

“Wedges Reaffirmed”
a short essay by Robert Socolow
and
Ten solicited comments on the essay
September 2011

The comments are by:

Nicholas Stern

David Hawkins

Freeman Dyson

Carter Bales

Robert Fri

Christopher Field

Phil Sharp

Ralph Cicerone

Rush Holt

Robert May

On Sept 27, 2011, the essay and these solicited comments were posted on the websites of Climate Central (<http://www.climatecentral.org/blogs/wedges-reaffirmed/>) and the *Bulletin of the Atomic Scientists* (<http://thebulletin.org/web-edition/features/wedges-reaffirmed>).

Wedges Reaffirmed

Robert Socolow

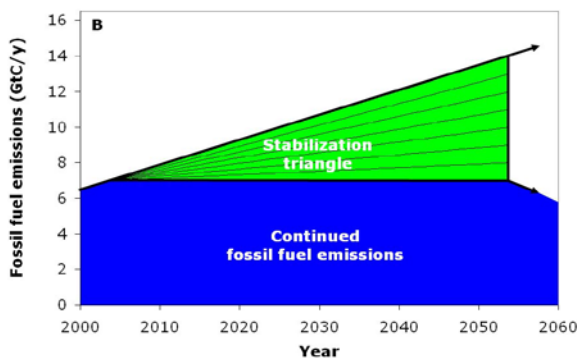
September 19, 2011

In August 2004 Steve Pacala and I published a [paper](#) in Science about climate change mitigation. Its core messages are as valid today as seven years ago, but they have not led to action. Here, I suggest that public resistance can be partially explained by shortcomings in the way advocates of forceful action have presented their case. Addressing these shortcomings might put the world back on the course we identified.

Let's review the messages in our 2004 paper. The paper assumes that the world wishes to act decisively and coherently to deal with climate change. It makes the case that "humanity already possesses the fundamental scientific, technical and industrial know-how to solve the carbon and climate problem for the next half-century." This core message surprised many people, because our paper arrived at a time when the Bush administration was asserting that, unfortunately, the tools available were not suited for addressing climate change. Indeed, at a conference I attended at that time, Energy Secretary Spencer Abraham insisted that a discovery akin to the discovery of electricity was required.

Our focus on "the next half century" was novel; the favored horizon at the time was a full century – and still is. We argued that "the next fifty years is a sensible horizon from several perspectives. It is the length of a career, the lifetime of a power plant, and an interval whose technology is close enough to envision."

In a widely reproduced Figure (see below) we identified a Stabilization Triangle, bounded by two 50-year paths. Along the upper path, the world ignores climate change for 50 years and the global emissions rate for greenhouse gases doubles. Along the lower path, with extremely hard work, the rate remains constant. We reported that starting along the flat emissions path in 2004 was consistent with "beating doubling," i.e., capping the atmospheric carbon dioxide concentration at below twice its "pre-industrial" concentration (the concentration a few centuries ago).



The paper is probably best known for having introduced the “stabilization wedges,” a quantitative way to measure the level of effort associated with a mitigation strategy: a wedge of vehicle fuel efficiency, a wedge of wind power, and a wedge of avoided deforestation have the same effect on the carbon dioxide in the atmosphere. Filling the stabilization triangle required seven wedges. The wedge concept fosters parallel discussion of alternatives and encourages the design of a portfolio of responses. Each wedge is an immense activity. In talks about this work, I like to say that we decomposed a heroic challenge into a limited set of monumental tasks.

In short, in addition to a hopeful message that humanity is not helpless, the paper contains the sobering message that the job ahead is daunting.

Today, *nine* wedges are required to fill the stabilization triangle, instead of seven. A two-segment global carbon-dioxide emissions trajectory that starts now instead of seven years ago – flat for 50 years, then falling nearly to zero over the following 50 years – adds another 50 parts per million to the equilibrium concentration. The delayed trajectory produces nearly half a degree Celsius (three-quarters of a degree Fahrenheit) of extra rise in the average surface temperature of the earth. (Note that there is a three-year lag in the posting of authoritative global data. We used 2001 data in our 2004 paper, and 2008 data are available now. Thus, available data do not yet reflect the recession. Between 2001 and 2008, the emissions rate climbed by more than a quarter.)

Worldwide, policymakers are scuttling away from commitments to regulations and market mechanisms that are tough enough to produce the necessary streams of investments. Given that delay brings the potential for much additional damage, what is standing in the way of action?

Familiar answers include the recent recession, the political influence of the fossil fuel industries, and economic development imperatives in countries undergoing industrialization. But, I submit, advocates for prompt action, of whom I am one, also bear responsibility for the poor quality of the discussion and the lack of momentum. Over the past seven years, I wish we had been more forthcoming with three messages: We should have conceded, prominently, that the news about climate change is unwelcome, that today’s climate science is incomplete, and that every “solution” carries risk. I don’t know for sure that such candor would have produced a less polarized public discourse. But I bet it would have. Our audiences would have been reassured that we and they are on the same team – that we are not holding anything back and have the same hopes and fears.

It is not too late to bring these messages forward.

Unwelcome news

Environmental science has brought unwelcome news – that the actions of our species are capable of changing the planet at global scale. Who wouldn't much rather live on a larger planet, where our actions mattered less? It is counterproductive for advocates of prompt action on climate change to pretend that the new knowledge has only positive consequences, such as the stimulation of green jobs and elegant new technology. Global prosperity now depends on our species' success at a totally unfamiliar assignment: to "fit" our many billions of people on this small planet, with its finite resources and finite capacity to withstand pollution. The job will be very hard and will require sustained focus.

Confronted with unwelcome news, human beings often shoot the messenger. Consider two earlier occasions. Galileo argued that the earth wasn't at the center of the universe. For this, he was excommunicated. Darwin argued that human beings were part of the animal kingdom, and he was cruelly mocked. The idea that humans can't change our planet is as out-of-date and wrong as the earth-centered universe and the separate creation of Man, but all three ideas have such appeal that they will fade away only very slowly.

In particular, just as steadily stronger evidence for the Copernican model and for evolution only gradually won the day, we should anticipate robust resistance to the message that we are fouling our own nest with fossil fuel emissions and deforestation. Armed with insights from psychology and history, communicators of the climate change threat will more deeply understand the hostility to their message. Perhaps, communication will be more effective when shared concerns are acknowledged.

Incomplete climate science

It would be productive for advocates of prompt action also to concede that the message from climate science is not only unwelcome but also incomplete. Feedbacks from clouds, ice, and vegetation are only partially understood – thwarting precise prediction of future climate. The best and worst future climate outcomes consistent with today's science are very different.

Pacala calls the worst credible climate outcomes "monsters behind the door." Among the monsters are a five-meter rise in sea level by the end of this century, major alterations of the global hydrological cycle, major changes in forest cover, and major emissions of greenhouse gases from the tundra. The monsters open their door in a world of very strong positive feedbacks, a world that spirals out of control. Today's science cannot predict how much atmospheric change would let these monsters in, nor how quickly they could enter.

Policymakers assessing the case for immediate forceful action and members of the general public deciding whether to endorse the policymaker's decisions want to know the full story –

both the average outcomes and the extremes (the “tails” of the distribution). In reaching a judgment about whether to act forcefully now, some will give greater weight to best guesses, others to the tails. The more risk-averse will assign greater weight to the tails.

Why, at the intersection of climate science and climate policy, is there more discussion of average outcomes than nasty ones? As I have speculated in [a recent paper](#), one reason is that average outcomes are safer to talk about, because the science is more solid; there is less risk of being accused of alarmism. Also, acknowledging terrible outcomes of low probability requires acknowledging the other tail – a world with rising emissions but little change for quite a while. I often hear that any concession to benign outcomes (or, more accurately, outcomes that remain benign for a relatively long time) will foster complacency. I don’t understand that fear. In my experience, when I tell someone “we could be lucky,” and then I pause, the listener completes the sentence for me: “or we could be unlucky.” The listener does not hear a lullaby.

Arguments for action based on what we don’t know reinforce those based on what we do know. To build a case on what we don’t know, however, takes courage, because it requires revealing how much experts disagree. There are many contending views about sea-level rise, for example. Advocates resist calling attention to the coexistence of contending expert views – far more certain than I am that lay audiences translate such conflicts into justifications for procrastination. I think it should be possible to convey that earth systems science is an evolving human enterprise where discordant views are the norm, and then to explain why certain issues have proved hard to resolve. My working assumption is that candor creates trust.

I wish some museum would prepare a climate exhibit with two adjacent displays that show two worlds with the same greenhouse gas concentrations at some future date (say, 50 years from now). One display would show a world in which human beings have been lucky and the worst manifestations of climate change have not yet arrived; in the other, we have been unlucky and at least a few of the more high-consequence outcomes are already on the scene. With the help of such an exhibit, the public would understand that neither those who proclaim with certainty that the world is facing imminent disaster nor those who seek to convince us that negligible suffering lies ahead can defend their case without going beyond today’s climate science.

Dangerous solutions

I was asked recently whether the right goal is to stop climate change as soon as possible. I realized that “as soon as possible” is not a simple concept. When driving a car, there are two ways to stop: slam on the brakes or brake carefully. Depending on the circumstances, either can be the right action.

Braking too slowly, in the context of climate change, creates excessive suffering from heat waves, floods and droughts, species extinctions, and sea level rise. Braking too quickly means

implementing “solutions” in ways that create unnecessary distress. Many of the stabilization wedges promoted in Pacala’s and my 2004 paper are ready for vigorous implementation, including ending deforestation, pursuing energy efficiency in all economic sectors (while monitoring actual energy savings), expanding large-scale wind and solar power (while attending to the associated infrastructure), and ramping up carbon dioxide capture and storage projects at coal and natural gas power plants (while radically reducing emissions that affect public health). There is not much risk of braking too quickly in these cases.

For other stabilization wedges, fast implementation seems more fraught. When land is converted to biofuel plantations on a very large scale, the global food supply can be disrupted and bio-diverse ecosystems can be simplified beyond recognition. A global expansion of nuclear power without effective international constraints on uranium and plutonium can make nuclear war more likely (a risk further discussed in Alex Glaser’s and my 2009 [Daedalus article](#)). Preemptive programs to compensate for global warming by deliberately reducing incoming sunlight (not on the list of wedges back in 2004 but pressed today by a few analysts as a way to counter slow progress elsewhere) can bring on changes in climate as nasty as those the world is seeking to prevent. All such negative outcomes can be avoided, but only when the pace of implementation is moderated and strict conditions are imposed.

Because everybody wants to brake neither too slowly nor too quickly, those of us advocating prompt action on climate change would develop better rapport with our audiences if we were to concede that the lowest conceivable greenhouse gas emissions targets are not ideal. By definition, such targets throw caution to the wind.

Iterative risk management

In our *Science* paper, Pacala and I envisioned a world where “policies... would inevitably be renegotiated periodically to take into account results of R&D, experience with specific wedges, and revised estimates of the size of the Stabilization Triangle.” In effect, we were anticipating the concept of *iterative risk management*, which works forward from the present instead of backward from the distant future, and which features learning as we go. Iterative risk management focuses on targets 10 and 20 years ahead, in addition to targets 50 years ahead. Target updating might occur as often as every 10 years, to incorporate new insights from earth-system science and lessons learned from wedge deployment.

Right now, especially in international politics, discussion focuses on a poorly defined, multi-century concept, the ultimate rise of the average temperature of the earth’s surface. There are heated arguments about whether that rise should be capped at 1.5 or 2.0 degrees Celsius (2.7 or 3.6 degrees Fahrenheit), relative to its pre-industrial value. By contrast, if diplomats were debating the implementation of iterative risk assessment, negotiations would become more

hard-headed. Specifically, there would be more attention to decade-scale global emissions targets.

What specific value for the 50-year target would I recommend? Given present knowledge, I would choose the target that is the analog of the one identified in the 2004 Figure in Pacala's and my *Science* article, reproduced above. Today's global emissions rate for carbon dioxide is 30 billion tons per year. For the world to emit in 2061 no more than 30 billion tons of carbon dioxide is as difficult a task as I could endorse today, taking into account the salience of other objectives to which I assign comparable importance, including preventing nuclear war, alleviating global poverty, and protecting the planet's biodiversity.

To be sure, "present knowledge" will be modified every decade by new insights into our planet and ourselves, which is the reason for iteration. (For more on iterative risk management, see [America's Climate Choices](#), a report from the US National Academy of Sciences, published last May. I was a co-author of the report.) For iteration to be maximally productive, it must be accompanied by strong global research and development efforts targeted at both the climate problem and innovative responses.

I hope this short essay counters an unfortunate report two months ago in the blogosphere to the effect that I now regret Pacala's and my wedges paper – that I consider it a "mistake" because it created false hopes that climate change could be achieved easily. The [blog](#), in *National Geographic News*, came from a longtime environmental journalist, Doug Struck, who heard a talk I gave at Harvard University. (I [responded](#) the next day.) I must have expressed myself poorly. On the contrary, I believe the messages of the wedges paper are as important as ever. The global greenhouse-gas emissions rate in 2061 is a better focus of attention than targets a century or more in the future. Achieving an emissions rate in 2061 no higher than today's is a goal that can be achieved by scaling up already deployed technologies. Given present knowledge, that goal is probably ambitious enough; pursuing tougher goals could lead us to opt for cures that are worse than the disease. And an iterative process for resetting goals is essential, in order to take into account both new science and newly revealed shortcomings of "solutions."

To motivate prompt action today, seven years later, our wedges paper needs supplements: insights from psychology and history about how unwelcome news is received, probing reports about the limitations of current climate science, and sober assessments of unsafe braking.

Ten solicited comments on the essay

“Wedges Reaffirmed”

Nicholas Stern, London School of Economics; lead author of the *Stern Report on the Economics of Climate Change* (2006)

The arguments for strong action to reduce emissions to manage climate change are immensely powerful. Yet, as Rob Socolow argues, they have not yet commanded the breadth and depth of understanding required for action on the necessary scale. I agree with this assessment, and with his position that part of the reason must lie in how the case has been presented, and with his description of how the arguments might be recast and marshaled in a more persuasive manner. My version of how the case can be made in a simple and direct form is as follows. It has much in common with, but is not identical to Rob's.

The risks from inaction on emissions, or delayed or weak action, are immense. Inaction could take, in a century, concentrations to levels that could imply a risk of 30-50 percent or so of temperature increases of 5 degrees Celsius above 19th century levels, temperatures the planet has probably not seen for 30 million years. Humans have been here as *homo sapiens* only for around 200,000 years. Such temperatures would likely transform where we could live, and hundreds of millions, possibly billions, of people would have to move, with the likely consequence of severe and extended conflict.

This is about risk management since, whilst we can be confident the risks may be very large, we can't be certain of consequences; we can at present deal only with probability distributions, at best. Of course, to recognize or speak in terms of risk and uncertainty must not be construed as “an admission that the science is unsound or unsettled.” We must be absolutely clear on the very strong and longstanding scientific foundations. In my view, as a humble economist, scientists can and must do a much better job at countering the unscientific, ill-informed, and aggressive attacks on the science. And they should provide the best account they can of the scale and meaning of the potential consequences. It is extremely hard to describe a 4, 5, or 6 degree Celsius world, in part because humans have no direct experience of one. But such a temperature change surely carries huge risks, and scientists are better capable of illustrating and explaining what these might be than are non-scientists. At stake here are not minor probabilities of discomfort, but substantial risks of catastrophic change of the relationship between humans and the planet.

Waiting for further clarification from the science of the probability distributions looks like a very dangerous policy. This is a flow-stock process (emissions to concentrations) and thus embodies a ratchet effect, since it appears very hard to directly reduce concentrations on any major scale. Further, delay locks in a high-carbon infrastructure. The necessary scale of action requires a new energy-industrial revolution. To have around a 50-50 chance of holding to a 2 degree centigrade increase, we would need to cut global emissions (in CO₂ equivalent) by a factor of around 2.5 by 2050 from their current levels. If world output grows by a factor of 3, we have to cut emissions per unit of output by a factor of 7 to 8. That means close to zero carbon per unit of output for most of the economy. Even if emissions or temperatures targets are relaxed somewhat, the scale of change must still be very large: it would be a new energy-industrial revolution, in any language.

That industrial revolution requires strong policies (it will not happen without pricing of carbon, taxes, regulation, and the like) and large investment. Like all industrial revolutions it will involve dislocation. We should not pretend that it will be easy. But past industrial revolutions (the great economic historian of technology, Chris Freeman, identifies five waves of technological change, from textiles in the later part of the 18th century to information and communication technology now and the last part of the 20th century) have brought a few decades of creativity, innovation, and growth. We can already see that creativity and innovation beginning. And there are the further likely benefits of energy security, a clean environment, safety, and biodiversity. It is absolutely not win-win-win—it will be difficult. But overall, it is a path that could be very attractive. It is the only plausible growth story. The high-carbon route will destroy itself.

The two defining challenges of our century are managing climate change and overcoming world poverty. If we fail on one, we fail on the other. If we cannot manage climate change, we will halt and reverse development. If we cannot tackle climate change in a way that creates opportunities for rising living standards in the developing world in the next few decades, we will never create the necessary international coalition for action.

The first part of the path is clear, in its rationale and sense of direction, its technologies, and its economic policies. We will learn along the way. What is missing is political will. That will not arise unless we are much more persuasive in our arguments. That must include strong and clear recognition of the uncertainties, difficulties, and dislocation associated with the new path, of the immensity of the risks of inaction, and of the great opportunities from a new way of producing and consuming.

Rob is absolutely right in insisting that we re-examine the way the case has been made. And his suggestions for re-casting are persuasive. This is where we have to think, work, and deliver.

Nicholas Stern

IG Patel Professor of Economics & Government,

Chairman of the Grantham Research Institute on Climate Change and the Environment

*** **

David Hawkins, director of climate programs, Natural Resources Defense Council

Rob Socolow and his colleague Steve Pacala did the world a great service with their 2004 paper setting forth the “wedges” framework for understanding how to tackle the problem of greenhouse gas emission reduction. In his above essay, Rob muses about the reasons for the failure of action (at least action by the Congress of the United States), and he offers some suggestions as to how advocates for forceful action might change the dynamic by talking about the need for action in different ways.

Rob is a friend and a mentor, but I disagree on several counts with his arguments.

First, Rob attributes the lack of action (presumably the failure of Congress to pass a federal cap-and-trade bill) to “public resistance.” I disagree. Based on my observation of the process, the failure of the Senate to take up the House-passed climate bill (or some variant of it) was not due to “public resistance,” but rather due to a very aggressive and organized opposition led by the Chamber of Commerce, American Petroleum Institute (API), and the National Association of Manufacturers (NAM). The senators influenced by this opposition were primarily Democrats (the Republicans having decided

well in advance of the interest group opposition campaign that they would oppose legislation as a matter of political strategy). The Chamber/API/NAM opposition convinced wavering Democrats that anyone who voted for a climate bill would be attacked aggressively for that vote in the 2010 campaign and elections. Those senators were unconvinced that supporters of the legislation would be able to mount a sufficient counter campaign to offset these attacks. So I regard the failure of climate legislation as due more to a lack of strong calls for action by the public rather than public resistance to action. This is an important distinction, because it has implications for what messaging, if any, can turn this situation around. I am skeptical that there is any way for supporters of action to talk about climate protection so as to generate a general public demand for action that is intense enough to cause swing politicians to vote for legislation if it is as aggressively opposed as were the cap bills in the last Congress. Removal of this impediment to action may lie not in efforts to get the public to demand action, but in efforts to ease the opposition of those who are fighting action.

There is also the efficacy of Rob's call for more nuanced descriptions of the climate problem. Rob's essay appears to suggest that it is uncertain members of the public who are the target audience, and his three message suggestions appear to be aimed at persuading that audience that supporters of climate protection action are not unreasonable zealots. To do this he suggests we should 1) not suggest that protecting the climate involves only good news; 2) acknowledge that the range of consequences from increased greenhouse gas concentrations is large and uncertain; and 3) that there are dangers presented by cutting emissions too fast.

While I share his discomfort with the message that fighting climate change means nothing but good news for everybody, I don't see any evidence that a more nuanced message would do anything to increase the demand for action from the public or reduce the opposition from groups like the Chamber, API, and NAM. We should acknowledge that protecting the climate is hard work, but we should not do so with the expectation that this will produce a consensus for action.

On the issue of describing the uncertain range of outcomes, I think that most advocates who are influential already do acknowledge this fact. We do not argue that science proves a particular set of disastrous impacts are certain to occur at some particular level of greenhouse gases. Rather we argue that the higher the concentration, the greater the risks are of significant damages, and that we cannot rule out that many of these impacts could be truly catastrophic. That risk profile warrants action now.

The most puzzling aspect of Rob's essay for me is his treatment of the issue of how fast to reduce emissions. He appears to argue that resistance to action will diminish if supporters acknowledge that some climate protection actions could have negative consequences. But the three examples he mentions –too rapid an expansion of nuclear power; wholesale conversion of lands to bio-energy production; and geoengineering to block sunlight – all have been the subject of substantial warnings and even opposition by strong advocates of climate protection. Ironically, an aggressive embrace of nuclear power has been argued by politicians like senators John McCain and Lindsey Graham as essential to get support for action from conservative politicians.

On this last question of how fast to cut emissions, Rob goes beyond advice about communication and presents conclusions about what level of emission reduction is advisable. He says the lowest global emission target for 2050 that he is comfortable endorsing is a level equal to today's emissions. And he concludes, "[g]iven present knowledge, that goal is probably ambitious enough; pursuing tougher goals could lead us to opt for cures that are worse than the disease."

This is a very provocative statement, and I would expect someone who is careful with analysis as Rob is to provide some support or citation for the proposition that setting a tighter target for 2050 will create significantly higher risks that unwise mitigation approaches will be pursued. But he provides no such support. Indeed, I believe that in connecting ambitious targets with unwise implementation actions, Rob is linking two aspects that need not and should not be linked. The proper response to the risk of taking stupid actions in the pursuit of appropriate goals is not to weaken the goals to inappropriate levels; it is to make the case that certain actions are stupid and should not be in the portfolio of responses unless modified to avoid the risks that they present.

*** **

Freeman Dyson, Mathematical Physics and Astrophysics Professor Emeritus, School of Natural Sciences, Institute for Advanced Study

When the Socolow-Pacala paper on "Wedges" was published in 2004, I welcomed the paper and agreed with most of it. It seemed to me a useful and realistic summary of possible future developments that might be required if the world economy were running out of fuel. I did not take seriously the notion that these developments might be undertaken in order to prevent climate change. At that time, the possibility of a world-wide fuel shortage appeared to be imminent, and the possibility of a global-warming catastrophe appeared to be remote. It was already clear that the greatest and most hopeful historic event of the new century would be the rise of China and India from poverty to prosperity. For the first time in the history of humankind, more than half of the population of the world would be rich. Compared with this historic achievement, the dubious dangers of climate change were clearly insignificant.

Now, seven years later, the situation has changed in two essential ways. First, the abundance of shale-gas, and its production in big quantities at low cost, have transformed the world fuel economy. It is now clear that we have enough accessible fossil fuels to maintain the rapid economic growth of China and India, not to mention Africa and Latin America, for at least half a century without additional "wedges". Second, the claims of scientific experts to understand climate change have become less and less credible. It has become clear that they neither understand the causes of climate change nor understand how to prevent it. The political machinations of the Intergovernmental Panel on Climate Change have been publicly revealed as unscientific, and its statements have been revealed as untrustworthy. As a consequence of these two changes, both of the motivations for pursuing the "wedges" program have weakened.

In the United States, the Democratic Party made a tragic mistake when it adopted the alarmist view of climate change as a part of its ideology. This mistake led the party to favor policies that increase the price of energy. Any increase of the price of energy hurts the poor far more than it hurts the rich. The ordinary citizen sees the subsidizing of expensive green energy projects as a welfare program for the rich. The result of this mistake is to drive millions of Democratic voters, who believe in social justice, into the arms of the Republicans. It is high time now for the scientific advisors of the Democratic Party to repair the damage that they have done. They should admit publicly that they were wrong about climate change, so that the Party can fight both for social justice and for cheap energy.

*** **

Carter Bales, chairman, NewWorld Capital Group; a Director of McKinsey & Company., 1978-98

Rob has provided a penetrating and different view on the climate change issue. His view is both subtle and balanced, fully acknowledging the deadly threat of climate disruption but also considering the costs and the risks of a solution, as well as the obvious benefits. I am particularly charmed by his case for openness and his acknowledging that we do not and will not know everything on which to base our actions. Although climate change discussions could be restarted along the lines that Rob suggests, no one should underestimate the difficulties ahead. In particular, the gaming of climate science must end, and climate science must be recognized as an ongoing process that provides the best available information to which leaders must add judgments. And the fossil fuel industries, in exchange for regulatory certainty, must help shape policies designed to close down "legacy" facilities in favor of new technology.

*** **

Robert Fri, visiting scholar, Resources for the Future; former Deputy Administrator, EPA

In his article Robert Socolow gets to the heart of how climate change science should be presented to policy makers and the public. His recommendation is to tell the story as straight as possible, even though that story is a bit complicated.

The challenge of explaining climate science is that while science can make a strong case that we should begin acting now to mitigate greenhouse gas emissions, science cannot yet tell us exactly what to do. That greenhouse gases result in warming the planet is black-letter science. There's also a strong case that increasing the ambient concentration of greenhouse gases in a complex climate system will increase global average temperature, though as Socolow points out there is a range of possible temperature outcomes for a given dose of greenhouse gases. But it is very hard to predict impacts on the natural world or on human activities like farming; science has a lot to learn about impacts. Not a terribly tidy scientific story, but it's clearly the one we've got and will have for some time to come.

The hard question that Socolow raises is whether telling this story would make a difference in the debate about climate change policy. I think it would do so in two ways. First, over time, understanding that there is a range of possible outcomes should help quiet the ardent advocates for one end of the range or the other. The climate debate is not a choice between the tails of a distribution, and allowing it to be so miscasts the debate in the public mind. Science should not be drawn into this false choice.

The other reason for hope is that, while it sounds complicated, dealing with uncertainty in policy is actually familiar territory for both policy makers and the public. Natural disasters always have a high degree of uncertainty—where a hurricane will make landfall, whether the levees will hold, when an earthquake might happen. And officials who deal with disasters have a very sensible strategy for dealing with this uncertainty: Hope for the best, but plan for the worst. I certainly hope that temperatures don't rise very much as we pump more greenhouse gases into the air, but it's only common sense to begin planning for something like the worst. That seems to me a story that's responsible scientifically and makes sense to the public..

One other point: Socolow has found a new use for the famous Pacala-Socolow wedges. With the passage of time, they have become a measure of the cost of delaying action. We're up to nine wedges from seven. That's a story that's easy to understand, too.

*** **

Christopher Field, Department of Global Ecology, Carnegie Institution, Stanford CA, and co-chair, IPCC Working Group 2 for the Fifth Assessment Report

From my perspective, one of the most important but underappreciated features of the wedges concept is the fact that they start small and grow gradually. They are really wedges and not boxes. It is tempting to think of the small starts as representing small commitments, but the opposite is actually true. Beginning to build a wedge at the small end requires a solid foundation of research and development, experience with scaling and technology diffusion, progress on cultural and psychological constraints, and a policy foundation that provides the confidence to support all of the other requirements. While building a wedge gradually from the small end is difficult, we know one thing for sure—building one much more rapidly is a lot more difficult. Yes, it costs something to start building wedges now. The question we all need to ask ourselves is whether we want to face the risk of making the task even more difficult by delaying.

*** **

Phil Sharp, President, Resources for the Future

The original "wedges" article by Pacala and Socolow provided a rebuke in 2004 to those in power who argued we did not have at hand the technology or fuels to get on a path toward stabilizing greenhouse gas emissions—a rebuke easily comprehended by the intelligent lay person.

In the above article he delivers wise counsel to the scientific and advocacy communities on how to reach those in power to get stronger action by employing an "iterative risk management approach" which helps one better grasp how to act in a world where there are uncertainties associated with what we know and with the consequences of our actions. Such a world is familiar to most smart people, and the effort by some advocates to articulate absolutes is both foreign and easily dismissed in the cacophony of today's public discourse. No one should underestimate the impact in delaying action that has resulted from highly financed attacks on science and on the advocates. But Socolow calls for greater recognition among scientists and advocates of the complex nature of the action required, the trade-offs involved, and the need for sustained, trustworthy communications.

The approach of "Iterative Risk Management," with Socolow's help, was the major theme of the recent National Academies report on America's Climate Choices. As a member of that committee, I became convinced that this framework provides a sustainable way for us to both think about climate change and to carry on serious public discourse. However, "iterative risk management" is still the language of specialists, and we need a better description for it. In simple terms, we act on what we know, aware of uncertainties; we learn as we go; and we adjust our actions in accord with that learning. To most intelligent persons, this is just common sense.

Since the failure last year by Congress to take serious action, some in the advocacy community have despaired at the thought of convincing the public by appeals to science. They would instead focus on the so-called "co-benefits" that might be derived from climate policy. While it is always worth pointing out such potential benefits, it would be a profound mistake to abandon a persistent effort to communicate the scientific arguments and new scientific findings. Our fundamental reason for taking strong action is the serious concern science has articulated about the warming path. And to sustain action, we need a clear and sustainable reason; we need not invent one or overstate the co-benefits to get the attention of leaders. I strongly believe that the "know-nothing" approach is not sustainable for major political leaders, and the imperatives of the economy cannot for long push climate change off the front pages.

*** **

Ralph J. Cicerone, President, National Academy of Sciences

In “Wedges Reaffirmed”, Robert Socolow revisits his 2004 paper (written with Steve Pacala), reasserts the validity of its main messages, and outlines the relative lack of progress toward its indicated actions. He also presents his views on why progress has been so meager and how to gain more momentum now toward ever more reliable solutions---by adopting a strategy based on continued learning and adjustments (or “iterative risk management”).

The overall framework of the 2004 Pacala and Socolow paper (and of its September 2006 *Scientific American* version by the same authors, but in reverse order) is difficult for readers who understand the Earth’s global carbon cycle, energy science and technology, and the fundamentals of climate science to reject. Indeed, I suggest that a large benefit of the new “Wedges Reaffirmed” piece might be that it stimulates more *Bulletin* readers and other scientists to read the original two papers.

The main challenge those original papers try to surmount is the stabilization of the concentration of atmospheric carbon dioxide at some target level. Decades of research have shown that natural sinks absorb about three billion tons per year of carbon globally (as carbon dioxide). This figure arises from estimates of the rates of uptake of carbon dioxide by oceans and of net biological uptake by photosynthesizing plants. The figure has been arrived at independently by stunningly precise measurements of atmospheric oxygen and related but more approximate calculations.

Thus, atmospheric carbon dioxide amounts will continue to rise as long as carbon emissions from fossil-fuel burning exceed three billion tons per year. In the last few years, these emissions have increased from about seven billion tons of carbon per year to about eight billion tons per year, and land-surface changes probably add another one billion tons of annual carbon dioxide emissions. Can one hope that natural sinks will increase in the future? Yes, but such hope does not qualify to be called a stabilization strategy, and there is evidence that growth in these sinks is likely to be small or even negative. Further, stabilization targets should take into account oceanic acidification brought about by more atmospheric carbon dioxide being absorbed into the oceans. .

The original papers showed how a seemingly intractable problem can be disaggregated into a reasonable number of portions, or wedges, for which focused actions toward an overall solution are potentially feasible.

The original framework and its specific wedges also served to portray the scale of the challenges that humans face in trying to stabilize atmospheric carbon dioxide concentrations. The scale is enormous. Indeed, Socolow notes that the original seven wedges (each of one billion tons of carbon per year) have grown to perhaps nine such wedges now. I add that radiative forcing of climate change involves other greenhouse chemicals (methane, nitrous oxide, a number of fluorine-containing gases, tropospheric ozone) so that carbon dioxide, while the most important of the human-added gases, is not the entirety of the greenhouse problem. From an Earth-system science research point of view, the forcing due to black carbon particles and other aerosols and their feedbacks on greenhouse-gas forcings require much better quantification than is available today. Even more wedges are likely to be needed.

A 50-year path for human actions does deserve much more attention than the various, more frequently described 100-year paths. Even the shorter period of 50 years can lure us into believing that the next generation should be responsible for hitting the most difficult targets, rather than the current generation. Socolow proposes that even with the shorter period for our focus, it is likely that we will

have to revise strategies and approaches, often in the light of new knowledge. His proposals are very valuable and sensible.

*** **

Rush Holt, Congressman (D-NJ)

The wedge rubric that Pacala and Socolow laid out in 2004 was very useful because it illustrated that, although the problem of climate change mitigation is daunting, it could be addressed by taking a finite number of steps using existing technologies. If addressing the problem of climate change required a tectonic change akin to the discovery of electricity (a dismissive comment Socolow attributes to a former secretary of energy), we might as well call it quits, but the wedge paper actually gives us hope.

Although public attention to the climate change problem seems to have evaporated, the problem has not gone away. Indeed, as Socolow points out, it has gotten worse. And so, when public interest and matching political interest return, the wedges rubric will once again be useful.

Socolow refers to the human tendency to shoot the messenger, even referring to Galileo, but I am pleased to note that no ecclesiastical inquisition has summoned the authors thus far. And Socolow remains undeterred in envisioning ways of engaging and sometimes challenging public perception, such as presenting alternative pictures of our future, ranging from one that is mildly unpleasant to one in which climate change monsters abound.

*** **

Robert May, Professor of Zoology, Oxford University and Imperial College of London; former president of the Royal Society

While I broadly agree with much of what Rob says, I do think his essay is more than a little generalizing from the USA to the world. And I also think it is a bit naïve when it fails to mention the active and very professional lobbies of denial (much of whose work has explicit connections with the same professionals who ran campaigns denying that smoking causes lung cancer).

So my first thought is that it might be a good idea if you took into account the recently published and excellent book entitled *Merchants of Doubt*. This makes rather clear that no matter how you went about presenting things -- and I do have a lot of admiration for much of what you are suggesting -- you would still be up against a very powerful and very skilled lobby of flat denial .

Second, I think what the UK has done makes a lot of sense, even if it is not working as perfectly as one would like. To begin with one headline statistic, surveys show that something like 80 percent of the general population here agree that climate change is real, largely human produced, and very serious (these are professional polls with properly randomized sampling). We also have detailed legislation creating a commitment to targets, backed up by an expert consultative process to set the targets and monitor them. In setting the targets, we begin by taking the IPCC estimates (along with their uncertainties) about what we should be aiming for by 2050 if we are to have no worse than a 50/50 chance of exceeding 2 degrees Celsius (which is also a less than 1 percent chance of exceeding 4 degrees Celsius). We then divide this by the estimated global total population in 2050, to get the output per person. The UK's fair share is then to meet this target, which means a massive (more than 80 percent) reduction in the UK's per capita output. Given this target, the Committee has recommended an achievable trajectory to 2050, and much more specifically to 2020. We are on target at the moment,

but on the other hand that is partly through the actions that have been taken, but equally importantly through the effects of the recession.

Third, what is happening in the UK is so vastly different from what is happening in the USA, that I do not think it makes sense to make general statements about what the world is doing without acknowledging the colossal differences between other countries -- and what, from the outside, looks like collective insanity in the USA at the moment.

As ever, I have stated my opinions with excessive emphasis! I do think the questions that you are raising are important, and I do think that on occasion we are all guilty of not giving sufficient emphasis to the fact that -- although it is by this time certain that climate change is real, human created, and worrying -- there remain very significant uncertainties about a lot of the details of non-linear processes and consequent timescales. The issue of global population size is also a key factor, one that is difficult to state explicitly, although again the Climate Change Committee in the UK has done so. But I can imagine that it would be virtually impossible to raise that issue given the religious right in the USA at the moment.

In short, I approve broadly with what you are doing, but do urge upon you a somewhat wider perspective.