



Reflections on Framing and Making Decisions in the Face of Uncertainty

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Almost all important decisions...

... involve considerable uncertainty.

At a personal level:

- Where to go to college
- Who to marry
- When and whether to have kids

In a company or other organization:

- Who to hire
- What products to develop

In a nation:

- How best to structure taxes
- How best to deal with social services & health care
- When to go to war
- When to sue for peace

In this talk I will:

- Discuss prescriptive analytical strategies that suggest how people should frame and make decisions in the face of uncertainty.
 - Decision rules
 - o Benefit-cost analysis
 - o Decision analysis
 - o Multi-criteria analysis
 - o Real options
 - Bounding analysis
- Discuss how people *actually* frame and make decisions in the face of uncertainty.
 - Cognitive heuristics
 - Ubiquitous overconfidence
 - o The need to be quantitative
 - o Methods for formal quantitative expert elicitation
 - Problems with the use of scenarios
 - o Two comments about integrated assessment.

As I go through these I will briefly mention of some relevant literatures. 3

Decision Rules

Binary or threshold

Safe/Unsafe; Regulate/Don't regulate; etc.

In the U.S. in addition to chemical risk assessment we have the example of the Clean Air Act which adopts a "rights based" formulation – "choose a level that protects the most sensitive population."

Balancing

Benefit-Cost; Maximize (expected) Net Benefits; etc. In the U.S. many federal water quality rules are *not* rights based. They call for a balance between water quality and control costs.

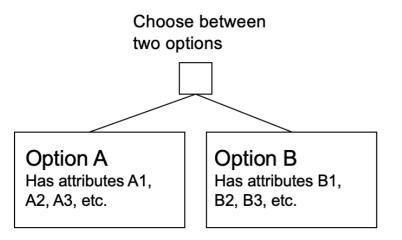
Avoid extremes

Minimize the chance of the worst outcomes, etc.

Most of the classic literature on decision making focuses on maximizing (expected) net benefits.

Benefit-cost analysis

Suppose I have two feasible options in which I could invest to achieve some desired end.



What strategy should I adopt in making my choice?

I could choose the one that is: Most energy efficient The one with the best engineering The one that increases entropy the least The one that wins in a survey of consumer preferences
The one favored by the Environmental Defense Fund
The one favored by the U.S. OMB
Choose the simplest
Choose the cheapest (relative effectiveness)

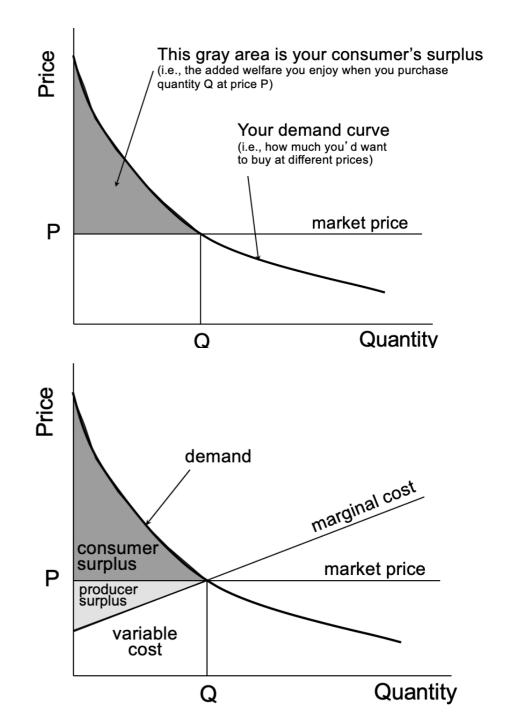
Benefit-cost analysis says choose the one with the highest net benefit:

$$\sum_{j=1}^{N} \mathbf{B}_{j} \sum_{k=1}^{M} \mathbf{C}_{k}$$

That sounds simple...

...but the details of how to perform a B-C analysis can get very complicated.

For example, one standard strategy to estimate benefits is to estimate "consumer surplus."



An example:

Lester B. Lave et al., "Controlling Emissions from Motor Vehicles: A benefitcost analysis of vehicle emission control alternatives," Environmental Science & *Technology*, *24*(8), pp. 1128-1135, August 1990.

Controlling emissions from motor vehicles

A benefit-cost analysis of vehicle emission control alternatives



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Duncan A. Ross William E. Wecker Associates Novato, CA 94945

U.S. ozone levels exceed the National Ambient Air Quality Standard (NAAQS) of 0.12 ppm in virtually every major urban area and in many nonurban areas in the East (1). Hydrocarbon emissions are a primary contributor to the photochemical reactions that produce ozone (2). These emissions from cars and light duty trucks (LDTs) account for approximately 35% of total man-made hydrocarbon emissions (1).

This article reports the results of a benefit-cost analysis of alternative strategies for controlling emissions from hydrocarbon refueling and evaporative emissions from cars and LDTs. Our analysis accounts for interactions

among the different control methods that influence both the costs and benefits of the available strategies. It also examines the role played by variations in temperature conditions and pollution levels across regions and seasons in estimating the costs and benefits. (A detailed report of the analysis is available from the authors.)

We have found that the most economically efficient control of refueling ceeds the capacity of the vehicle's emisand evaporative hydrocarbon emissions from cars and LDTs would result from a mixed strategy that includes fuel volatility controls and controls on service station pumps. The most cost-effective control strategy involves fuel volatility and gasoline pump controls, which can be tailored to each region; the former can be changed with each season. Such flexible controls can be targeted to the specific regions and season where they will do the most good, while avoiding the wasteful cost of controls when and where ozone is not a problem. Vehiclebased controls do not have these advantages

Sources of emissions

In a vehicle's fuel system, gasoline may be heated and vaporized by diurnal ambient temperature deviations (excursions) as well as by the engine and exhaust system after the engine is turned off ("hot soak") or when it is operated under extreme conditions ("running loss") (3). Evaporative emissions occur when the amount of gasoline vapors exsion control system.

Refueling emissions occur primarily when liquid fuel from the gas pump displaces the vapor in the fuel tank. These vapors escape through the vehicle fuel tank fillpipe. A secondary source of refueling emissions is the escape of vapor from the service station's underground fuel tank. When liquid fuel is pumped from the underground tank, it is replaced by outside air. The increased concentration of air reduces the partial pressure of the gasoline vapor in the tank. More gasoline evaporates to return the liquid-vapor system in the underground tank to equilibrium. The

1128 Environ. Sci. Technol., Vol. 24, No. 8, 1990

0013-936X/90/0924-1128\$02.50/0 © 1990 American Chemical Society

While there is no reason...

...that it *can't* incorporate uncertainty, most B-C analysis has included little or no characterization or analysis of uncertainty.

The best critical assessment I know of B-C analysis was written by Lester, who was one of the method's leading practitioners.

Lester B. Lave, "Benefit-Cost Analysis: Do the benefits exceed the costs?" from *Risks Costs and Lives Saved: Getting better results from regulation,* Robert Hahn (ed.), Oxford, 1996, pp. 104-134. RISKS, COSTS, AND LIVES SAVED Getting Better Results from Regulation

Edited by Robert W. Hahn

Oxford University Press New York and Oxford The AEI Press Washington, D.C. Chapter 6

BENEFIT-COST ANALYSIS Do the Benefits Exceed the Costs?

Lester B. Lave

OVERVIEW

Many economists see benefit-cost analysis as a rational, analytic tool that is neutral in its values. They assert that benefit-cost analysis is essential for complicated social issues. Our eloquence about the value of this framework has enabled us to convince Congress to write benefitcost analysis into various laws and convinced President Reagan to embrace it. President Clinton has reaffirmed the Reagan order with minor changes.

Despite the objections of "unenlightened" environmentalists, political scientists, ethicists, and others, we economists believe that social desistons should be subject to benefit-cost analysis and that the analysis identifies, at least approximately, the social optimum. During the beginning of the Reagan administration, economists at the Office of Management and Budget terrorized those who could not produce analyses with positive net benefits (Clark, Kosters, and Miller 1980).

But from the outset environmental, labor, and other "public interest" groups objected to cost-benefit tests of regulations. Their viewpoint was partly emotional, but they had some valid points, including the contention that while costs can be measured fairly accurately, benefits are often difficult to quantify, particularly in dollar terms.

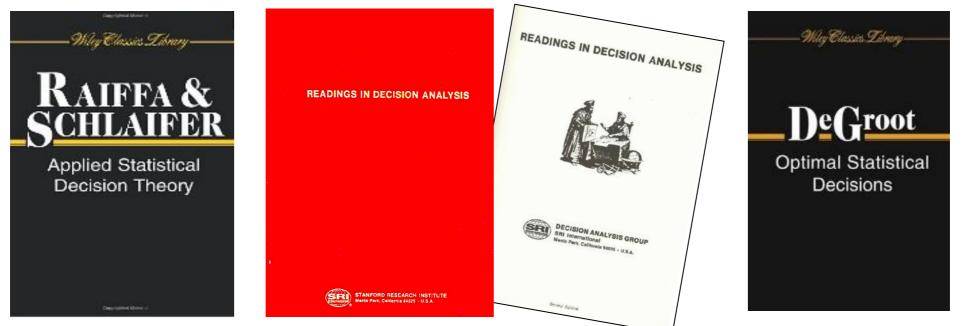
The problems go far beyond a focus on costs. Benefit-cost advocates rely, often unwittingly, on a Pandora's box of utilitarian ethical beliefs as well as assumptions about the quality of current methods. If they examined those assumptions carefully, economists would reject

104

The fact that there is uncertainty...

...should not by itself be grounds for inaction. Indeed, the consequences of doing nothing often carry comparable or larger uncertainty.

There is a large literature on analytical strategies for framing and making decisions in the face of uncertainty.



The methods they developed are now termed Decision Analysis

Identify a set of choices with outcomes *x*.

For each choice, use all available current knowledge *c* to assess the probability that each of the outcomes *x* will occur. That is, assess p(x|c).

Decide how you value each of those outcomes. That is, assess your "utility function" U(x)

Make the choice that will maximize your expected utility. That is: $Max[\int p(x|c) U(x) dx]$

Rather than deal with continuous functions DA typically discretizes everything.

Decision Analysis

The convention in DA is

that a square is used to

choice

choice 2

Shoice,

P(X) C2)

P (talca)

5(X262)

indicate a choice or

"choice node"

available to the

decision maker

The convention in DA is that these values show the probability that the various outcomes x will occur given that choice c has been made

outcome x_1 which has utility $U(x_1)$

outcome x_2 which has utility $U(x_2)$

outcome x_n which has utility $U(x_n)$

While I will not take time to talk about them, decision analysis is based on a set of axioms that guarantee that the choice will maximize your expected utility.

The convention in DA is that a circle is used to indicate a "chance node" which indicates the range of outcomes that could result if the specific choice is made

To do a decision analysis one needs to know the decision maker's preferences

Many economists operate with the assumption that we all have well articulated utility functions in our heads, so the issue is just how best to observe U(x).

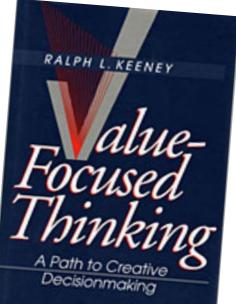
Psychologists and decision analysts believe people often need help in figuring our their preferences.

Fischhoff (1991) lays out this continuum of possibilities.

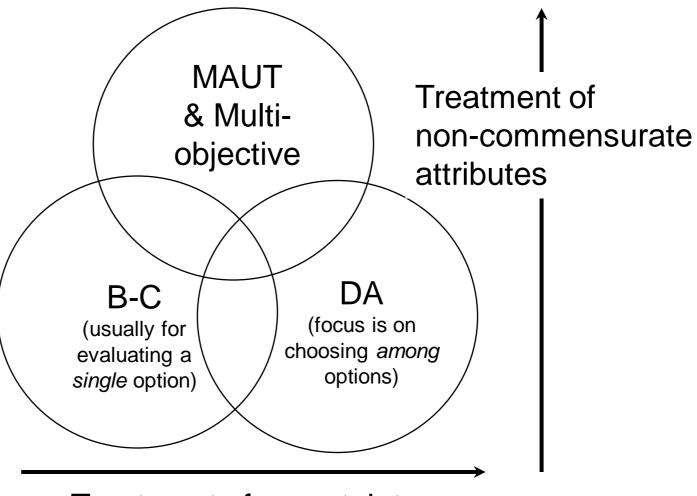
People have stable but incoherent perspectives (causing divergent responses to formally equivalent forms)

People know what they want about all possible questions (to some degree of precision)

People lack articulated values on specific topics (but have pertinent basic values)



A simple taxonomy of analytical methods



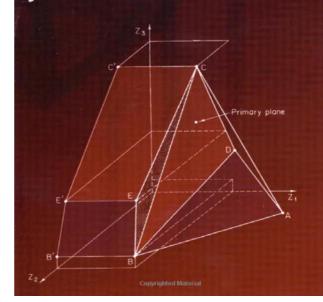
Treatment of uncertainty

Dealing with multiple objectives

<u>Decisions</u> with Multiple <u>Objectives</u>

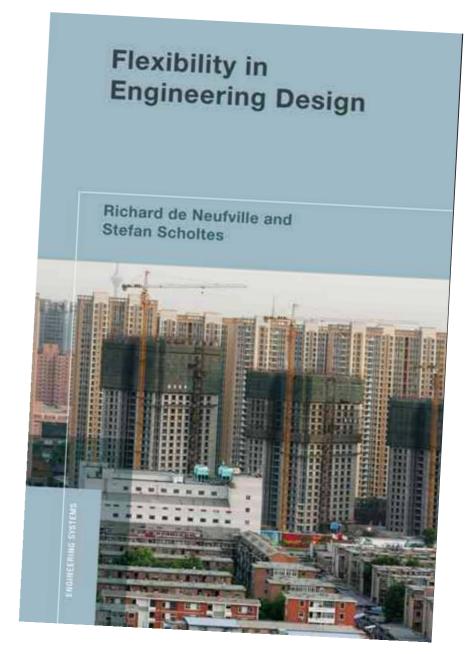
Preferences and Value Tradeoffs

Ralph L. Keeney Howard Raiffa Multiobjective Programming and Planning JARED L. COHON



One other strategy

The use of real options as an alternative to net present value can and better address uncertain future contingencies.



Bounding Analysis

While there has been no mention of this approache in the talks we have heard, sometimes the best we can (or should) do, is to use order of magnitude methods to set bounds.

The Neglected Art of Bounding Analysis Are the answers provided by today's detailed risk analyses reasonable? Is April 1, 2001 / Volume 35, Issue 7 / pp 162 A — 164 A. Are the answers provided by today's detailed risk analyses reasonable? Is valued insight being overlooked as a result of analysts' focus on the intimate details of environmental problems? If so what can we do about this? valued insight being overlooked as a result of analysts focus on the in details of environmental problems? If so, what can we do about this? Environmental risk analysis has fallen into a standard front-to-back mode of operation: Environmental risk analysis has tailen into a standard front-to-back mode of operation: Estimate the magnitude and pattern of releases of the pollutants of concern; model their Estimate the magnitude and pattern of releases of the politicants or concern, moot transformation through the environment; estimate the location and elements and elements and elements and the environment determined the environment.

transport and transformation through the environment, estimate the location and physiological state of people, animals, and plants and the exposures they will receive; physiological state of people, animals, and plants and the exposure apply dose-response functions; and estimate the resulting impacts. All of this makes perfect sense if the relevant science is pretty well known and good data All of this makes perfect sense if the relevant science is pretty well known and good (are available on factors such as the behaviors of the populations at risk. However, in are available on factors such as the behaviors of the populations at risk. However, in practice, the science is often highly uncertain. The release rates may not be known with

practice, the science is often highly uncertain. The release rates may not be known with precision. There is often great uncertainty about transport and transformation processes. precision. There is often great uncertainty about transport and transformation processes. Good measurements, or model estimates, of exposure are frequently lacking. There may be fundamental uncertainties about the analytical form of the data measurement of the data. Good measurements, or model estimates, of exposure are frequently lacking. There may fundamental uncertainties about the analytical form of the dose-response functions, and undamental uncertainties about the analytical form of the dose-response functions, and even when there are not, there may be uncertainty about the specific coefficient values that even when mere are not, mere may be uncertainty about me specific coefficient (define that function. We often have only a rough idea of where people (or other container) are what they are doing, or what their obviological state is define that function. We often have only a rough idea of where people (of organisms) are, what they are doing, or what their physiological state is. What to do? The conventional answer has been to plow on-do the best one can by adding What to do? The conventional answer has been to plow on-do the best one can by adding uncertainty analysis to the standard front-to-back mode of operation. Develop probabilistic uncertainty analysis to the standard front-to-back mode of operation. Develop printed in the standard fight is a standard if that is the standard standard if that is the standard standa

models. Use available data to describe uncertainty and variability. And if that is insufficient, as it usually is, elicit expert judgments in the form of subjective probability distributions. For the second state of the second insufficient, as it usually is, elicit expert judgments in the form of subjective probability distributions. Insert those distributions into the models. Perform stochastic simulation or distributions, insert mose distributions into the models. Perform stochastic simulation (some other form of uncertainty analysis. Report results as probability distributions, or performs in summery form as best estimates (or a semantic) with accordent uncertainty some other form of uncertainty analysis. Report results as probability distributions, or perhaps in summary form as best estimates (e.g., as means) with associated uncertainty $\frac{1}{2}$ Today's approach represents a big improvement over the typical analysis of 25 years ago,

Use of Expert Judgment to Bound Lung Cancer Risks

ELIZABETH A. CASMAN* AND M. GRANGER MORGAN Department of Engineering & Public Policy, Carnegie Mellon University, Pittsburgh, Pennsylw

A bounding analytic technique for interring the contr of poorly characterized risk factors to a common t endpoint is demonstrated. Lung cancer mortality was for the case study because the exposures responsi for the bulk of the deaths are very well-known, and contribution of other putative causes is a focus of o research and regulatory scrutiny. We elicited experi opinions on the upper and lower bounds on the frac of the total lung cancer mortality due to individual n factors. Interactive second-order uncertainty analysis used to improve the experts' confidence in their bour om this information we calculated an upper bound o idual fraction of deaths due to minor causes not

illistic risk analysis is best suited for estimating li th clearly defined population exposures. Especi oplied to poorly understood risks with uncert s, these methods can result in very wide confider This problem is magnified when the results of su extrapolated to large populations ulatory decisions must often be made bef science is complete, an independent test of th a preliminary impact assessment would ! eviously (1, 2) we have proposed a method fr antribution of poorly documented risk factor ealth endpoint where the sources of large risk are known. More precisely, given what Il causes of that health endpoint, we estimate ses of the health endpoint that the poorly ctors, taken as a group, could not exceed apply the method to the case of annual ity in the United States. This method is nent, not replace, existing risk analytic r this method is derived from the results talyses. For bounding analysis to work, of the risk factors must be well icable only to situations where the y by some risk factors is well-known, ng data are insufficient to sure

bound on the contribution that could be made by the causes for which there are incomplete data. Conservation principles (such as mass or energy mass balance calculations) are commonly invoked in science and engineering, as are order of magnitude arguments (3). Also common in engineering and risk analysis is the use of err elicitation to provide subjective pro-

Risk Analysis, Vol. 24, No. 5, 2004

Bounding Poorly Characterized Risks: A Lung Cancer Example

Minh Ha-Duong,12 Elizabeth A. Casman,2* and M. Granger Morgan2

For diseases with more than one risk factor, the sum of probabil of cases caused by each individual factor may exceed the total especially when uncertainties about exposure and dose respon high. In this study, we outline a method of bounding the fractio due to specific well-studied causes. Such information serves as a of the impacts of the minor risk factors, and, as such, complement With lung cancer as our example, we allocate portions of the ol to known causes (such as smoking, residential radon, and asb uncertainty surrounding those estimates. The interactions an quantified, to the extent possible. We then infer an upper boun to "other" causes using a considency constraint on the total m uncertainty principle, and the mathematics originally develop

KEY WORDS: Bounding analysis; export elicitation; lung cancer; a

1. INTRODUCTION **1.1. Bounding Analysis**

The familiar "front-to-back" procedure for calculating disease or mortality risk from exposure to environmental contaminants3 which involves estimating toxic releases, modeling environmental transformations, and employing exposure models and dose-response functions, works best when the relevant science is well developed. When the science is poorly understood, probabilistic risk analysis is now inely used to obtain estimates of health impacts

the results can substi cases actually observ Morgan argued ysis could be used in avoid such problem with multiple ex

with results typically

broad subjective proba

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made separately, by o

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	Technological formation	
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Bounding US electr	icity demand in 2050	1
Vanessa J. Schweizer*, M Department of Engineering and Public Policy	I. Granger Morgan Carriege Metion University. 129 Baker Hall, 5000 Farber Avenue, Petaburgh, IM 15213, USA	CrossMari
ittide history: Retived 25 June 2015	A B S T R A C T Limiting climate change groups :	
visonă: miding aulysis deran projection gy demand fingt demand alte change	Limiting climate change requires a radical shift in energy supply and use. Because of time metry, the policical process, and that dimate system, potential developments decade free energy policy devices in the system of the system of the system of the system of the targe, however, pate energy default of possibilities under uncertainty. However, with system of the s	used to conceptualize onfidence, or a tenden- femonstrates a simple nd is parsed into two plicitly to account for
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st efforts to project future US	Climate Change (IPCC)	

ver long time horizons (i.e. multiple decades) have consumption over using time instruction (i.e. managine vacuues) since been remarkably unsuccessful. Even when projections have included ricity or overall energy been remainably unsuccessitia. Even miles projections mark include the values uncertainty bounds, these bounds have often failed to include the values that were ultimately realized (Greenberger, 1983; Shlyakhter et al., ting were transmery remove (treenberger, rand, any anti-ext m-1994; Smil, 2003). Although more recent mid-term US energy demand projections from the Energy Information Administration (EIA) have smaller errors of approximately 4% (projections with lead times of 10-13 years), these hide much larger errors for projecting the drivers of a years, time new men taken target when no proposing the server to energy demand, which at least in recent years, have tended to offset energy username, while non-sense in resense years, have remained in viscous each other (O Neill and Desai, 2005). However, analysis intent on examining a range of issues, including the implications of future climate change, need plausible and unbiased projections as inputs to their work.

There are a variety of analytical approaches for characterizing the http:// Carter et al. (2007) have reviewed many of them. Three numer curves as an (2007) have reversed many to ment, more approaches are relevant to this paper: (1) scenarios and storylines, (2) projections, and (3) artificial experiments. Carter et al. (2007) contrast these according to their comprehensiveness, or degree to which the characterization captures details of the socioecr

norios (SRES) (Nakicenovic et al., 2000). The range of scenarios featured in the SRES were based on detailed story lines, which made them highly in measurements one on ormers not y mes, when many men more norm non-comprehensive and plausible. However, much of the detail in these story lines was never used in subsequent assessment activity, and a number of scenarios that were at least as internally consistent and plaunumero to scenarios trait were an east an internary turnstens and patter sible as those presented were not developed nor used (Schweizer and Kriegler, 2012). Morgan and Keith (2008) have provided a detailed entique of such scenario methods, arguing further that the use of a few detailed storylines may cause users to ignore other possible futures as a result of a cognitive bias known as "availability," which can result in systematically overconfident projections (Dawes, 1988), Lloyd and inveizer (2014) have also argued that intuitively derived storylines are inappropriate for scientific assessments due to their demonstrably low levels of objectivity in comparison to other methods. In our view, this recent critical scholarship raises questions about the

webliness of scenarios and storylines for long-term energy demand projections. Instead, Morgan and Keith (2008) as well as Casman et al

In this talk I will:

- Discuss prescriptive analytical strategies that suggest how people should frame and make decisions in the face of uncertainty.
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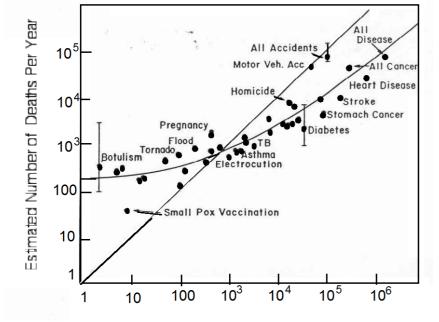
There is a large literature...

...based on empirical studies, that describes how people make judgments in the face of uncertainty.

PSYCHOLOGICAL	Journal of Experimental Psychology:	occupation from a list of possibilities (for example, farmer, salesman, airline pilot, librarian, or physician)? How do people order these occupations from
	Human Learning and Memory	must to least likely? In the contraction
REVIEW	findman Dearning and Memory	Judgment under Uncertainty:
		Heuristics and Biases Steve is a librarian, for example, is assessed by the degree to which he is
Copyright @ 1973 by the American Psychological Association, Inc.		representative of, or similar to, the
	Vol. 4. No. 6 November 1978	Biases in judgments reveal some heuristics of stereotype of a librarian. Indeed, re-
	VOL. 4, NO. 6 NOVEMBER 1978	thinking under uncertainty.
Vol. 80, No. 4 July 1973		thinking under uncertainty. tions by probability and by similarity in exactly the same way (1). This ap-
ON THE DEVELOP OF PREPARITION I	Judged Frequency of Lethal Events	Amos Tversky and Daniel Kahneman proach to the judgment of probability
ON THE PSYCHOLOGY OF PREDICTION ¹	Judged Trequency of Lethia Events	Amos i verský and Damer Kamernan leads to serious errors, because sim-
DANIEL KAHNEMAN ⁴ and AMOS TVERSKY	Sarah Lichtenstein, Paul Slovic, Baruch Fischhoff,	 ilarity, or representativeness, is not in- fluenced by several factors that should
	Mark Layman, and Barbara Combs	affect judgments of probability.
Hebrew University of Jerusalem, Israel, and Oregon Research Institute	Decision Research, A Branch of Perceptronics	Many decisions are based on beliefs mated when visibility is good because <i>Insensitivity to prior probability of</i> concerning the likelihood of uncertain the objects are seen sharply. Thus, the <i>outcomes</i> . One of the factors that have
Intuitive predictions follow a judgmental heuristic-representativeness. By	Eugene, Oregon	concerning the intermodul of uncertaint the objects are seen sharpy. Thus, the outcomest, one of the factors that have events such as the outcome of an elec-
this heuristic, people predict the outcome that appears most representative of	A series of experiments studied how people judge the frequency of death	tion, the guilt of a defendant, or the distance leads to common biases. Such should have a major effect on probabil-
the evidence. Consequently, intuitive predictions are insensitive to the relia- bility of the evidence or to the prior probability of the outcome, in violation	A series of experiments studied now people judge the incluency of dealing from various causes. The judgments exhibited a highly consistent but sys-	future value of the dollar. These beliefs biases are also found in the intuitive ity is the prior probability, or base-rate judgment of probability. This article frequency, of the outcomes. In the case
of the logic of statistical prediction. The hypothesis that people predict by	tematically biased subjective scale of frequency. Two kinds of bias were identi-	as "I think that ," "chances are describes three heuristics that are em- of Steve, for example, the fact that
representativeness is supported in a series of studies with both naive and so-	fied: (a) a tendency to overestimate small frequencies and underestimate	, "it is unlikely that," and ployed to assess probabilities and to there are many more farmers than li- so forth. Occasionally, beliefs concern- predict values. Biases to which these brarians in the population should enter
phisticated subjects. It is shown that the ranking of outcomes by likelihood coincides with their ranking by representativeness and that people erroneously	larger ones, and (b) a tendency to exaggerate the frequency of some specific	so form. Occasionary, beness concern- protect values, biases to which these brarians in the population should enter ing uncertain events are expressed in heuristics lead are enumerated, and the into any reasonable estimate of the
predict rare events and extreme values if these happen to be representative.	causes and to underestimate the frequency of others, at any given level of ob- jective frequency. These biases were traced to a number of possible sources,	numerical form as odds or subjective applied and theoretical implications of probability that Steve is a librarian
The experience of unjustified confidence in predictions and the prevalence of fallacious intuitions concerning statistical regression are traced to the repre-	including disproportionate exposure, memorability or imaginability of vari-	probabilities. What determines such be- liefs? How do people assess the prob-
sentativeness heuristic.	ous events. Subjects were unable to correct for these sources of bias when	ability of an uncertain event or the affect the similarity of Steve to the
	specifically instructed to avoid them. Comparisons with previous laboratory	value of an uncertain quantity? This Representativeness stereotypes of librarians and farmers. article shows that people rely on a If people evaluate probability by rep-
In this paper, we explore the rules that the diagnosis of a patient, or a person's	studies are discussed, along with methods for improving frequency judg- ments and the implications of the present findings for the management of	limited number of heuristic principles Many of the probabilistic questions resentativeness, therefore, prior proba-
determine intuitive predictions and judg- future occupation. In a numerical case,	ments and the implications of the present indings for the management of societal hazards.	which reduce the complex tasks of as- sessing probabilities and predicting val- to one of the following types: What is was tested in an experiment where prior
ments of confidence and contrast these the prediction is given in numerical form,	Sourcest interview.	sessing probabilities and predicting val- ues to simpler judgmental operations. the probability that object A belongs to probabilities were manipulated (1).
rules to the normative principles of statis- tical prediction. Two classes of prediction stock or of a student's grade point average.	Here will be a such a since the feather well a difference in featurement on the	In general, these heuristics are quite class B? What is the probability that Subjects were shown brief personality
are discussed: category prediction and In making predictions and judgments	How well can people estimate the fre- ouencies of the lethal events they may en-reliably detected? Do people have a con-	useful, but sometimes they lead to severe event A originates from process B? descriptions of several individuals, al- and systematic errors. What is the probability that process B legedly sampled at random from a
numerical prediction. In a categorical under uncertainty, people do not appear	quencies of the fethal events they may en- fenancy detected: bo people may a con- counter in life (e.g., accidents, diseases, sistent internal sale of frequency for such	The subjective assessment of proba- will generate event A? In answering group of 100 professionals-engineers
case, the prediction is given in nominal to follow the calculus of chance or the	homicides, suicides, etc.)? More specifically, events? What factors, besides actual fre-	bility resembles the subjective assess- ment of physical quantities such as the representativeness heuristic, in to assess, for each description, the prob-
form, for example, the winner in an election, statistical theory of prediction. Instead,	quency, influence people's judgments?	ment or physical quantities such as the representativeness neurosic, in to assess, for each description, the prob- distance or size. These judgments are which probabilities are evaluated by the ability that it belonged to an engineer
they rely on a limited number of heuristics	The answers to these questions may have	all based on data of limited validity, degree to which A is representative of rather than to a lawyer. In one experi-
¹ Research for this study was supported by the which sometimes yield reasonable judg- following grants: Grants MH 12972 and MH 21216 ments and sometimes lead to severe and	This research was supported by the Advanced Research Projects Agency of the Department of great importance to society. Citizens must	which are processed according to heu- ristic rules. For example, the apparent resembles B. For example, when A is that the group from which the descrip-
following grants: Grants MH 12972 and MH 21216 from the National Institute of Mental Health and systematic errors (Kahneman & Tversky,	Defense and was monitored by the Office of Naval assess risks accurately in order to mobilize	distance of an object is determined in highly representative of B, the probations had been drawn consisted of 70
Grant RR 05612 from the National Institute of systematic errors (Kalmernan & Tversky,	Research under Contracts N00014-76-C-0074 and society's resources effectively for reducing N00074-78-C-0100 (ARPA Order Nos. 3052 and hazards and treating their victims. Official	part by its clarity. The more sharply the object is seen, the closer it appears to to be high. On the other hand, if A is condition, subjects were told that the
Health, U. S. Public Health Service; Grant GS 3250 from the National Science Foundation. Computing The present paper is concerned with the	3469) under subcontract to Oregon Research In- recognition of the importance of valid risk	be. This rule has some validity, because not similar to B, the probability that A group consisted of 30 engineers and 70
assistance was obtained from the Health Services role of one of these heuristics representa-	stitute and Subcontracts 76-030-0714 and 78-072-	in any given scene the more distant objects are seen less sharply than nearer For an illustration of judgment by description belongs to an engineer
Computing Facility, University of California at tiveness-in intuitive predictions	0722 to Perceptronics, Inc. from Decisions and Designs, Inc.	objects are seen less sharply than nearer For an illustration of judgment by description belongs to an engineer objects. However, the reliance on this representativeness, consider an indi-
Los Angeles, sponsored by Grant MH 10822 from the U. S. Public Health Service. Given specific evidence (e.g., a person-	We would like to thank Nancy Collins and reported to the public (see Figure 1). There	rule leads to systematic errors in the vidual who has been described by a higher in the first condition, where there
The authors thank Robyn Dawes, Lewis Gold- ality sketch), the outcomes under consider-	Peggy Roecker for extraordinary diligence and is, however, no guarantee that these statis- patience in typing and data analysis. We are also	estimation of distance. Specifically, dis- tances are often overestimated when very shy and withdrawn, invariably second condition, where there is a
berg, and Paul Slovic for their comments. Sundra Gregory and Richard Kleinknecht assisted in the ment) can be ordered by the degree to	grateful to Ken Hammond, Jim Shanteau, Amos tics are reflected in the public's intuitive	visibility is poor because the contours helpful, but with little interest in peo- majority of lawyers. Specifically, it can
Gregory and Richard Kleinknecht assisted in the ment) can be ordered by the degree to preparation of the test material and the collection which they are representative of that evi-	Tversky, and an anonymous reviewer for percepjudgments.	of objects are blurred. On the other hand, distances are often underesti- and tidy soul, he has a need for order the ratio of these odds should be (.7/.3)?.
of data.	tive comments on various drafts of this article. Requests for reprints should be sent to Sarah	and structure, and a passion for detail." or 5.44, for each description. In a sharp
³ Requests for reprints should be sent to Daniel Kahneman, Department of Psychology, Hebrew people predict by representativeness, that	Lichtenstein, Decision Research, 1201 Oak Street, tions. Most investigations of judged fre-	The authors are members of the department of psychology at the Hebrew University, Jerusaten Israel. How do people assess the probability violation of Bayes' rule, the subjects that Steve is engaged in a particular in the two conditions produced essen-
University, Jerusalem, Israel. is, they select or order outcomes by the	Eugene, Oregon 97401. quency have been laboratory experiments	that Steve is engaged in a particular in the two conditions produced essen-
237	Copyright 1978 by the American Psychological Association, Inc. 0096-1515/78/0406-0551\$00.25	1124 SCIENCE, VOL. 185
231	Copyright 1978 by the American Psychological Americana, and Copyright 1978	

Examples of cognitive heuristics

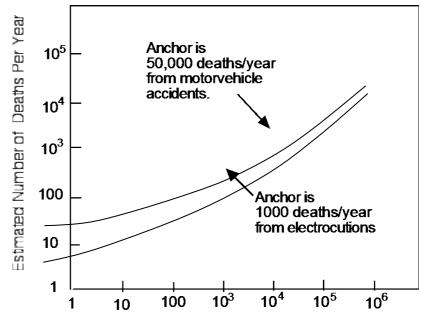
Availability: probability judgment is driven by ease with which people can think of previous occurrences of the event or can imagine such occurrences.



Actual Number of Deaths Per Year

Redrawen Lichtenstein, S., B. Fischhoff, and L.D. Phillips (1982) Calibration of probabilities: The state of the art to 1980," pp. 306-334 in D. Kahneman, P. Slovic, and A. Tversky (eds.), *Judgment Under Uncertainty: Heuristics and Biases*, Cambridge University Press, 555pp.

Anchoring and adjustment: probability judgment is frequently driven by the starting point which becomes an "anchor."



Actual Number of Deaths Per Year

As Scott Ferson noted yesterday, brain science is beginning to figure out where in the brain some of the relevant processes occur.

In this talk I will:

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Let's try a demonstration:

I am going to name four canals. I would like every one to write down three numbers

Your lower 1% estimate of the length of the canal i.e., only 1 chance in 100 it could be shorter.

Your best estimate of the length of the canal. Your upper 99% estimate of the length of the canal i.e., only 1 chance in 100 it could be longer.

Here are the four canals:



Kile Canal Between the North Sea and the Baltic Sea



Panama Canal Between the Caribbean and the Pacific Ocean



Suez Canal Between the Mediterranean and the Red Sea



Cape Cod Canal Between Cape Cod Bay and Buzzards Bay

Here are the four canals:



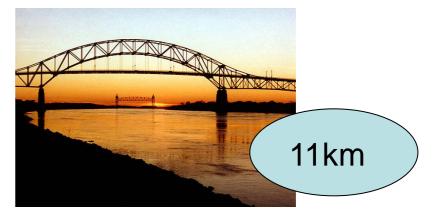
Kile Canal Between the North Sea and the Baltic Sea



Panama Canal Between the Caribbean and the Pacific Ocean

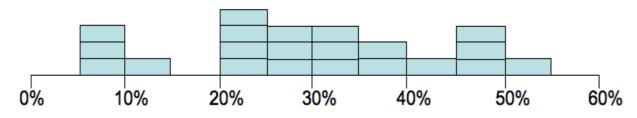


Suez Canal Between the Mediterranean and the Red Sea

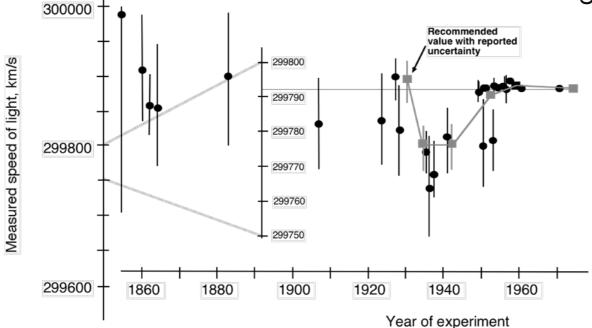


Cape Cod Canal Between Cape Cod Bay and Buzzards Bay

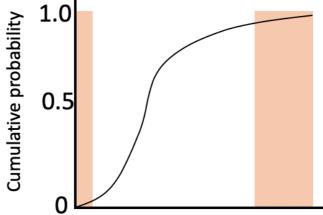
Over Confidence



Percentage of estimates in which the true value lay outside of the respondent's assessed 98% confidence interval. Source: Morgan and Henrion, 1990



Surprise index: Should be 2%. The probability that the true value lies below the 1% lower bound or above the 99% upper bound



For details see: Henrion and Fischhoff, "Assessing Uncertatinty in Physical Constants," American Journal of Physics, 54, pp791-798, 1986.

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Yesterday...

...Karl Teigen talked at length about the problems associated with using probability words to support decision making.

As he noted, such words can mean very different things in different circumstances and different things to different people in the same circumstance.

> I can illustrate with an example from the U.S. EPA's Science Advisory Board

The SAB was discussing...

...words to use to describe whether a substance is or is not a likely carcinogen.

The minimum probability associated with the word "likely" spanned four orders of magnitude.

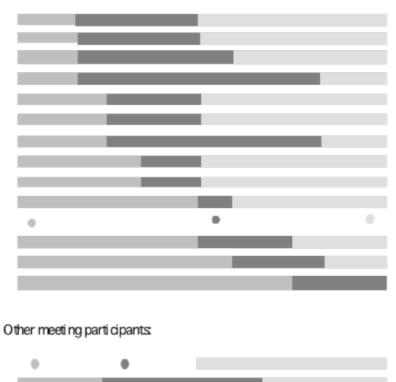
The maximum probability associated with the word "not likely" spanned more than five orders of magnitude.

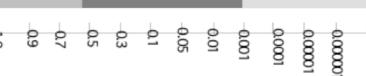
There was an overlap of the probability associated with the word "likely" and that associated with the word "unlikely"!

Figure from: M. Granger Morgan, "Uncertainty Analysis in Risk Assessment," *Human and Ecological Risk Assessment, 4*(1), 25-39, February 1998.



SAB members:





Probability that the material is a human carcinogen

Words are not enough...(Cont.)

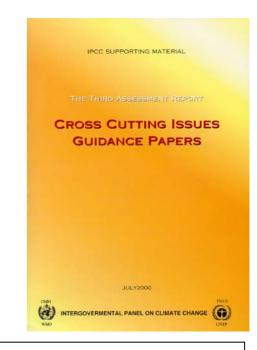
Without some quantification, qualitative descriptions of uncertainty convey little, if any, useful information to decision makers.

The climate assessment community is gradually learning this lesson.

Steve Schneider and Richard Moss worked hard to promote a better treatment of uncertainty by the IPCC.

At my insistence, the first U.S. National Climate Assessment Synthesis Team gave quantitative definitions to five probability words:

LITTLE CHANCE"	"UNLIKELY"		"LIKELY"	"VERY LIKELY"
VERY UNLIKELY"	"SOME CHANCE"	"POSSIBLE"	"PROBABLE"	"VERY PROBABLE



Mapping of probability words into quantitative subjective probability judgments, used by WG I and II of the IPCC Third Assessment (2001) based on recommendations developed by Moss and Schneider (2000).

word	probability range
Virtually certain	> 0.99
Very likely	0.9-0.99
Likely	0.66-0.9
Medium likelihood	0.33-0.66
Unlikely	0.1-0.33
Very unlikely	0.01-0.1
Exceptionally unlikely	< 0.01

Note: The report of the IPCC Workshop on Describing Scientific Uncertainties in Climate Change to Support Analysis of Risk and of Options (2004) observet.¹ Although WGIII TAR authors addressed uncertainties in the WG3-TAR, they did not adopt the Moss and Schneider uncertainty guidelines. The treatment of uncertainty in the WG3-AR4 can be improved over what was done in the TAR.¹

Many other communities have not yet gotten the message

In this talk I will:

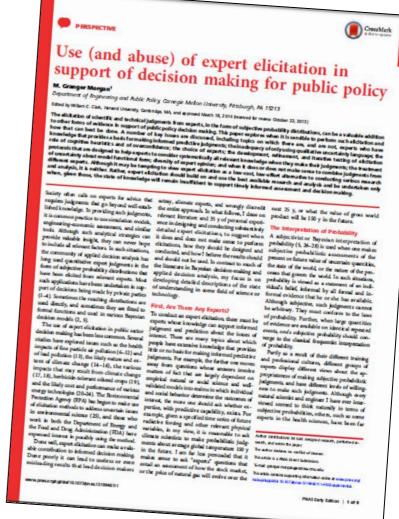
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Expert elicitation

Eliciting probabilistic judgments from experts requires careful preparation and execution.

Developing and testing an appropriate interview protocol typically takes several months. Each interview is likely to require several hours.

When addressing complex, scientifically subtle questions of the sorts involved with problems like climate change, there are no satisfactory short cuts. Attempts to simplify and speed up the process almost always lead to shoddy results.



I've done a bunch of expert elicitations

While I was going to talk about a couple I've decided instead to offer just three insights on:

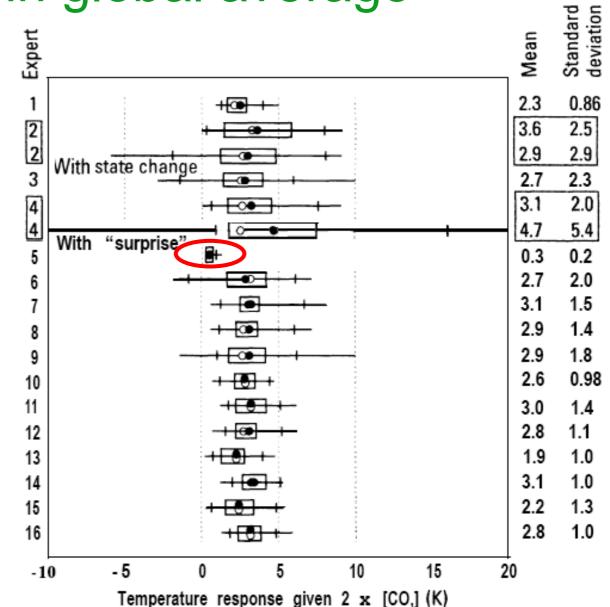
- Motivational bias;
- Individual elicitation versus group consensus;
- Combing experts and situations where different experts have different view about of how the world works.

When we did it.	Topics we asked about.	Reference at the end of this chapte to the paper we published that describes the results.
1980-1	Interviews with 9 air pollution experts and with 7 health experts to better understand and model the health impacts of the sulfur air pollution that comes from power plants that burn coal.	Morris, Henrion, Amaral and Rish, (1984); Morgan, Morris, Henrion and Amaral (1985).
1993-4	Interviews with 16 leading U.S. climate scientists to ask about how much warming may happen and other uncertainties in climate science.	Morgan and Keith (1994)
1999-2000	Interviews with 11 leading forest experts (and 5 biodiversity experts) to ask about the impacts that climate change may have on tropical and northern forests.	Morgan, Pitelka and Shevlikova (2001)
2005-6	Interviews with 12 leading oceanographers and climate scientists to ask about how climate change may influence the circulation of water and heat in the Atlantic Ocean.	Zickfeld, Levermann, Kuhlbrodt. Rahmstorf, Morgan and Keith (2007)
2005-6	Survey of 24 leading atmospheric and climate scientists to explore how the direct and indirect ways in which high-altitude small particles in the atmosphere warm or cool the planet.	Morgan, Adams, Keith (2006)
2006-7	Interviews with 18 experts about conventional and advanced technology for solar cells to explore how cost and performance may change over time.	Courtright, Morgan, Keith (2008)
2008-9	Interviews with 14 leading U.S. climate scientists (four who were the same as in the earlier study) to ask about how warming will change over time and about other uncertainties in climate science.	Zickfeld, Morgan, Frame and Keith (2010)
2011-12	Interviews with 16 nuclear engineers about how the cost and future performance of small modular nuclear reactors (MRs) are likely to compare with the cost of existing large reactors.	Abdulla, Azevedo and Morgan (2013)

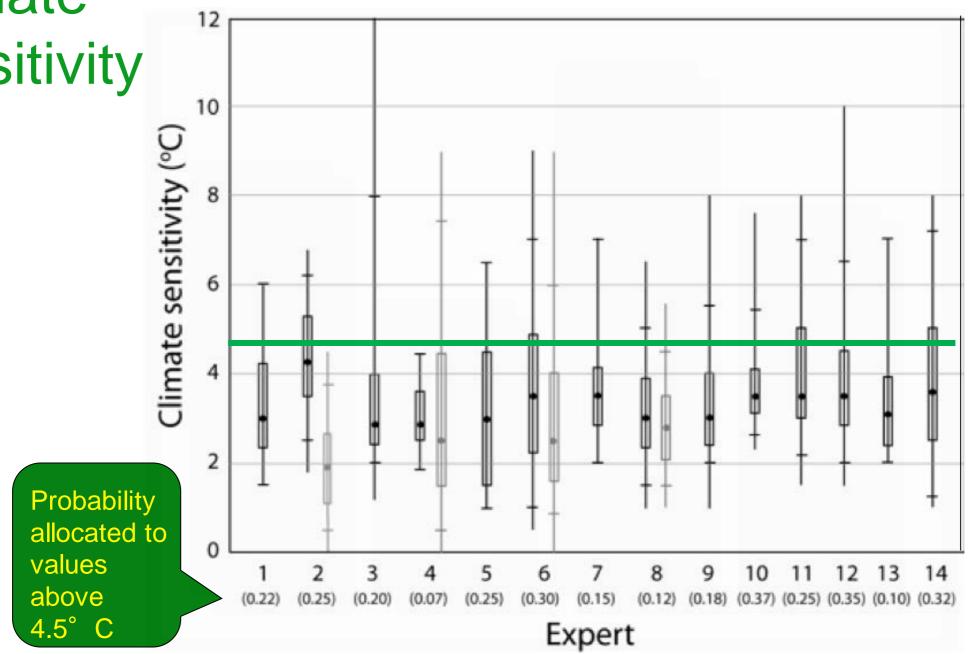
Equilibrium change in global average temperature

200 years after a $2xCO_2$ change

M. Granger Morgan and David Keith, "Subjective Judgments by Climate Experts," *Environmental Science* & *Technology*, *29*(10), 468A-476A, October 1995.

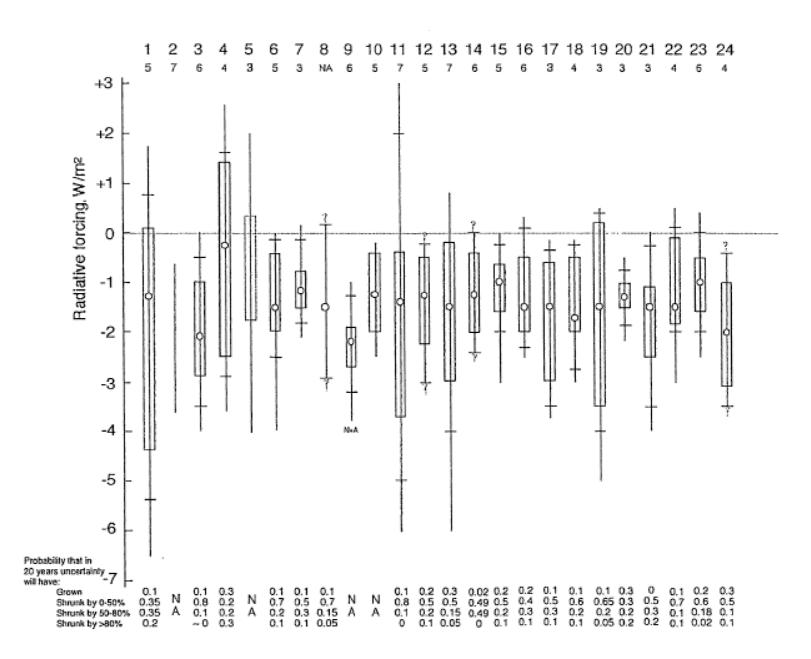


Climate sensitivity



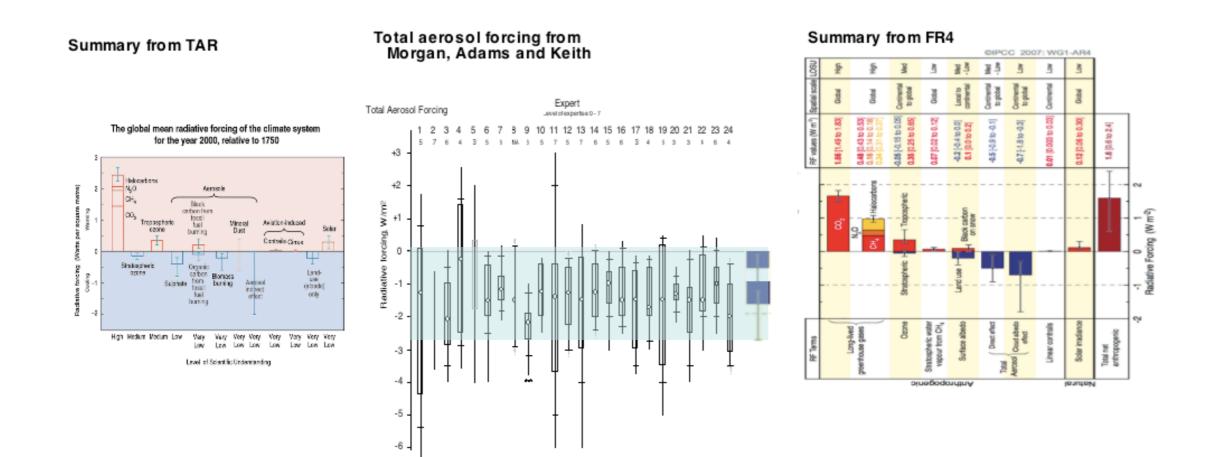
Kirsten Zickfeld, M. Granger Morgan, David Frame and David W. Keith, "Expert Judgments About Transient Climate Response to Alternative Future Trajectories of Radiative Forcing," *Proceedings of the National Academy of Sciences*, *107*, 12451-12456, July 13, 2010.

Total aerosol forcing (at the top of the atmosphere)

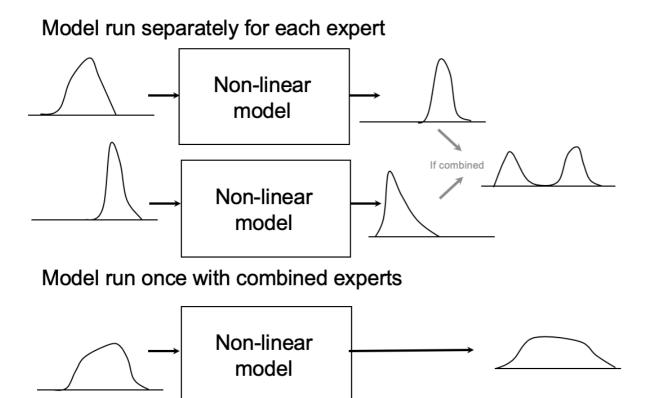


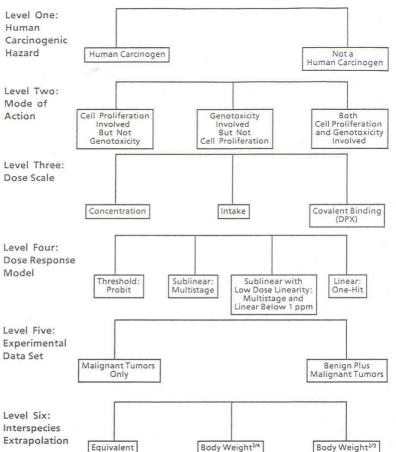
M. Granger Morgan, Peter Adams, and David W. Keith, "Elicitation of Expert Judgments of Aerosol Forcing," Climatic Change, 75, 195-214, 2006.

Comparison with IPCC 4th assessment consensus results



Different experts have different views of how the world works





For details see: John S. Evans et al., "A distributional approach to characterizing low-dose cancer risk," *Risk Analysis, 14*, 25-34, 1994; and John S. Evans et al., "Use of probabilistic expert judgment in uncertainty analysis of carcinogenic potency," *Regulatory Toxicology and Pharmacology, 20*, 15-36, 1994.

In this talk I will:

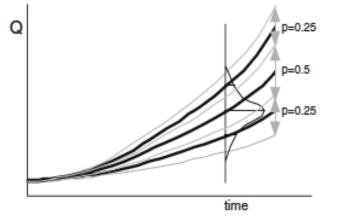
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Scenarios are widely used



For example, the previous IPCC assessment made use of the very detailed SRES scenarios in making its projections.

While in principle there are ways to create scenarios that span ranges across the space of plausible futures, this is very rarely done.



Folks who construct scenarios often argue that they should not be viewed as "predictions" but rather as a strategy to help people think about how things might unfold in the future.

But, there is a problem with this argument...

Again, from the work of Tversky and Kahneman

Tom W. is of high intelligence, although lacking in true creativity. He has a need for order and clarity, and for neat and tidy systems in which every detail finds its appropriate place. His writing is rather dull and mechanical, occasionally enlivened by somewhat corny puns and by flashes of imagination of the sci-fi type. He has a strong drive for competence. He seems to have little feel and little sympathy for other people and does not enjoy interacting with others.

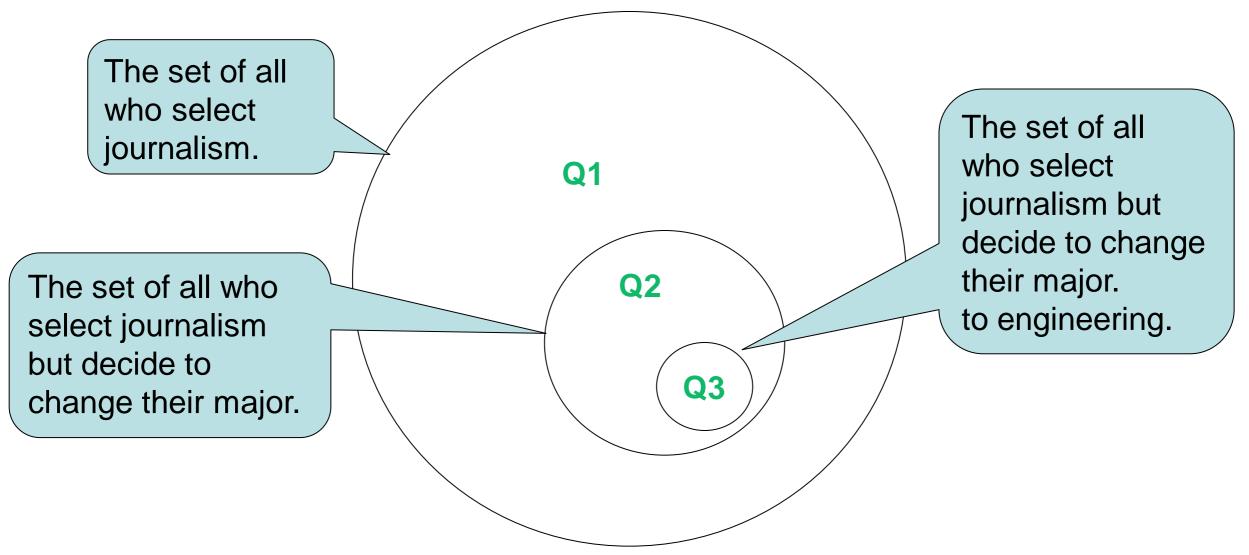
Group 1 got Q1: What is the probability that Tom W. will select journalism as his major in college?

Group 2 got Q2: What is the probability that Tom W. will select journalism as his major in college but decide he does not like it and decide to change his major?

Group 3 got Q3: What is the probability that Tom W. will select journalism as his college major but become unhappy with his choice and switch to engineering?

Assessed probabilities went *up* but should have gone down.

All people who fit...



The more detail...

...that gets added to the "story line" of a scenario, the harder people find it to remember that there are typically many other ways that one could reach the same outcome, as well as many other possible outcomes that could result - this is because of the heuristic of "availability."



For additional elaboration of this and related arguments, and some suggestions for how to improve on past practice, see:

M. Granger Morgan and David Keith, "Improving the Way We Think About Projecting Future Energy Use and Emissions of Carbon Dioxide," *Climatic Change*, *90*(3), 189-215, October 2008.

My concern with scenarios is well illustrated...

...by a quotation from a book by W.L. Gregory (2001) promoting the use of scenarios who argues:

Practitioners can find several advantages in using scenarios. First, they can use scenarios to enhance a person's or group's expectancies that an event will occur. This can be useful for gaining acceptance of a forecast. . . Second, scenarios can be used as a means of decreasing existing expectancies. . . .Third. . . scenarios can produce greater commitment in the clients to taking actions described in them.

Gregory, R. (2001). "Scenarios and Acceptance of Forecasts." in J.S. Armstrong (ed.), *Principles of Forecasting: A Handbook for Researchers and Practitioners*, Kluwer, 849pp.

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Comparison of two approaches to integrated assessment models to support decisions about climate change

DICE

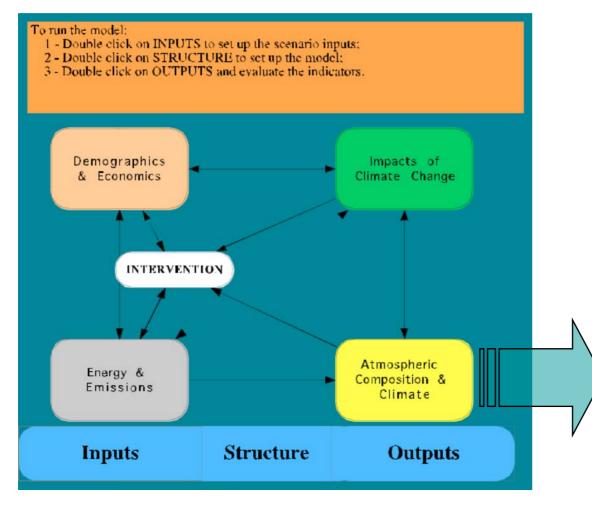
Dynamic Integrated Climate-Economy model.

Bill Nordhaus et al.

ICAM

Integrated climate assessment model.

Hadi Dowlatabadi et al.



See for example:

Hadi Dowlatabadi and M. Granger Morgan, "A Model Framework for Integrated Studies of the Climate Problem," *Energy Policy*, *21*(3), 209-221, March 1993.

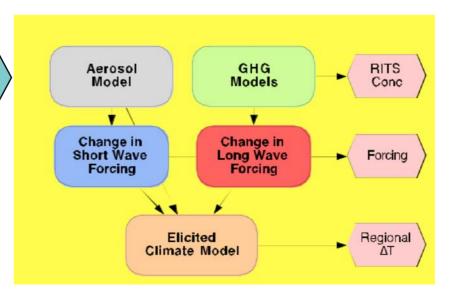
and

M. Granger Morgan and Hadi Dowlatabadi, "Learning from Integrated Assessment of Climate Change," *Climatic Change*, 34, 337-368, 1996.

ICAM

Integrated Climate Assessment Model

A very large hierarchically organized stochastic simulation model built in Analytica[®].



ICAM was focused on...

...doing a good job of dealing with uncertainty.

It treats all important coefficients as full probability distributions and produces results that are PDFs.

It contains switches that allow the user to use a variety of different functional forms.

We found that:

- One could get a large variety of answers depending on how the model was structured.
- In light of this, we concluded that global integrated assessment models that do optimization, using just one assumed structure, make absolutely no sense.

So...while others continue to build optimizing IA models, we now just focus on how to reduce GHG emissions. See: CEDMCenter.org

Incidentally, on the subject of model and parameter uncertainty...

...Ullrika Sahlin and I have been having fun discussing types of uncertainty. In my recent book on theory and practice in policy analysis I wrote

Much of the literature divides uncertainty into two broad categories, termed opaquely (for those of us who are not Latin scholars) *aleatory* uncertainty and *epistemic* uncertainty. As Paté-Cornell (1996) explains, aleatory uncertainty stems "...from variability in known (or observable) populations and, therefore, represents randomness" while epistemic uncertainty "...comes from basic lack of knowledge about fundamental phenomena (...also known in the literature as ambiguity)."

While this distinction is common in the more theoretical literature, I believe that it is of limited utility in the context of applied problems involving assessment and decision making in technology and public policy where most key uncertainties involve a combination of the two.

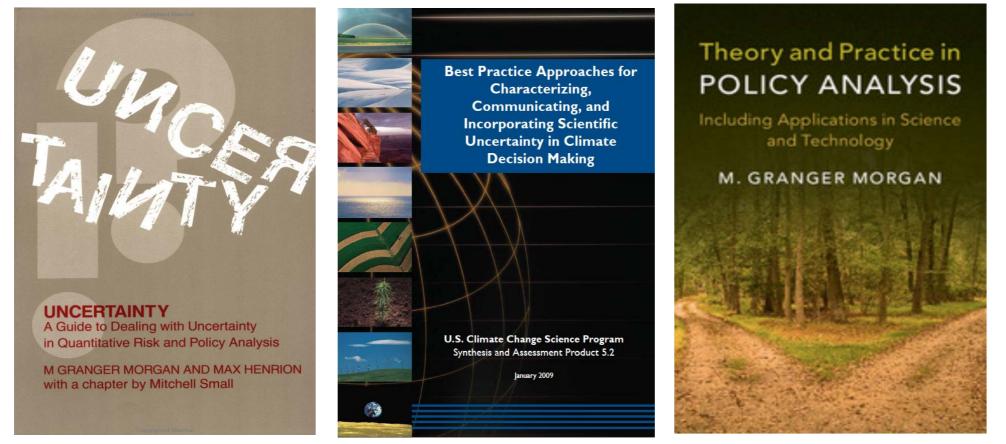
A far more useful categorization for our purposes is the split between "uncertainty about the value of empirical quantities" and "uncertainty about model functional form." The first of these may be either aleatory (the top wind speed that occurred in any Atlantic hurricane in the year 1995) or epistemic (the average global radiative forcing produced by anthropogenic aerosols at the top of the atmosphere during 1995). There is some disagreement within the community of experts about whether it is even appropriate to use the terms epistemic or aleatory when referring to a model. The Random House Dictionary defines *aleatory* as "of or pertaining to accidental causes; of luck or chance; unpredictable" and defines *epistemic* as "of or pertaining to knowledge or the conditions for acquiring it."

Five bottom lines

- 1. Uncertainty is present in virtually all important decisions.
- 2. We make decisions in the face of such uncertainty all the time.
- 3. Our mental capabilities are limited when it comes to assessing and dealing with uncertainty.
- 4. Hence, especially for important decisions, we should seek help in making such decisions.
- 5. There are a wide variety of formal analytical strategies, such as decision analysis, that can be very helpful in providing insight and guidance when we need to make important decisions in the presence of uncertainty.

Finally I have written...

...quite a bit on how to incorporate many of these ideas into policy analysis. For example:



M. Granger Morgan, Max Henrion, with Mitchell Small, Uncertainty: A guide to dealing with uncertainty in quantitative risk and policy analysis, 332pp., Cambridge University Press, New York, 1990. (Paperback edition 1992. Best Practice Approaches for Characterizing, Communicating, and Incorporating Scientific Uncertainty in Decision-making. [M. Granger Morgan (Lead Author), Hadi Dowlatabadi, Max Henrion, David Keith, Robert Lempert, Sandra McBride, Mitchell Small, and Thomas Wilbanks (Contributing Authors)]. A Report by the Climate Change Science Program and the Subcommittee on Global Change Research. National Oceanic and Atmospheric Administration, Washington, DC, 96pp., 2009. Granger Morgan, Theory and Practice in Policy Analysis: Including applications in science and technology, Cambridge University Press, 590pp., 2017.

Acknowledgments

Most of the specific examples I have presented are drawn from work that has been supported by NSF.

This includes support under SBR-9521914, SES-8715564, SES-9309428, SES-9209940, SES-9209553, SES-9975200 and support through the Center for the Integrated Assessment of Global Change (SES-9022738), the Climate Decision Making Center (SES-0345798) and the Center for Climate and Energy Decision Making (SES-0949710) operated through cooperative agreements between the National Science Foundation and Carnegie Mellon University. Support has also come from EPRI under contracts RP 2955-3, 2955-10, 2955-11, and EP-P26150C12608 as well as from Carnegie Mellon University and several other sources.