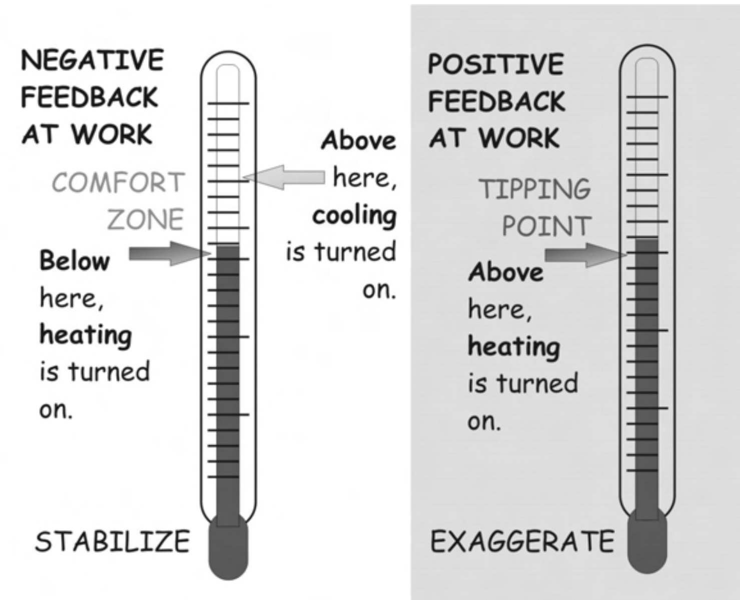

NEGATIVE FEEDBACK AT WORK
COMFORT ZONE
Above here, cooling is turned on.
Below here, heating is turned on.
STABILIZE
POSITIVE FEEDBACK AT WORK
TIPPING POINT
Above here, heating is turned on.
EXAGGERATE

8

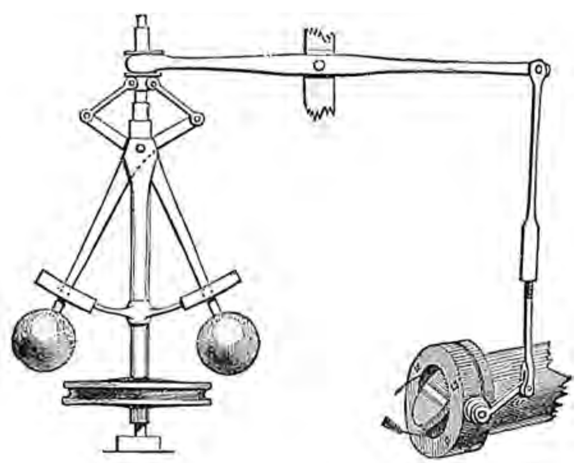
What Makes a Cycle Vicious?

For droughts, it was just one damn thing after another—not identical dominos falling into one another, but rather a varied knock-on chain of causation. Rube Goldberg is said to be the patron saint of biology because life forms feature such long chains of causation. They have some virtues, as they provide multiple ways to interfere with the end product—medicines often work by interrupting the chain. Perhaps the knock-on chains in climate mechanisms will similarly offer some promising targets for intervention.

But there are also vicious cycles in which one action repeats, building up steam. You'll need to understand vicious cycles to appreciate the greatest climate change of all time, "Snowball Earth," in which even the oceans froze down into the depths (sea ice today is seldom more than several meters deep).

Most people associate the term "feedback" with suggestion boxes and critiques, with positive feedback being good and negative feedback being bad. There are no such connotations to the scientific use of the terms. Negative feedback is commonly used to stabilize something. Let the room temperature fall below the desired temperature, and the modern thermostat turns on the furnace. If temperature rises too much, the cooling mode starts up instead.

One of the earliest industrial applications of negative feedback was the speed governor of James Watt's steam engine. The faster it spun, the more the spinning weights "stood up" and slowed the steam supply. Let the speed fall and the balls drop, the air supply opens up, and the speed drop starts to reverse. This enables the engine to run at a steady speed (to set it for a lower speed, just tighten up the linkage rod).



Negative feedback serves to hold speed constant.

All this is pretty obvious when you look at it working in a science museum, but analyzing it mathematically confounded one of the great physicists of the nineteenth century, James Clerk Maxwell. "Try as I may, its analysis defies me," he is reported to have said. There is no standard Cartesian cause-and-effect way of thinking about it; the logic becomes circular. The whole has become something more than the sum of its parts.

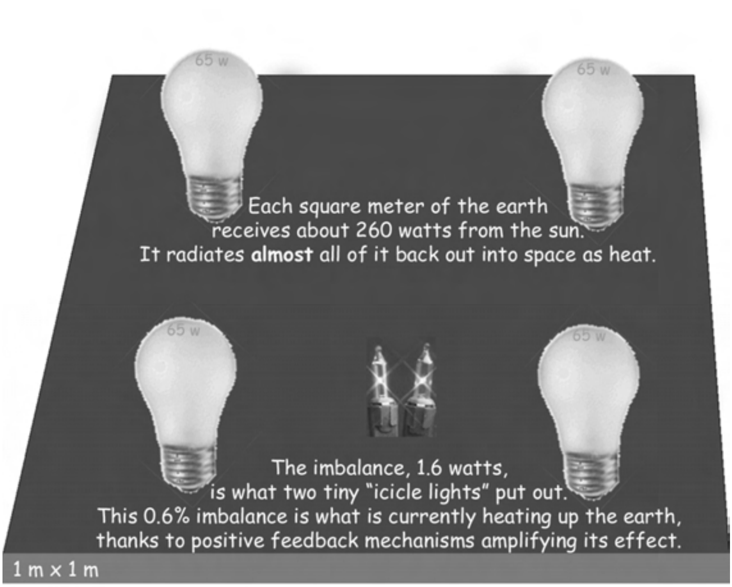
The real world is full of such negative feedback mechanisms where cause and effect get all mixed up. When I was a graduate student in the early 1960s, researchers were busy studying the feedback loops for adjusting our body temperature, our blood pressure, and our body fat. I can well remember how confusing it was to make the transition from simple cause-and-effect reasoning to the thinking needed for dynamic systems with feedback.

The Earth's wide swings in climate during the ice ages were greatly exaggerated by feedback. So too is our present global fever: it's those feedback loops that make a mountain out of a molehill. We'd better understand them thoroughly.

Most vicious cycles involve positive feedback. Besides compound interest and potholes, you have also likely encountered the squeal when a microphone picks up a sound from the loudspeaker and amplifies it even more. And more. Fortunately, the amplifier's power supply has a limit beyond which it cannot go, or the exponential growth of the sound wave might shake apart the entire universe.

There is a version of positive feedback for snow and ice on the timescale of days. When it is cold enough to snow, it can get colder automatically. That's because white surfaces reflect a lot of sunlight back out into space—about 90 percent of the incoming energy, as long as the snow is nice and white. Uncovered, the ground might have absorbed most of the incoming sunlight, changing it into heat. With snow, this usual input gets rejected, bounced out of this world. The same thing happens with sea ice capping an ocean. And so the world cools a little. The climate changes over the years.

With it cooler, snow covers even more of the Earth, and for more of the year. That's the vicious cycle. Colder means whiter, which means even colder.



The reason that a small 0.6 percent imbalance can cause such big climate changes is that it is amplified greatly by a series of feedback loops, as when green replaces white in the Arctic.

You can see how the earth might become one big white ball rotating through space, with the remaining oceans frozen solid. Indeed, the earth might get stuck in that unhappy state, with no way to warm itself back up. This is known as the White Earth Catastrophe. Like a black hole, once you're in it, you can't get out. (It must not have happened, the reasoning went, because here we are, not frozen.)

This was one of those homework exercises for students until recently, when it was discovered that it had actually happened. Not once, but at least three times, all back in Precambrian times perhaps 700 million years ago. Something reversed each episode of Snowball Earth. It's called the greenhouse effect.

More CO_2 warms things up because it traps some of the heat that would otherwise escape into space. But a hotter earth also radiates more heat back out into space. This eventually brings solar input and earth's heat output back into balance, whereupon things settle down at some higher temperature. So it's as if more CO_2 nudged up the thermostat setting for the Earth. It's much like tweaking the linkage rod on that engine governor of Watt's.

During Snowball Earth conditions, parts of the ocean remained unfrozen because they were adjacent to hot springs—and that's how life forms survived. Here and there, a volcano poked through the snow and ice. A volcano emits a lot of CO_2. And the major route for removing CO_2 was missing. Normally some CO_2 is carried down by rain and reacts chemically with rocks. With no rain to "weather" the rocks, the CO_2 hung around in the atmosphere, accumulating.

Eventually the surface of the equatorial snow began to melt a little from the combination of greenhouse warming and summer sunshine. This started another positive feedback cycle that repeatedly warmed the Earth. What was it?

> Palaeoclimate data show that the Earth's climate is remarkably sensitive to global forcings. Positive feedbacks predominate. This allows the entire planet to be whipsawed between climate states.
>
> One feedback, the 'albedo flip' property of ice/water, provides a powerful trigger mechanism. A climate forcing that 'flips' the albedo of a sufficient portion of an ice sheet can spark a cataclysm. Inertia of ice sheet and ocean provides only moderate delay to ice sheet disintegration and a burst of added global warming.
>
> Recent greenhouse gas (GHG) emissions place the Earth perilously close to dramatic climate change that could run out of our control, with great dangers for humans and other creatures.
>
> —James Hansen, Makiko Sato, Pushker Kharecha, Gary Russell, David Lea, and Mark Siddall, 2007

Well, it's not surprising that you didn't know, as it's only recently that I've heard the earth scientists emphasizing it. (They call it an albedo flip.) But it is simple enough.

Fresh snow and ice reflect about 90 percent of the sunlight, with 10 percent remaining to heat up things on Earth. That's when skiers and climbers need really dark sunglasses on a clear day, with sun block to match.

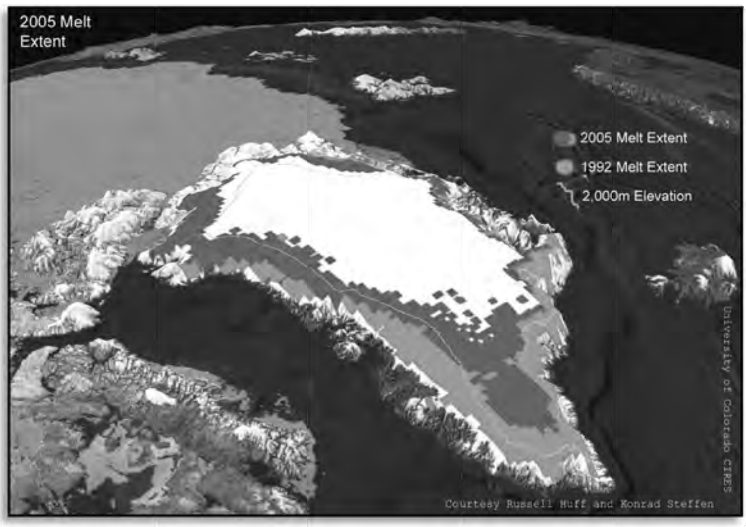
With a little moisture forming on the snow surface during the day (what skiers near Seattle usually experience), the snow is no longer as bright and ordinary sunglasses suffice. Wet snow is slightly gray, reflecting only 70 percent of sunlight. This may triple the amount of solar energy retained by the snow pack. And so, unless there is a fresh snowfall to restore things, the surface warms up.

In Snowball Earth, the greenhouse warmth finally wetted the surface, which in turn caused even more snow to turn gray around the edges, and so it warmed some more. Pretty soon, the ice melted in the tropics, leaving a blue ocean that retained most of the solar energy that reached it. Eventually, when the ice retreated from the subtropics, positive feedback finally shifted into high gear and finished the melting job.

Saved by the greenhouse. But there is one little problem with going this route, one we wouldn't want to suffer through. It stays really hot and humid for millions of years after the ice is gone.

Getting rid of the greenhouse excess can be a slow business. Some of the CO_2 can be gradually stashed in the ocean depths. Photosynthesis cleans out some more, converting CO_2 into more plants. But the major way of removing CO_2 from the air, certainly back in the Precambrian era, is through the "weathering" of rocks. The CO_2 in the air combines with the water vapor to form a weak acid. When that rains on rocks, it is corrosive. Thus some CO_2 fails to return to the air. Instead the carbon compounds are washed down the rivers and sink in the ocean depths.

Weathering is so slow that, for many millions of years after the melt-off, the Earth remained quite hot, about $50^{\circ C}/120^{\circ F}$. That compares to about $15^{\circ C}/60^{\circ F}$ for a present-day global average temperature. Our current excess greenhouse could take a long time to counter, given that we've already cut down most of the forests.



The white areas of Greenland on this map are where the air temperature remained low enough in 2005 so that summer sunshine never succeeded in melting the surface layers, not even for a day. All of Antarctica is that cold too, except for the Peninsula. The light gray shows the areas that melted in 1992; the darker gray the additional areas that melted in 2005. In northwest Greenland, little melted in 1992, but more than a million square kilometers melted in 2005. Huff and Steffen (2005).

"Climate feedbacks" is a phrase you see in the news, especially when a newspaper editor has decided that the issue is too complicated for ordinary mortals to understand. But it really isn't so difficult, as you see in these two examples of positive feedback in climate change. Brighter-is-cooler-is-even-brighter in one direction, then greenhouse warming makes it possible to melt it all when getting progressively gray.

There is, of course, a normal heat-trapping effect, as those nineteenth century physicists realized. Things would be pretty cold if there were not. The "greenhouse problem" is simply about the unfortunate change toward too much of a good thing. Everything is a poison at a high enough dose, even water. Now we know that we have to treat fossil fuels that way too.

What you may not have heard is that the most common heat-trapping gas is not CO_2 but humidity. There is a lot of it around clouds. That's the reason why those cloudless nights are cooler. Water vapor accounts for 60 percent of the normal greenhouse effect. In second place is CO_2, and third place goes to methane.

You hear about CO_2 effects on climate change because it is clear that cutting down forests and burning fossil fuels are things that are likely to increase CO_2 levels (so is the Portland cement-making process). But don't get distracted by the blame game, those arguments over whose fault it is. Even if the whole overheating problem were to turn out to be a brighter sun or methane seeps, we'd still have to do something to save our civilization, and CO_2 is the heat-trapping gas over which we have the most voluntary control.

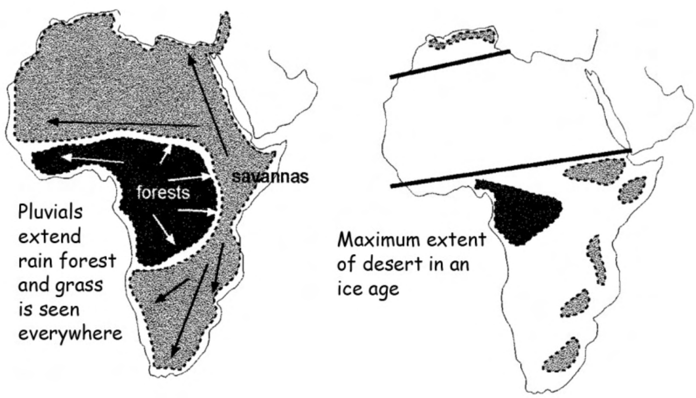
Now note that humidity amplifies the CO_2 warming effect by about 50 percent. When CO_2 increases the storage of heat in the lower atmosphere, it promotes more evaporation from the tropical oceans. And thus even more warming. Positive feedback strikes, once again. A 1°C warming increases both humidity and rainfall by 7 percent. (The models had predicted that rainfall should only increase by 2 percent—but the data say otherwise.)

Besides amplification, has humidity caused a greenhouse by itself in the past? (Say, via changes in atmospheric circulation that allow more water vapor to circulate?) It is difficult to measure anything about average humidity from the usual paleoclimate records until you get to the time span of tree rings, but the geophysicists have been very clever about inventing new methods and perhaps some information will emerge.

What is, however, already clear is that the lower atmosphere (containing most of the humidity and clouds) has gotten thicker over the last half century, as well as warmer. That's more troposphere and less stratosphere. Now there is room for more water vapor in the atmosphere—and so more blankets are wrapped around an already feverish Earth as part of the reaction to the added CO_2.

Positive feedback is also found in systems that bounce the sunlight back into space before it heats up the Earth very much. The sunlight rejection mechanism involves things that make the earth lighter and darker.

For example, for about 9,000 years out of every 25,000 years or so, there is enough hot-summer monsoon rainfall to allow the Sahara and the Arabian Peninsula to grow grass. With the earth's surface darker, less sunlight was bounced back into space. Which, of course, helped warm things a little more.



At the maximum extent of African savanna, about 6,000 years ago, most of Africa was green. During an ice age when even grass has a hard time, Africa is bright, reflecting much sunlight back out into space.

The last such "pluvial" period ended suddenly about 5,500 years ago. We know this as the period around 3500 B.C., when the great civilizations got started in the Nile and Tigris-Euphrates river valleys. In Egypt, a famous historical relief from about 3100 B.C., the mace head of Scorpion King, shows one of the last predynastic kings ceremonially cutting a ditch in a grid network.

Climate change can, it seems, stimulate innovation in government—at least back then. Tax collectors found that they needed to keep records of who paid what, and so writing was invented about 3200 B.C.

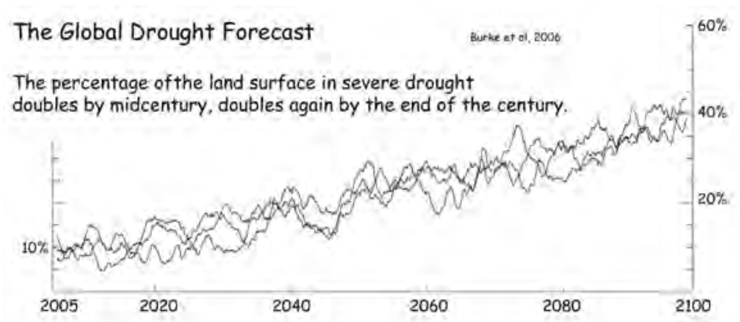
> Melting ice means more of the dark ocean is exposed, allowing it to absorb more of the sun's energy, further increasing air temperatures, ocean temperatures, and ice melt. It seems that this feedback, which is a major reason for the pronounced effects of greenhouse warming in the Arctic, is really starting to kick in.
>
> —climate scientist Ted Scambos, 2006

Changes in the land surface may be less dramatic than the melting of sea ice, but it is estimated that about 40 percent of the Earth's fever comes from cutting down trees over the centuries. When there is less uptake of CO_2 for growing trees, things warm even without fossil fuels.

But encouraging forests may not reverse this problem, as trees may also change the balance between reflection and absorption of sunlight. For urban trees with roads beneath them, more trees will mean less CO_2. But the present warming in high latitudes is causing the trees to grow farther north. Like melting the sea ice, this warms up the locality by absorbing more sunlight. Similarly, irrigation of sandy soils changes a light-colored surface into a dark one.

This isn't a major consideration in the tropics, but replanting there can be thwarted by the loss of biomass. Forest clearing for agriculture burns off the biomass that would have ordinarily gone into rebuilding the soil when the vegetation decomposed in the ordinary chain of events. And in the tropical rain forests, the web of roots is so efficient at recycling that the soil is quite thin in many places. Burn off the trees and you kill off the root system, allowing rains to wash away soil. Slash-and-burn agriculture exhausts the soil in only a few years, and so the farmers slash and burn somewhere else in order to feed their families.

They badly need a different agricultural economy. Indeed, given the global drought forecast, we all do.



While climate change helped get civilization started, it is equally clear that climate change can collapse a civilization.

It depends, as Diamond makes clear in *Collapse,* on how people respond to the challenge. And how early they act (it's that weakening frog in the hot tub again).

GLOBAL
How to Treat Climate Change
FEVER

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