse effect in which gases such as carbon dioxide and methane prevent energy radiation into space. Human industrial activity has produced huge increases in the amounts of such gases in the atmosphere over the past few hundred years.

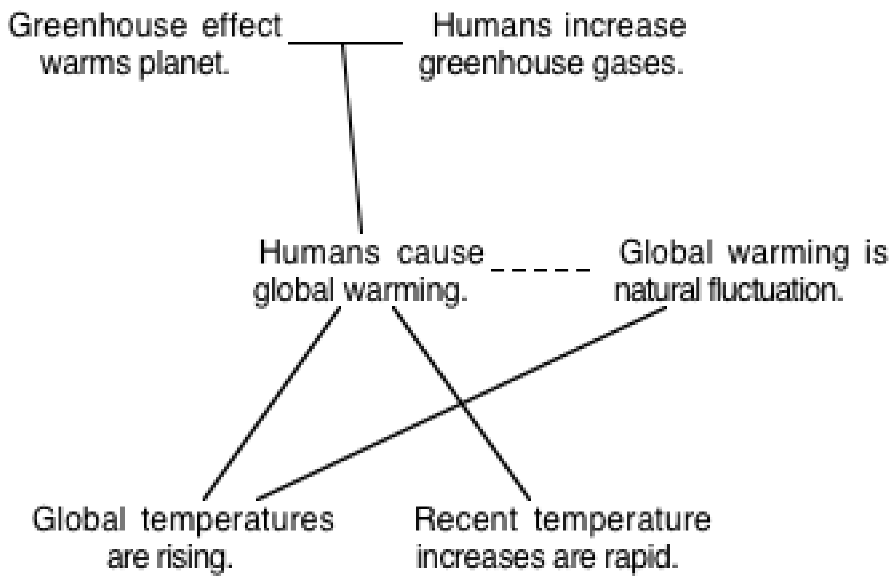

Figure 2. Highly simplified view of part of the controversy over climate change, with straight lines indicating coherence relations and dotted lines indicating incoherence ones.

Figure 2 shows only a small part of the explanatory structure of the controversy over climate change, and our full analysis is presented in figure 3, with more pieces of evidence and a fuller range of hypotheses. The input to our simulation using the program ECHO can be found in the appendix. The key competing hypotheses are GH3, that global warming is caused by humans, and NH4, global warming is a natural fluctuation. As you would expect from the greater connectivity of hypothesis GH3 with the evidence, it wins out over NH4, which is rejected. The inputs to ECHO given in the appendix and the constraint structures shown in figure 3 capture much of the logical structure of the current debate over climate change. In accord with the current scientific consensus, ECHO accepts the basic claim that climate change is being caused by human activities that increase greenhouse gases.

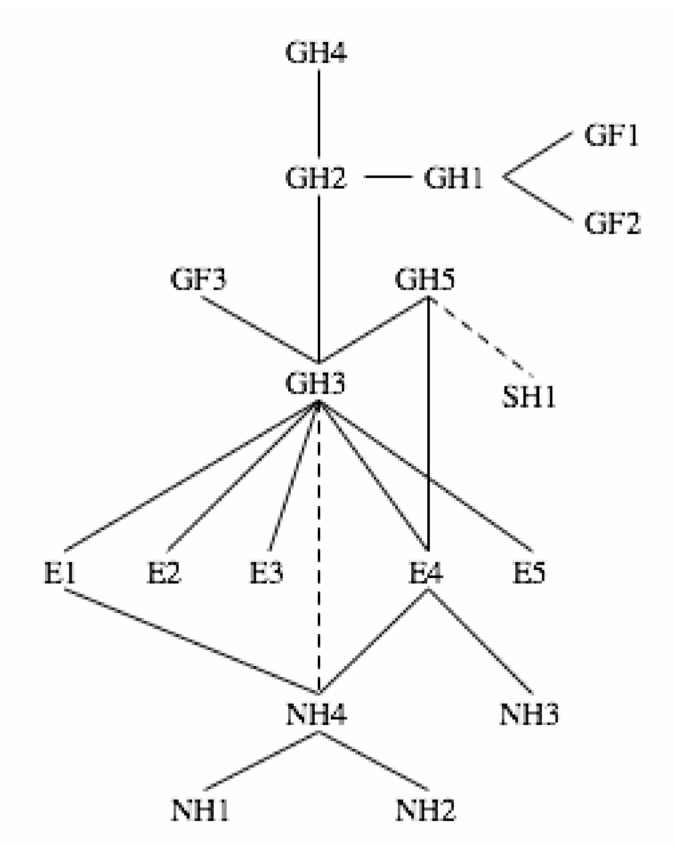

Figure 3. More detailed analysis of the controversy over climate change, with straight lines indicating coherence relations and dotted lines indicating incoherence ones. See the appendix for full description of the propositions and their relations.

ECHO can model belief revision in the previously skeptical by simulating what happens if only some of the evidence and explanations shown in figure 3 are available. For example, we have run a simulation that deletes most of the evidence for GH3 as well as the facts supporting GH1. In this case, ECHO finds NH1 more acceptable than GH3, rejecting the claim that humans are responsible for global warming. Adding back in the deleted evidence and the explanations of it by GH3 and the other global warming hypotheses produces a simulation of belief revision of the sort that would occur if a critic of human warming was presented with more and more evidence. The result eventually is a kind of gestalt switch, a tipping point in which the overall relations of explanatory coherence produce adoption of new views and rejection of old ones. Thus explanatory coherence can explain the move toward general acceptance of views currently dominant in the scientific community about climate change.

What explanatory coherence can *not* explain is why some political and business leaders remain highly skeptical about global warming caused by human activities and the need to take drastic measures to curtail it. To understand their resistance, we need to expand the explanatory coherence model by taking into account emotional attitudes.

SIMULATING RESISTANCE TO BELIEF REVISION

Scientific theory choice has the same logical structure as juror decisions in criminal cases. Just as scientists need to decide whether a proposed theory is the best explanation of the experimental evidence, juries need to decide whether the prosecutor's claim that the accused committed a crime is the best explanation of the criminal evidence. Ideally, juries are supposed to take into account all the available evidence and consider alternatives explanations of it. Often they do, but juries are like all people including scientists in having emotional biases that can lead to different verdicts than the one that provides the best explanation of the evidence. Thagard (2003, 2006, ch. 8) analyzed the decision of the jury in the O. J. Simpson case: explanatory coherence with respect to the available evidence should have led to the conclusion that Simpson was guilty, but the jury nevertheless acquitted them. However, jurors' decision to acquit was simulated using the program HOTCO that simulates "hot coherence", which includes the contribution of emotional values to belief revision. Emotional values are a perfectly legitimate part of decision making as psychological indicators of the costs and benefits of expected outcomes. In the language of decision theory, deliberation requires utilities as well as probabilities. But normatively belief revision should depend on evidence, not utilities or emotional values.

We have already mentioned the motivations that lead some business and political leaders to be skeptical about claims about global warming. If climate change is a serious problem caused by human production of greenhouse gases, then measures need to be taken to curtail such production. Particularly affected by such measures will be oil companies, so it is not surprising that the research aimed at defusing alarm about global warming has been heavily supported by them. Moreover, some of the most powerful opposition to the Kyoto Protocol and other attempts to deal with global warming have come from politicians closely allied with the oil industry, such as American president George W. Bush and Canadian Prime Minister Stephen Harper. In 2002, when he was leader of the Alberta-based Canadian Alliance which later merged with the Conservative Party that he now leads, Harper wrote:

> We're gearing up for the biggest struggle our party has faced since you entrusted me with the leadership. I'm talking about the "battle of Kyoto" — our campaign to block the job-killing, economy-destroying Kyoto Accord.
>
> It would take more than one letter to explain what's wrong with Kyoto, but here are a few facts about this so-called "Accord":
>
> — It's based on tentative and contradictory scientific evidence about climate trends.

— It focuses on carbon dioxide, which is essential to life, rather than upon pollutants.

— Canada is the only country in the world required to make significant cuts in emissions. Third World countries are exempt, the Europeans get credit for shutting down inefficient Soviet-era industries, and no country in the Western hemisphere except Canada is signing.

— Implementing Kyoto will cripple the oil and gas industry, which is essential to the economies of Newfoundland, Nova Scotia, Saskatchewan, Alberta and British Columbia.

— As the effects trickle through other industries, workers and consumers everywhere in Canada will lose. THERE ARE NO CANADIAN WINNERS UNDER THE KYOTO ACCORD.

— The only winners will be countries such as Russia, India, and China, from which Canada will have to buy "emissions credits." Kyoto is essentially a socialist scheme to suck money out of wealth-producing nations. (http://www.thestar.com/article/176382)

Prime Minister Harper has since moderated his position on global warming, as has George W. Bush, but both have been slow to implement any practical changes.

We conjecture that at the root of opposition to claims about global warming are the following concerns. Dealing with climate change would require government intervention to restrict oil usage, which is doubly bad for a conservative politician with a preference for free market solutions and a long history of association with oil producing companies. Figure 4 expands figure 2 to include the strong emotional values of avoiding limiting oil use and production and avoiding government intervention in the economy. When the explanatory coherence relations shown in the appendix and figure 3 are supplanted with these values, belief revision is retarded, so that more evidence is required to shift from rejection to acceptance of the hypothesis that global warming is being caused by human activities.

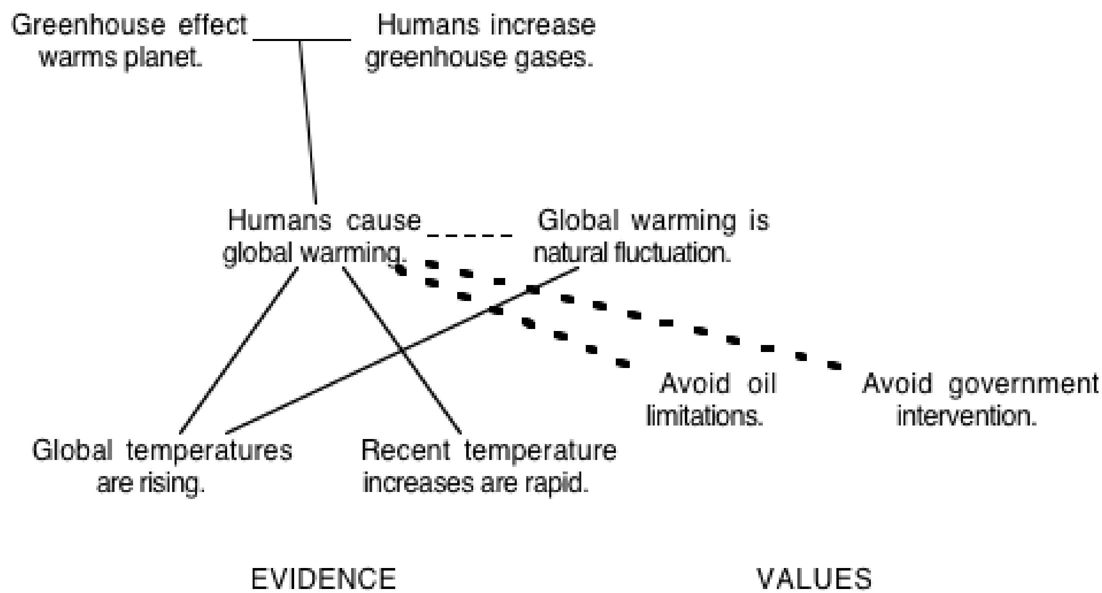

Figure 4. View of the controversy over climate change including emotional constraints as well as explanatory ones. As in previous figures, the solid lines indicate positive constraints based on explanatory relations and the thin dotted line indicates a negative constraint based on incompatibility. The thick dotted lines indicate negative emotional constraints.

In the ECHO simulation of just the hypotheses and evidence shown in figure 4, the obvious result is the acceptance of the hypothesis that global warming is caused by humans, implying that political action can and should be taken against it. But we have also used the extended program HOTCO to yield a different result. If, as figure 4 suggests, the hypothesis that humans caused global warming is taken to conflict with the values of avoiding oil limitations and government intervention, then the simulation results in the rejection of human causes for global warming and acceptance of the alternative hypothesis of natural fluctuation. Of, course, the actual psychological process of motivated inference in this case is much more complex than figure 4 portrays, leading skeptics to challenge evidence and explanations as well as hypotheses. But figure 4 and the HOTCO simulation of it show how values can interfere with belief revision by undermining hypotheses that are better supported by the evidence. Hence a psychologically natural extension to ECHO can explain resistance to belief revision.

ALTERNATIVE THEORIES OF BELIEF REVISION

Explanatory coherence is not the only available account of scientific belief revision, which include at least the following: Popper's conjectures and refutations, Hempel's confirmation theory, Kuhn's paradigm shifts, Lakatos's methodology of research programs, and social constructionist claims that scientists revise their beliefs only to increase their own power. These are all much vaguer than the theory of explanatory coherence and its computational implementation in ECHO. Among formally exact characterization of belief revision, the two most powerful approaches are Bayesian ones that explain belief change using probability theory, and logicist ones that use ideas about logical consequence in deductive systems.

Detailed comparisons between explanatory coherence and Bayesian accounts of belief revision have been presented elsewhere (Thagard 2000, ch. 8; Eliasmith and Thagard 1997; Thagard, 2004; Thagard and Litt, 2008). It should be feasible to produce a Bayesian computer simulation of the full climate change case shown in figure 3 and the appendix. A simulator such as JavaBayes (http://www.cs.cmu.edu/~javabayes/Home/) could be used to produce a Bayesian alternative to our ECHO simulator, as was done for a rich legal example in Thagard (2004). But doing so would require a very large number of conditional probabilities whose interpretation and provenance are highly problematic. In the simplest case where you have two hypotheses, H1 and H2, explaining a piece of evidence E1, JavaBayes would require specification of 8 conditional probabilities, such as P(E1/H1 & not-H2). For example, the simplified model shown in figure 2 would require specification of P(global temperatures are rising/humans cause global warming & global warming is not a natural fluctuation) as well as 7 other conditional probabilities. In general, the nodes in an explanatory coherence network can be translated into nodes in a Bayesian network with the links translated into directional arrows. The price to be paid is that for each node that has *n* arrows coming into it, it is necessary to specify 2^{n+1} conditional probabilities. In our ECHO simulation specified in the appendix, a highly connected node such as E4 which has 3 global warming hypotheses and 4 alternative hypotheses explaining it would require specification of 2^8 = 256 conditional probabilities, none of which can be estimated from available data. To produce a JavaBayes alternative to our full ECHO simulation, thousands of conditional probabilities would simply have to be made up. Bayesian models are very useful for cases where there are large amounts of statistical data, such as sensory processing in humans and robots; but they add nothing to understanding of cases of belief revision such as climate change where probabilities are unknown.

Writers such as Olsson (2005) have criticized coherence theories for not being compatible with probability theory, but probability theory just seems irrelevant in qualitative cases of theory change. The comprehensive report of the Intergovernmental Panel on Climate Change sensibly relies on qualitative characterizations such as “extremely likely” and “very high confidence”. Probability theory should be used whenever appropriate for statistics-based inference, but applying it to qualitative cases of causal reasoning such as climate changes obscures more than it illuminates.

The other major formal approach to belief revision uses techniques of formal logic to characterize the expansion and contraction of belief sets (see e.g. Gärdenfors 1988, 1972; Tennant 1994, 2006). We will not attempt a full discussion, but the explanatory coherence approach seems to us superior to logicist approaches in several respects that we will briefly describe.

First, the explanatory coherence approach is both broad and deep, having been applied in detail to many important cases of scientific belief revision. In this paper, we have shown its applicability to a belief revision problem of great contemporary interest, climate change. To our knowledge, logicist approaches to belief revision have not served to model any historical or contemporary cases of belief change. Explanatory coherence has less generality than logicist approaches, because it does not attempt algorithms for computing revision and contraction functions for an *arbitrary* belief system. Rather, it focuses on revision in systems of hypotheses and evidence, which suffices for the most important kinds of belief change in science, criminal cases, and everyday life.

Second, the explanatory coherence approach has philosophical advantages over logicist approaches. It does not assume that that changes in belief systems should be *minimal*, retaining as much as possible from our old beliefs. The principle of minimal change has often been advocated (e.g. by Gärdenfors, Tennant, Harman, and Quine) but rarely defended, and Rott (2000) has argued that it is not even appropriate for logicist approaches. Aiming for minimal change in belief systems seems to us no more justifiable than aiming for minimal change in political and social systems. Just as political conservatism should not serve to block needed social changes, so epistemic minimalism should not get in the way of needed belief changes. Explanatory coherence theory shows how to make just the changes that are needed to maximize the coherence of evidence and hypotheses. As long as they are productive, both epistemic and social innovations are to be valued. Just as aiming for minimal change in production of greenhouse gases may prevent dealing adequately with forthcoming climate crises, so aiming for minimal change in belief revision may prevent arriving at maximally coherent and arguably true theories. Coherence approaches have often been chided for neglecting the importance of truth as an epistemic goal, but Thagard (2007) argues that applications of explanatory coherence in science do in fact lead to truth when they produce the adoption of theories that are both broad (explaining much evidence) and deep (possessing underlying mechanistic explanations).

Third, explanatory coherence has computational advantages overlogicist approaches that assume that a belief set is logically closed. Then belief sets are infinite, and cannot be computed by any finite machine. The restricted problem of belief contraction in finite beliefs sets has been shown to be NP-complete (Tennant 2003).

Problems in NP are usually taken by computer scientists to present computational difficulties, in that polynomial-time solutions are not available so they are characterized as intractable. It might seem that the coherence approach is in the same awkward boat, as Thagard and Verbeurgt (1998) showed that the coherence problem is NP-hard. However, many hard computational problems become tractable if a problem parameter is fixed or bounded by a fixed value (Gottlob, Scarcello, and Sideri 2002; van Rooij 2008). Van Rooij has shown that coherence problems become fixed-parameter tractable if they have a high ratio of positive to negative constraints. Fortunately, all programmed examples of explanatory coherence have a high positive-negative ratio, as you would expect from the fact that most constraints are generated by explanatory coherence principle 2. In particular, our simulation of the climate change case using the input in the appendix generates 10 negative constraints and 53 positive ones. Hence explanatory coherence in realistic applications appears to be computationally tractable.

Fourth, explanatory coherence has a major psychological advantages over logistic approaches, which are not intended to model how people actually perform belief revision, but rather how belief revision should ideally take place. Explanatory coherence theory has affinities with a whole class of coherence models that have been applied to a wide range of psychological phenomena (Thagard 2000). The psychological plausibility of explanatory coherence over logicist approaches will not be appreciated by those who like their epistemology to take a Platonic or Fregean form, but is a clear advantage for those of us who prefer a naturalistic approach to epistemology. A related psychological advantage is that explanatory coherence meshes with psychological accounts that can explain what people are doing when they irrationally resist belief revision, as we saw in the case of political opposition to theories of climate change.

CONCLUSION

Our brief discussions of Bayesian and logicist accounts of belief revision hardly constitute a refutation of these powerful approaches, but should suffice to indicate how they differ from the explanatory coherence approach. We have shown how explanatory and emotional coherence can illuminate current debates about climate change. We can use it to understand the rational adoption of the hypothesis that global warming is caused by human activities. Moreover, deviations from rational belief revision in the form of emotion-induced rejection of the best explanation of a wide range of evidence can be understood in terms of intrusion of emotional political values into the assessment of the best explanation.

Scientific belief revision is not supposed to be impeded by emotional prejudices, but such impedance is common. The acceptance of Darwin's theory of evolution by natural selection was slowed in the nineteenth century by fears of its threat to established theological theories of the creation of species. Such resistance continues today, as many people – but very few scientists – continue to reject evolutionary theory as incompatible with their religious beliefs and desires. In practical settings, encouraging belief change about Darwin's theories, as about climate change, requires dealing with emotional constraints as well as cognitive ones generated by the available evidence, hypotheses, and explanations. Thus a broadly applicable, computationally feasible, and psychologically insightful account of belief revision such as that provided by the theory of explanatory coherence should be practically useful as well as philosophically informative.

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APPENDIX

Input to the ECHO simulation of the acceptance of the claim that global warming is caused by humans.

Global warming: A simplified model of anthropogenic forcing vs. natural causes.

Evidence:

E1. Average global temperatures have risen significantly since 1880.

E2. The rate of warming is rapidly increasing.

E3. The recent warming is more extreme than any other warming period as far back as the record shows to 1000 AD.

E4. Arctic ice is rapidly melting and glaciers around the world are retreating.

E5. Global temperature shows strong correlation with carbon dioxide levels throughout history.

IPCC/ Gore's facts

GF1. Carbon dioxide, methane gas, and water vapour are greenhouse gasses.

GF2. Greenhouse gasses absorb infrared radiation, some of which is reemitted back to the Earth's surface.

GF3. Carbon dioxide levels in the atmosphere have been increasing since the beginning of the industrial revolution.

IPCC/ Gore's main hypotheses: "Anthropogenic forcing"

GH1. There is a greenhouse effect that warms the planet.

GH2. The greenhouse effect has the potential to be enhanced.

GH3. Global warming is a human caused crisis.

Secondary hypotheses

GH4. Increasing the concentration of greenhouse gasses in the atmosphere directly increases the warming of the Earth.

GH5. Small changes in global temperature have the potential to drastically upset a variety of climate systems through causal interactions.

Opposing hypotheses/ beliefs

NH1. Long term cycling of Earth's orbital parameters, solar activity and volcanism and associated aerosols are natural causes that can warm the globe.

NH2. The impact of natural factors on global temperature dwarfs the enhanced greenhouse effect.

NH3. Climate systems will be affected by natural cycles and fluctuations.

NH4. Global warming is natural and not a concern.

SH1. Small changes in temperature will not have significant negative effects on global climate.

Explanations:

Gore's Explanations:

of the enhanced greenhouse effect and anthropogenic forcing.

explain (GF1, GF2) GH1

explain (GH1, GH4) GH2

explain (GH2, GF3, GH5) GH3

of the evidence:

explain (GH2, GH3) E1

explain (GH2, GH3) E2

explain (GH2, GH3, GH4, GF3) E3

explain (GH2, GH3, GH5) E4

explain (GH2, GH3, GH4, GF3) E5

Natural Explanations:

of a natural cause for global warming:

explain (NH1, NH2) NH4

of the evidence:

explain (NH1, NH2, NH4) E1

explain (NH1, NH2, NH3, NH4) E4

Contradictions:

contradict NH4 GH3

contradict NH2 GH2

contradict GH5 SH1