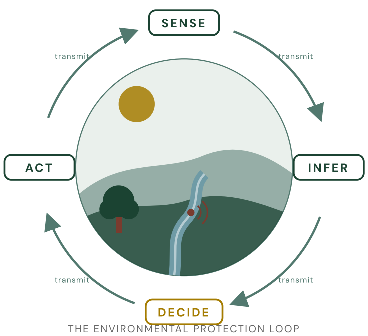
The environmental loop through time: *who closed it, how slowly, and why.*

What the protection loop looked like in every era of Earth's history, which physical limit bound it at each stage (delay, noise, bandwidth), and why the era now opening is the first break in a four-billion-year rule. With the computations shown, not just the claims.



THE ENVIRONMENTAL PROTECTION LOOP

01 · THE LOOP

Four jobs, one clock, and a goal set from outside

Protecting anything, a cell, a child, a river, a planet, means running one loop. Something has to notice that the world changed (**sense**), work out what is happening and where it is heading (**infer**), choose what to do about it against a goal (**decide**), and then change matter (**act**). The act changes the world, the world is sensed again, and the loop repeats. Everything else in this analysis is about how long each job took, who did it, and what physically limited them.

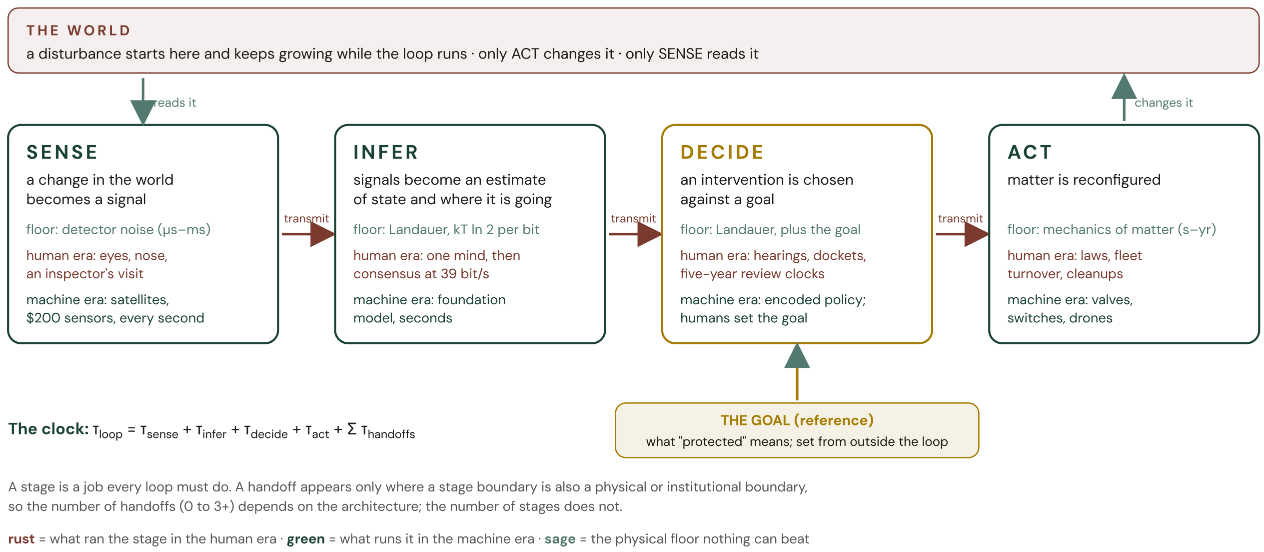


Figure 1. The protection loop. Four stages every instance must run; transmission is the cost of each arrow, and how many arrows cross a physical or institutional boundary depends on the architecture. The goal (what "protected" means) enters at DECIDE and is never produced by the loop itself.

> **IN PLAIN TERMS**
> A ball rolling around inside a bowl always ends up at the bottom. That is feedback. Nothing chose the bottom, nothing is defending it, and if the bowl is tilted the ball simply settles somewhere else. A thermostat is different: someone set 20 °C, and the furnace works to hold it. That is a regulator. Only the second kind protects anything, and it needs three things the bowl lacks: a goal, a way to tell the difference between the goal and the world, and enough speed to act before the difference becomes permanent.

Three physical limits govern every loop ever built, by chemistry, by evolution, or by engineers. **Delay**: the time between a change and the correction. **Noise**: the time it takes to be sure a change happened at all, against a background that is always fluctuating. **Bandwidth**: how many bits per second, and how many operations per second, the loop's parts can move and process. Each era in Earth's history is a particular answer to the question of who ran the four jobs, and which of these three limits bound them. Section 2 shows each limit with a small experiment and compares the two instruments, human and machine, that can run the loop; Section 3 walks the eras; Section 4 measures where the decades actually went in the regulatory era; Section 5 shows why the loop can close now, by routing decisions by reversibility rather than by jurisdiction; Section 6 lists what the machine era does not fix; Section 7 states what the history predicts.

02 · THREE LIMITS, THREE EXPERIMENTS

Delay, noise, and bandwidth, each shown rather than asserted

2a. Delay: past a threshold, the controller becomes the disturbance

Delay is not friction. A feedback loop with a pure time delay τ loses phase in proportion to frequency, $\varphi = -\omega\tau$, and once the phase lost at the disturbance's own frequency exceeds the loop's margin, corrections arrive on the wrong half of the cycle and push instead of pull. To make this concrete I simulated the simplest possible case: a first-order plant with time constant T, a proportional controller with gain 3, and a step disturbance, with three different dead times. For this system the critical delay is exactly computable, $\tau_{crit} = (\pi - \arctan\sqrt{(K^2-1)})/\sqrt{(K^2-1)} = 0.68\ T$.

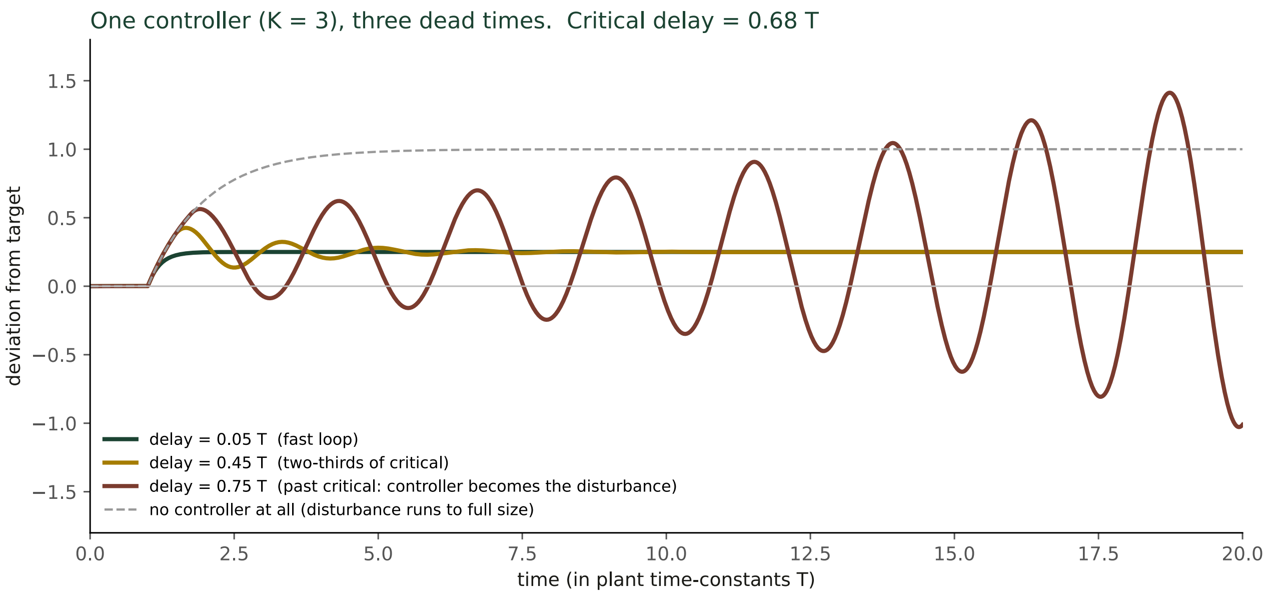


Figure 2. Same plant, same controller, three delays. At 0.05 T the loop holds the disturbance to a quarter of its size. At 0.45 T it still holds, with a wobble. At 0.75 T (past the critical 0.68 T) the oscillation grows without bound; by t = 20 T the deviation reaches 1.41, larger than the disturbance would have been with no controller at all (dashed line, 1.0). No gain setting rescues the third case: raising K lowers τ_{crit}. Only shortening the delay does.

IN PLAIN TERMS

Try steering a car using a photograph of the road taken ten seconds ago. At walking pace you will manage. At highway speed every correction you make answers a curve you already passed, and you will swerve harder and harder until you leave the road. The cure is not a better driver or a stronger grip on the wheel; it is a fresher photograph. In the regulatory era, environmental protection steered a planet from a photograph that was, in many cases, decades old.

The design rule that falls out is the one the manuscript already states: a loop with latency τ cannot stabilize disturbances faster than roughly $1/\tau$, at any budget, with any mandate. A river plume that crosses a town in an hour, a bloom that doubles in a day, a reef that bleaches in two weeks: these set the frequencies. A loop that closes in years is not a weak regulator of them. It is not a regulator of them at all.

2b. Noise: how long it takes to know something changed

Sensing is not free of time even when the instrument is instantaneous, because every real measurement sits on a fluctuating background and a single reading cannot tell a real change from a bad day. The mathematics of this, sequential change detection (Page's CUSUM, 1954; Lorden, 1971), gives a clean answer. If each sample has signal-to-noise ratio δ (the size of the change in units of the background scatter) and you allow one false alarm per budget period, the number of samples needed before you can declare a change is about $2 \cdot \ln(ARL_0 \cdot \delta^2/2)/\delta^2$, where ARL_0 is the false-alarm budget counted in samples. The wall-clock time to know is that number times the sampling interval. Two consequences matter here. First, time-to-know scales almost linearly with how often you look, because the false-alarm penalty is only logarithmic. Second, it scales with $1/\delta^2$: a change half as large takes four times as many samples to confirm.

I ran the detector rather than trusting the formula: 300 Monte-Carlo trials per cell, false-alarm budget fixed at one per ten years of wall-clock regardless of sampling rate, and the threshold checked against a directly simulated false-alarm run length (target 3,650 samples; measured 3,709).

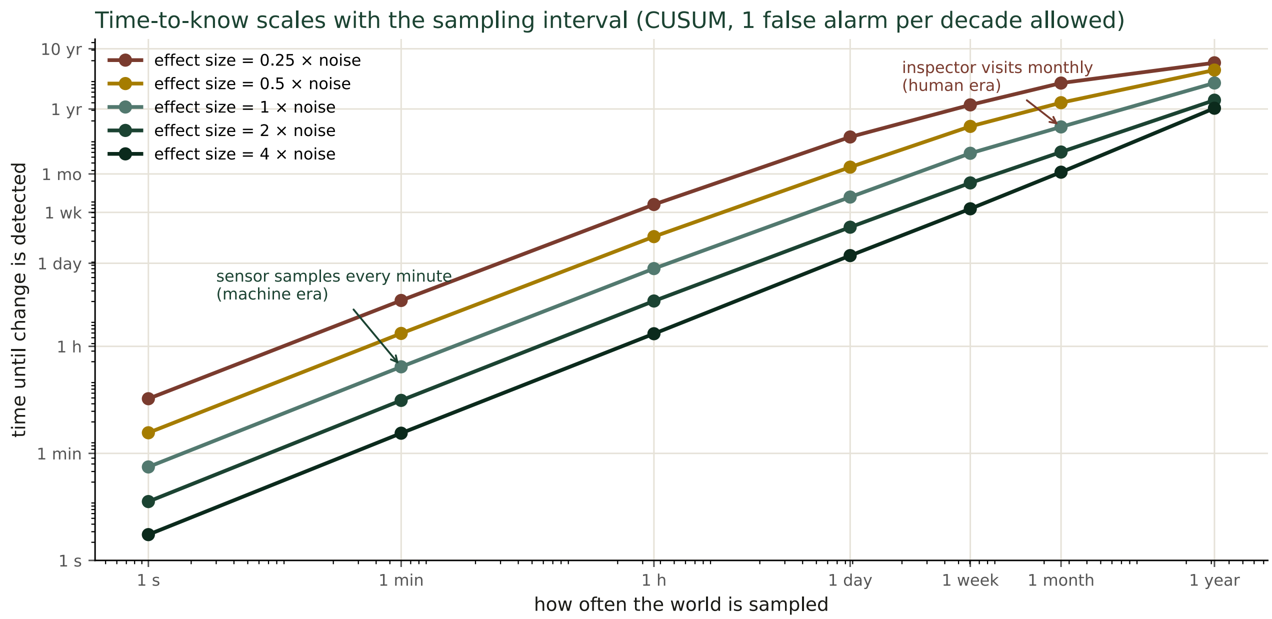


Figure 3. Time until a change is confirmed, as a function of sampling interval and effect size, at a fixed budget of one false alarm per decade. A one-sigma change (effect size 1) is confirmed in 27 minutes by a sensor sampling every minute and in 6 months by an inspector who visits monthly: a ratio of about 10,000 for a sampling ratio of about 44,000. Slower sampling never buys back reliability; the budget is held constant across the whole figure.

effect size (change ÷ noise)	sampled every 1 s	every minute	every hour	every day	every week	every month	every year
0.25 × noise	8 min	5.8 h	9.5 d	4.1 mo	1.2 yr	2.7 yr	5.8 yr
0.5 × noise	2 min	1.6 h	2.8 d	1.3 mo	6.2 mo	1.3 yr	4.4 yr
1 × noise	36 s	27 min	19.6 h	12.6 d	2.2 mo	6.0 mo	2.7 yr
2 × noise	10 s	8 min	5.7 h	4.0 d	21.6 d	2.3 mo	1.4 yr
4 × noise	3 s	2 min	1.6 h	1.3 d	8.0 d	1.1 mo	1.0 yr

Table 1. Simulated time-to-know (CUSUM, one false alarm per decade). Read across a row to see the cost of sampling rarely; read down a column to see the cost of a small effect.

> IN PLAIN TERMS
>
> A smoke detector faces a dilemma. Set it sensitive and it shrieks at toast; set it tolerant and it sleeps through a fire. The only way out of the dilemma is to sample often: a detector that checks the air a thousand times a second can afford to be tolerant on each reading and still raise the alarm within a second, because a real fire keeps the evidence coming. A human inspector who visits once a month is a smoke detector that samples monthly. For that inspector to be sure, the fire has to be enormous.

This is the quantitative core of the human era's slowness at the first stage, and it has three parts that stack. **No channel.** Human senses have no receptor for carbon dioxide, lead, methylmercury, chlorofluorocarbons, or ozone; the effect had to route through something a person can see, cats convulsing in Minamata (noticed around 1950, attributed to methylmercury in 1959), birds dying, a fog that killed thousands in five days. In the language of the detector, the human era could only see changes with $\delta \gg 1$, so the harm had to grow until it was unmistakable. **Sparse sampling.** Before instruments, the world was sampled by chance and by season; in the regulatory era, many decisions were clocked rather than triggered, with the five-year review cycle of the U.S. air standards as the canonical example. A clocked stage adds, on average, half its period before it even begins. **Aliasing.** Nyquist's theorem says a process sampled slower than twice its own frequency cannot be seen at all, only misread. A monthly water sample does not show a bloom that doubles daily; it shows a random number.

Noise also enters at every handoff. Speech is a lossy channel, memory is a lossy store, and a finding that passes from instrument to scientist to committee to legislator to operator is copied four times through channels that lose information at each step, the telephone game run at planetary stakes. The regulatory era's inference stage had a further property worth naming plainly: its output had to reach social consensus, and consensus is a channel that interested parties can jam. Patterson published in 1965; the lead industry's toxicologist told a symposium that December there was not enough lead in the environment to harm anyone; the first federal phase-down rule came in 1973. Eight of the 73 years in the lead loop were spent in a contested channel. Machine inference does not remove politics from DECIDE, but it does remove the social channel from INFER: an attribution that rests on a million sensors is harder to argue with than one that rests on a paper.

2c. Bandwidth: the two instruments that can run the loop

The third limit is throughput. A loop's stages and handoffs are channels and processors, and each has a ceiling in bits per second. The human ceilings are measured and, for the purpose of this analysis, fixed: they have not changed since the Pleistocene and no training changes them.

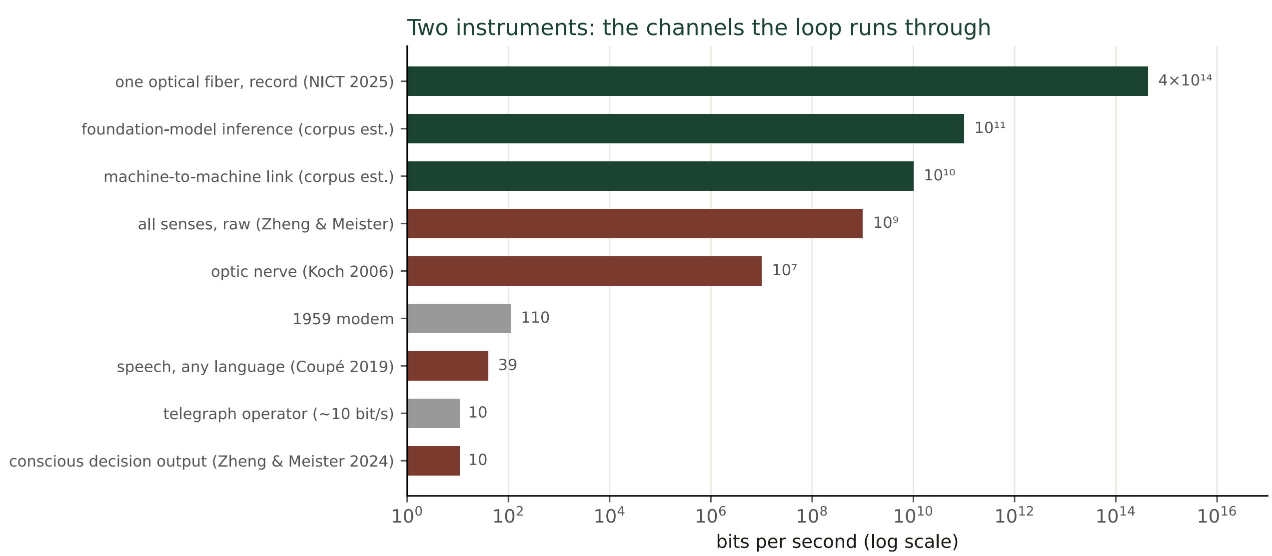


Figure 4. Channels on a log scale. The human instrument takes in about 10^9 bits/s across its senses (Zheng & Meister 2024), passes about 10^7 bits/s down each optic nerve (Koch et al. 2006), and emits decisions at about 10 bits/s; the channel between two human minds, speech, runs at 39 bits/s in every language measured (Coupé et al. 2019). A single standard optical fiber carried 430 terabits per second in 2025 (NICT). The 1959 modem and the telegraph are included for scale: the human inter-mind channel is slower than the first modem.

property	human instrument	machine instrument	ratio (order of magnitude)
raw sensory intake	~10^9 bit/s, but almost entirely discarded before awareness	limited by sensor count and fiber: 10^{14} bit/s per fiber	10^5 per fiber

decision throughput	~10 bit/s, serial, one thing at a time (contested; 10–50 range)	~10^{11} bit/s for a foundation model (corpus estimate)	10^{10}
channel between units	39 bit/s (speech), ~10–50 bit/s (reading, typing)	10^{9}–10^{14} bit/s, error-corrected, effectively lossless	10^{7}–10^{12}
what is held at once	about 4 chunks in working memory (Cowan 2001)	10^{5}–10^{6} tokens of context; the full sensor field	10^{5}
copying learned state	impossible; 25 years of expertise is re-taught through the 39-bit channel, lossily	every parameter copied losslessly to any number of endpoints in seconds	unbounded
reaction latency	0.2–0.3 s (reflex); seconds to days (deliberation); the institution adds months	10–100 ms per hop at the speed of light; seconds per inference	10^{2}–10^{7}
duty cycle	8–16 h/day, degrades with fatigue, one place at a time	continuous, replicated, everywhere the sensors are	—
energy	~20 W for the whole brain; ~2 J per behavioural bit at 10 bit/s	Landauer floor 2.9×10^{-21} J/bit at 300 K; hardware today runs ~10^{9} above it	—
characteristic failures	sparse sampling, lossy memory, bias, fatigue, pride, jammable consensus	out-of-distribution error, spoofed sensors, correlated failure, a mis-specified goal	different, not absent

Table 2. The two instruments. Human figures: Zheng & Meister (Neuron 2024; the 10 bit/s figure is disputed, with critics arguing for higher inner-brain rates), Coupé et al. (Science Advances 2019), Koch et al. (Current Biology 2006), Cowan (2001). Machine figures: NICT fiber records (2024–25), Landauer (1961) and the manuscript's estimates for inference throughput and the gap above the Landauer floor.

WHY MORE PEOPLE NEVER FIXED IT

Putting every environmental scientist alive in one room does not raise the ceiling, because the room coordinates through language, and a coordination that runs through a 39-bit channel inherits that channel's speed and then adds meetings. A billion telegraph operators passing notes do not assemble into a visual cortex. This is the reason the regulatory era's loop stayed at years to decades through a century of growing expertise: the instrument did not change, and the channel between instruments did not change.

03 · THE ERAS

Who ran the loop, and how slowly, from the Hadean to now

The clean version of the history has three regimes, not six. For four billion years there was feedback but no regulator: nothing had a goal. For a few centuries at any scale beyond a village, there was a human regulator: a human goal, run by a human loop. What is emerging is a human goal run by a machine loop. The finer eras below are the steps between those regimes, and the interesting fact about them is that each one sped up exactly one stage or one kind of handoff, while the loop as a whole stayed at years to decades, because a loop is only as fast as its slowest stage.

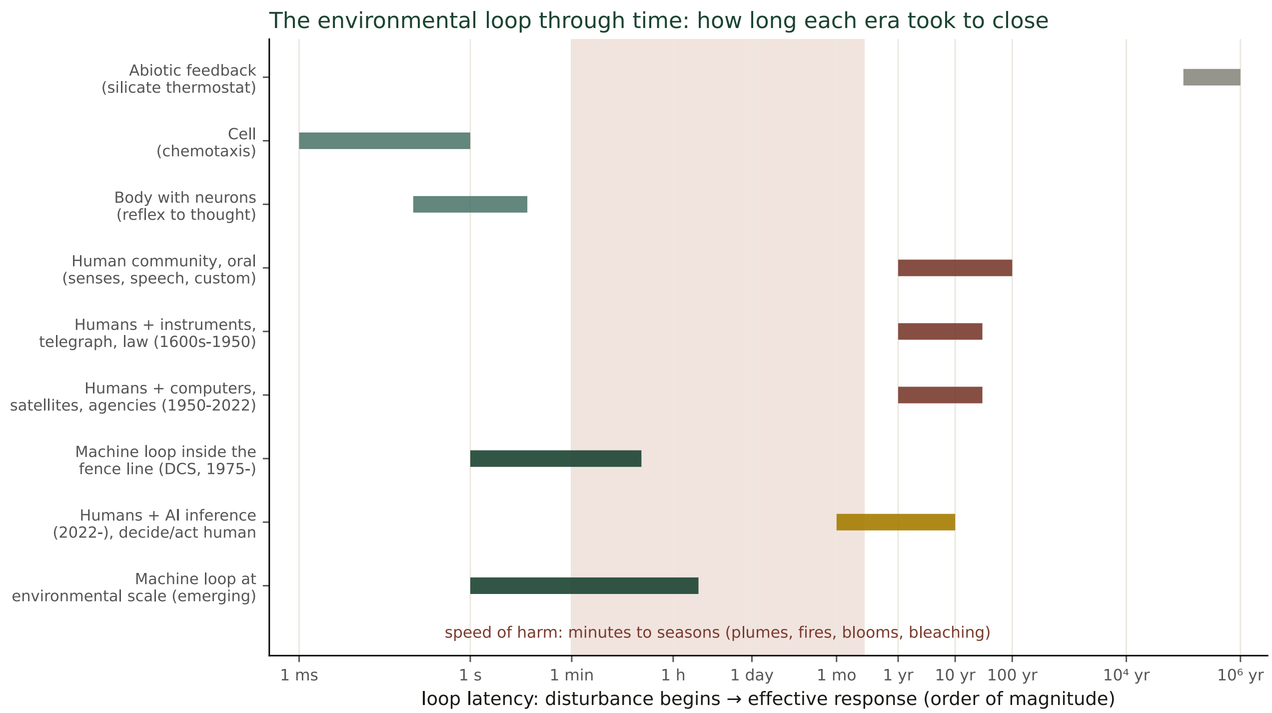


Figure 5. Loop latency by era, order of magnitude. The shaded band is the speed of the harms the loop exists to catch: river plumes at 0.3–1.2 m/s, wildfire fronts at 15–20 km/h, algal blooms doubling roughly daily, reefs bleaching in weeks. Every human-era loop sits entirely to the right of the band. The organism's loop sits to its left, and both machine loops begin to its left and overlap only its fastest end.

REGIME 0 · BEFORE 4 BILLION YEARS AGO TO THE PRESENT

Feedback without a regulator: the planet's thermostat has no setpoint

SENSE

none; the rate law itself responds to temperature

INFER

none

DECIDE

none; there is no goal

ACT

weathering consumes CO_2 faster when it is warm and wet

delay: 10^5–10^6 years **noise:** not applicable **bandwidth:** not applicable **domain:** planet

The carbonate–silicate cycle is real and it is a negative feedback: more CO_2 warms the planet, a warmer wetter planet weathers silicate rock faster, and weathering draws CO_2 back down. Walker, Hays and Kasting described it in 1981 and it is the standard explanation for why Earth did not freeze under a faint young Sun. But its e-folding time for drawing down a CO_2 pulse is about 240,000 years in Colbourn et al. (2015; range 170–380 kyr), and 80–160 kyr in the most recent Earth-system estimates (Kaufhold et al. 2025). Against a century-scale fossil-fuel ramp it is a thousand to ten thousand times too slow. More fundamentally, it has no reference. It drifts toward whatever equilibrium the volcanic outgassing rate and the continental configuration happen to set, and it defends nothing: the Great Oxidation Event around 2.4 billion years ago, the Snowball Earth episodes, and the five mass extinctions all ran to completion inside it. The Gaia debate of the 1970s–90s was, in these terms, a confusion between a feedback and a regulator. The corpus's phrase "latency was infinite" is defensible if it means this: the latency of a regulator is undefined when there is no regulator.

Case. The only pre-human planetary feedback is a ball in a bowl. It returns to the bottom of the bowl in a few hundred thousand years, and nobody chose the bottom.

REGIME 1 · FROM ABOUT 3.5 BILLION YEARS AGO; NERVOUS SYSTEMS FROM ABOUT 540 MILLION

Life's loop: the four stages inside one organism, with the organism as the goal

SENSE

receptor proteins; later, sense organs

INFER

signalling cascades; later, neural circuits

DECIDE

a switch (tumble or run); later, a brain

ACT

a flagellar motor; later, muscle

delay: ms–s in a cell; 0.1–10 s in a body **noise:** receptors near the single-molecule limit
bandwidth: chemistry, then neurons at 1–120 m/s **domain:** µm to m; the organism's own state

The loop architecture is ancient. A bacterium senses a chemical gradient, processes it through a phosphorylation cascade, decides whether to keep swimming or tumble, and drives a motor; that is all four stages in one cell. The reference was always the organism's own essential variables, never the environment. At body scale the limit was transmission: diffusion covers a distance L in about L^2/D, which for a small molecule in water is a millisecond across a cell, a quarter of an hour across a millimetre, and thirty-two years across a metre (the corpus's figures; I re-derived them and they hold). A metre-sized body could not be one responsive thing on chemistry alone, so around the Cambrian, life laid down a dedicated channel, the neuron, and compressed the loop until a whole body could flinch. The organism's loop runs at about one metre per second of "care speed" (domain size over loop time), matched to the speed of the threats it evolved against, which is presumably why organisms exist at all. Planet-scale effects of life in this regime were side effects, not regulation: the oxygen that anaerobic life released poisoned anaerobic life, and nothing was watching.

Case. The hand pulled from the flame before the mind has named the heat: a loop that closes in a tenth of a second because every stage and every handoff lives inside one body.

REGIME 2A · FROM ABOUT 300,000 YEARS AGO

Humans without instruments: the first loop with the environment as a goal, at the speed of a season

SENSE

five senses; memory as the only store; sampling by season and by chance

INFER

folk models, carried in speech at 39 bit/s

DECIDE

elders, chiefs, councils

ACT

labour, taboo, custom, moving camp

delay: years to generations **noise:** only unmistakable effects were visible
bandwidth: 39 bit/s between minds; 10 bit/s within **domain:** a band, a valley, an island

For the first time a loop existed whose reference included something outside the body: a fishing ground, a forest, a soil. But every stage ran on the human instrument and every handoff ran on speech. Sensing had no channel for anything invisible; a poisoned well was sensed by the sick. Inference was one mind, then a council, each link a lossy copy. Decisions were reached at the speed of conversation and enforced at the speed of custom. The documented successes are local and slow, closing over decades: the regenerative forestry of Tokugawa Japan is the best-studied case, and it relied on written edicts, placing it at the border with the next era. The documented failures are the civilizations that salinized their fields or stripped their hills faster than a generation could notice. It is worth being honest that most loops of this era protected a resource for its users rather than an ecosystem for itself; the reference was human welfare, locally defined.

Case. Care speed at village scale: about 30 micrometres per second, the domain size divided by a loop that took years. A plume moves ten thousand times faster.

REGIME 2B · 1600S TO 1950

Instruments, print, the telegraph, and the first inspectorates

SENSE

thermometer (1610s), barometer (1643), chemical assay; inspectors

INFER

one expert mind, then the scientific literature

DECIDE

legislatures and commissions

ACT

statutes, engineering works

delay: years to decades **noise:** measurable but sparsely sampled
bandwidth: signals moved at light speed after 1844; meaning still at 39 bit/s **domain:** a city, then a nation

Two things fell in this era, and it matters which. Sensing gained instruments, so invisible quantities could be made visible in principle. The signal edges fell: the telegraph (1844) and then the telephone moved a measurement across a continent in seconds rather than weeks. Britain's Alkali Act of 1863 is the first recognisably modern loop, because it designated all four stages in law: an inspectorate to sense, an inspector's judgment to infer, a statutory standard as the decision, and enforcement as the act. What did not fall was the handoff between minds. A finding still had to be argued into a committee at the speed of speech, and the decision was still clocked by parliamentary sessions. When the signal was unmistakable the loop could be fast by the standards of the era: London's December 1952 smog killed thousands in five days, and the Clean Air Act followed in 1956, a four-year decision with implementation through the 1960s. When the signal was subtle the loop did not close at all: Robert Angus Smith described acid rain in Manchester in 1852 and named it in 1872; the first U.S. control program began in 1990.

Case. The telegraph collapsed the instrument-to-scientist handoff from weeks to seconds in the 1840s, and the regulatory loop stayed at decades for the next 150 years, because the two handoffs after it still ran between minds.

REGIME 2C · 1950 TO 2022

Computers, satellites, and agencies: faster forecasts, the same loop

SENSE

TIROS-1 (1960), Landsat (1972), national monitoring networks, continuous emissions monitors

INFER

physics simulation on supercomputers (hours) plus scientific consensus

DECIDE

agencies on statutory clocks (EPA 1970; NAAQS review every 5 years); treaties

ACT

rules, fleet and capital-stock turnover, cleanups

delay: years to decades, unchanged **noise:** parts-per-billion detection; consensus still jammable
bandwidth: electronic for data; 39 bit/s for meaning **domain:** nation, and once (Montreal) the planet

Numerical weather prediction began on ENIAC in 1950, satellites began reading the planet in 1960, and the forecast got dramatically better: the National Hurricane Center's 24-to-72-hour track errors fell by 60–70% between 1990 and the early 2020s, and its 72-hour forecast is now as accurate as its 48-hour forecast was in 2010. Yet the protection loop did not shorten. U.S. air standards still took 15–25 years from evidence to attainment; Endangered Species Act listings still took a median of 12 years against a two-year statutory limit; the one planetary loop that closed, Montreal, took 13 years from the Molina–Rowland paper to the treaty and a further nine to the developed-country phase-out. Computers entered the inference stage for physics and left every other stage, and every handoff between minds, exactly where they were. The slowest stage rules.

The exception proves the rule, and it is the most useful fact in this history. Inside the fence line of a plant, machines have closed the loop in seconds since Honeywell's TDC 2000 distributed control system of 1975, and pneumatic proportional controllers did it before that. A distributed control system senses a process variable, infers nothing more than an error, decides by a fixed law, and moves a valve, every second, with no human in the fast loop; the human sets the setpoint. Continuous emissions monitors, spill-response protocols and hurricane evacuation orders are the same pattern: wherever DECIDE and ACT were delegated in advance, the loop closed in seconds to hours; wherever they were not, it closed in decades. The history since 1970 is the history of where that boundary sat, and it sat at the fence line.

Case. Elk River, West Virginia, 2014: a chemical leak noticed by smell around 8 a.m., inspected by late morning, and a do-not-use order for 300,000 people by about 6 p.m. Twelve hours, because the order was an act someone already had the authority to take. Deepwater Horizon, 2010: sensed at once, decided at once, and not closed for 87 days, because the actuator did not yet exist.

REGIME 3A · 2022 TO THE PRESENT

AI inference: the long pole falls, and the loop is now bounded by the stages that are still human

SENSE

dense, cheap, continuous: sub-$300 air monitors, daily whole-Earth imaging

INFER

foundation models: GraphCast (2023), Pangu-Weather (2023), GenCast (2024), Aurora (2025), seconds to minutes on one accelerator

DECIDE

still mostly human and clocked

ACT

still mostly human; automated where already delegated

delay: hours where delegated; months to decades where not
noise: sub-noise detection by statistics over millions of samples
bandwidth: 10^{11} bit/s inference; 10^{14} bit/s fiber **domain:** planet, in principle

Between 2022 and 2025 four independently built models trained on the planet's own record matched or beat the operational physics forecasts on most standard targets, at thousands of times less compute, in seconds rather than hours. The stage that held every environmental loop open has been separated from the 39-bit constraint of language and the supercomputer constraint of simulation. What that does and does not change follows directly from the clock. Where DECIDE and ACT are already delegated, the whole loop now runs at machine speed. Where they are not, the loop is exactly as slow as the committee, and a faster forecast changes nothing except how long the committee knows in advance. The way out is not to make committees fast; it is to stop routing every decision through one (Section 5).

Case. A 10-day global forecast in under a minute on one TPU (GraphCast). A 50-member 15-day ensemble in about eight minutes (GenCast). The forecast is solved; the docket is not.

REGIME 3B · EMERGING

The machine loop at environmental scale: humans move from inside the loop to the reference

SENSE

sensors in the river, not the pipe; satellites; 1 Hz

INFER

models; sub-noise change detection across the sensor field

DECIDE

rungs 1–2 of the decision ladder (Section 5): reversible, bounded actions under a written envelope; people keep rungs 3–4

ACT

valves, switches, pumps, drones, automated notifications

delay: seconds to hours; floor set by detector statistics, the speed of light, Landauer, and the mechanics of matter
noise: false alarms managed at network scale **bandwidth:** not the binding constraint

domain: watershed, airshed, planet

This is the fence-line loop moved outdoors. Its care speed at planetary scale is about 10^5 m/s, against harms that move at metres per second, which is what "care faster than harm" means as arithmetic. It is also the first regulator in the history of the planet for which a larger domain does not mean a slower loop (Figure 6). The humans do not leave the system. They leave the fast loop and take the one position that was always theirs and that no loop can fill for itself: the goal.

Case. The bloom caught at its first cell rather than its first fish kill; the leak answered in the minute it opens rather than the lawsuit it eventually provokes. Prevented during, not punished after.

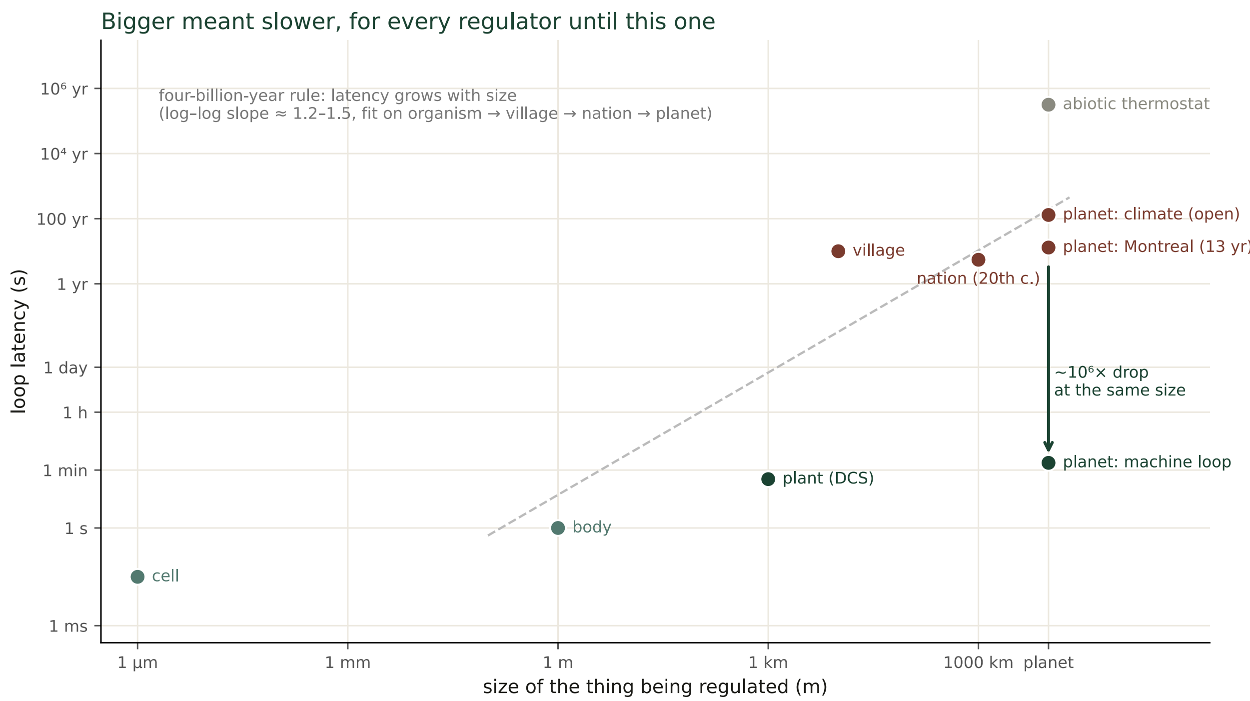


Figure 6. Loop latency against the size of the regulated domain. Across the organism, village, nation and planet, latency grew with size at a log–log slope of about 1.2–1.5, which is to say roughly in proportion. The abiotic thermostat sits on the same rule, at the top. The two machine loops are the only points far below the line, and the emerging planetary one drops latency by about a million times at the same size.

The same history as a table

era	sense	infer	decide	act	handoffs	sampling	can detect	loop latency
abiotic feedback	rate law	—	— (no goal)	rate law	none	continuous	n/a	10^5–10^6 yr
cell	receptors	signalling cascade	tumble / run	motor	diffusion inside the cell	continuous	chemical gradients	ms–s
body	sense organs	neural circuits	brain	muscle	neurons, 1–120 m/s	continuous	five senses	0.1–10 s

humans, oral	senses, memory	folk model	elders	labour, custom	speech 39 bit/s; walking	by season, by chance	only huge, visible effects	years–generations
instruments + law	instruments, inspectors	one expert, then a literature	legislature	statute, engineering	post → telegraph; hearings	months–years	measurable, sparsely	years–decades
computers + agencies	satellites, networks, CEMS	physics simulation (hours) + consensus	agencies on 5-year clocks	rules, fleet turnover	electronic for data; 39 bit/s for meaning	daily data; decadal decisions	parts per billion	years–decades
fence-line DCS (1975–)	transmitters	error signal	PID law; human setpoint	valves	wire	~1 s	process variables	s–min
AI inference (2022–)	dense sensors	foundation models (s)	humans	humans	electronic + human	seconds; decisions still clocked	sub-noise, by statistics	hours–decades
machine loop, environmental scale	dense sensors	models	encoded policy; human goal	actuators	electronic	~1 s	sub-noise, by statistics	s–hours

Table 3. Who ran each stage, how the handoffs were carried, how often the world was sampled, what could be detected, and the resulting loop latency. Every column moves together except one: the number of stages.

04 · WHERE THE DECADES WENT

Eight regulatory-era loops, decomposed by stage

The manuscript argues that understanding was the long pole. The historical record lets that be tested, case by case, by splitting each loop into three measurable intervals: from the onset of harm to its detection and attribution (sense plus infer, which the record rarely separates), from attribution to the binding decision, and from decision to the point where the act took effect. The boundaries are judgment calls and are stated in the methods; the pattern does not depend on them.

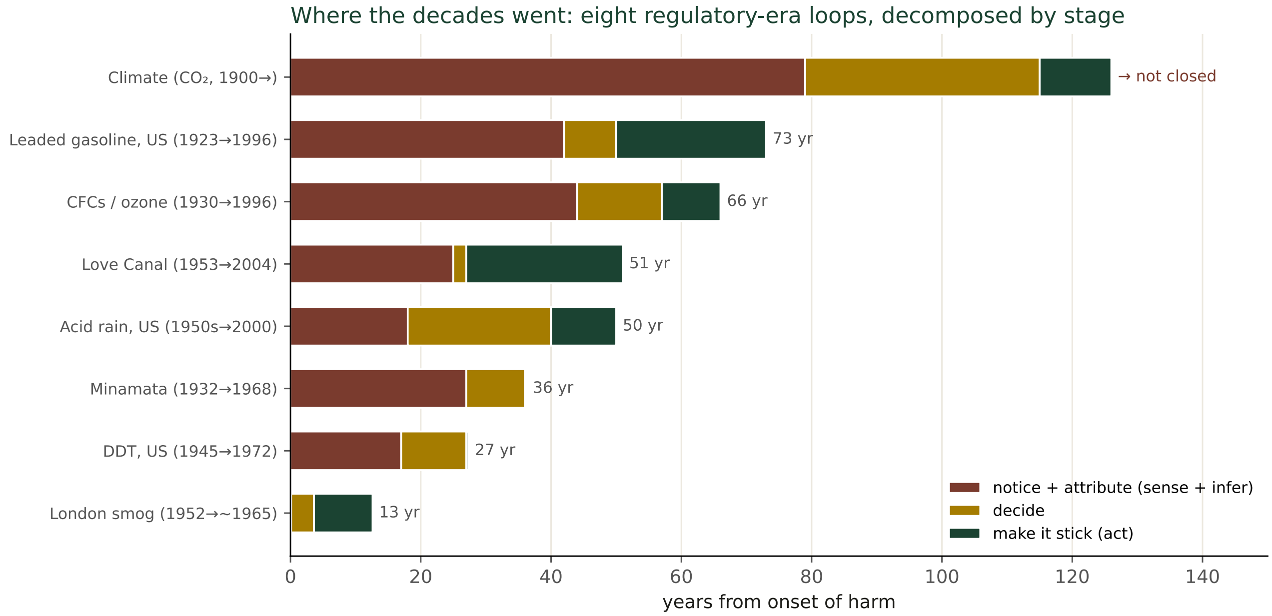


Figure 7. Years from the onset of harm, by stage. Dates: leaded gasoline sold 1923, Patterson's paper 1965, EPA phase-down rule 1973, ban 1996. CFCs commercial 1930, Molina–Rowland 1974, Montreal 1987, developed-country phase-out 1996. Minamata discharge from 1932, disease recognised 1956, methylmercury identified 1959, discharge stopped and disease officially recognised 1968. DDT in civilian use 1945, Silent Spring 1962, EPA ban 1972. Love Canal dumping ended 1953, emergency 1978, CERCLA 1980, delisted 2004. Acid rain: large-scale SO_2 from about 1950, Odén 1968, Clean Air Act Title IV 1990, Phase II 2000. London smog December 1952, Clean Air Act 1956, implementation through the 1960s. Climate: industrial CO_2 from about 1900, the Charney report 1979, the Paris Agreement 2015, emissions still rising in 2026.

SENSE + INFER

51% of the time, median 26 years

The largest share in six of eight cases. Not because instruments were slow but because nobody was looking at the right variable, with the right instrument, often enough, and because attribution had to pass through a contested channel.

DECIDE

25%, median 9.5 years

Once the signal was unmistakable and public, decisions were often quick: two years at Love Canal, two years from the ozone hole to Montreal, four years after the London smog. The long decisions (acid rain, 22 years; climate, 36 and counting) were the contested ones.

ACT

24%, median 9.5 years

Binary when the actuator was a switch (Minamata: stop production; DDT: a ban) and decades when it was a fleet or a capital stock (lead, 23 years of vehicle turnover; Love Canal, 24 years of cleanup). This is the one stage some disturbances place beyond compression.

Two things follow. First, the long pole of the regulatory era was *noticing*, the combined time to sample the right variable and attribute the change, and that is exactly the quantity the detection experiment in Section 2b describes: sparse sampling, no channel for the pollutant, and a huge effect size required before anyone was sure. Second, decision time was short precisely when salience was high, which is another way of saying the regulatory era's decide stage was event-triggered only by catastrophe and clocked otherwise.

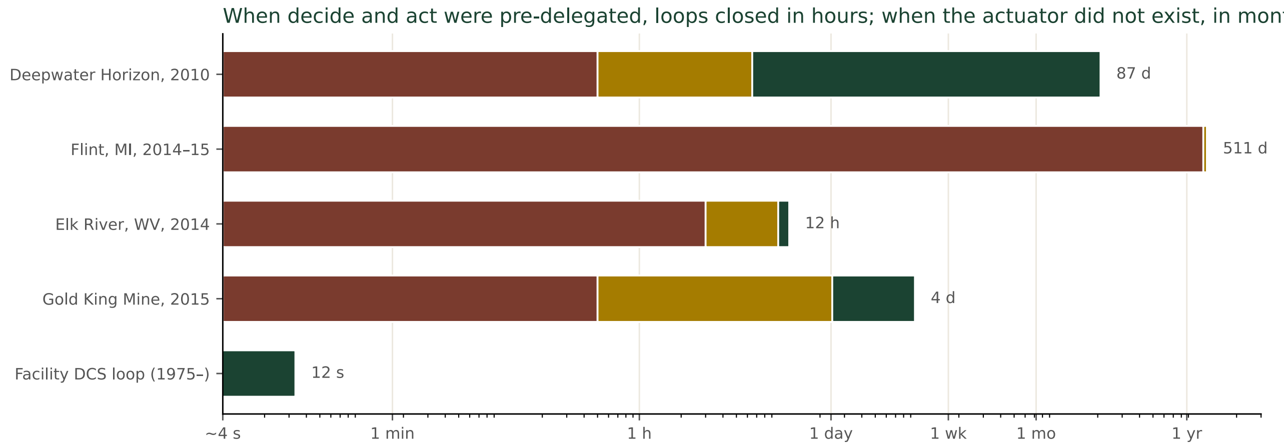


Figure 8. Four modern loops and one industrial loop, on a log time axis. Elk River (2014) closed in about twelve hours because a do-not-use order was an act someone already had authority to take. Gold King Mine (2015) was sensed by the crew that caused it, yet downstream notification took about a day. Flint (2014–15) took seventeen months almost entirely in sense-plus-infer. Deepwater Horizon (2010) was sensed and decided within hours and took 87 days to act, because the capping technology had to be built. The plant loop closes in seconds because every stage is delegated to a machine and the human only holds the setpoint.

THE RULE THE CASES TEACH

Latency fell wherever decision and action were delegated in advance, and nowhere else. Faster sensing and faster forecasting did not shorten any loop whose decision still waited for a committee. That is a prediction as much as a finding: AI will close the environmental loop exactly where authority to act has been pre-delegated, and will otherwise only lengthen the interval during which the committee knows. Section 5 shows how much that delegation is worth, and which decisions it should cover.

05 · THE DECISION LADDER

Why the loop can close now: route decisions by reversibility, not by jurisdiction

Sections 3 and 4 land on a fact that reads, at first, like a ceiling: with sensing and inference at machine speed, the loop is as slow as its decision stage, and the decision stage is human. Read correctly it is the largest remaining lever, because the regulatory era did not go slow because people are slow at large decisions. It went slow because people, and often committees, stood in the path of every small one.

One channel, one latency. Outside the fence line, the regulatory era had a single decision channel. A permit exceedance and a new national standard went to the same kind of process: a person, a file, a meeting, a docket. The channel's latency was set by its slowest use, and it charged that latency to every decision that passed through it, regardless of stakes. Inside the fence line the decision stage had been split into rungs since 1975: the controller decides a million times a day inside an envelope, the operator changes setpoints a few times a shift, the company sets the plan a few times a year. That split is why a refinery can be run safely by a dozen people, and why a watershed could not be run by a thousand.

The organism did this first. The same two numbers from Section 2 explain it: the outer brain handles about 10^9 bits per second, the conscious inner brain about 10. A body works at ten bits per second of deliberate decision because almost no decision reaches that loop. Balance, gait, pupil size, heart rate, the hand off the stove, are decided by faster, lower loops inside envelopes the organism did not consciously write, and the conscious loop is reserved for what is novel or costly. A planet wired, as the regulatory era wired it, so that every decision went to the ten-bit loop is a body with no spinal cord. An airliner has the same architecture: flight-control computers decide thousands of times a second, the pilots decide dozens of times a flight, the airline decides a few things a year, and that is why flying is safe rather than why it is dangerous.

RUNG	WHAT IS DECIDED	WHO DECIDES	LATENCY	SHARE
RUNG 4 · GOAL people keep this irreversible by nature: a goal is a commitment	What 'protected' means; trade-offs between values; the thresholds and envelopes that define every rung below	people, deliberating; political by design	**months – years**	a few per year
RUNG 3 · JUDGMENT people keep this irreversible or contested	Novel situation, competing protected values, large cost, or an action that cannot be undone	people, advised by the loop, with rungs 1–2 already holding the line	**days – months**	rare
RUNG 2 · PLAYBOOK delegated to the loop reversible, bounded cost	Choose among pre-approved responses from the inferred state: which crew, which boom, which dose, which intake to divert	the loop, under an envelope people wrote; people notified, able to override	**minutes – hours**	common
RUNG 1 · REFLEX delegated to the loop reversible, bounded cost	Threshold crossed → bounded, reversible protective action: pause a discharge, close a valve, issue an advisory, divert an intake	the loop; no human in the path	**seconds**	most events

The routing rule: delegate by reversibility and bounded cost, not by size. A high-stakes event still gets rung 1 at once; what waits for people is the part that cannot be undone.
In the regulatory era, outside the fence line, every rung ran through rung 3 or 4: one channel, one latency, for every decision.

Figure 9. The decision ladder. Each rung has its own latency and its own decider. The two lower rungs are delegated to the loop under envelopes written by people; the two upper rungs stay with people. In the regulatory era, outside the fence line, every decision ran through rung 3 or 4.

The routing rule. The obvious version, "give the machine the small decisions and keep the big ones," is half right, and the wrong half matters. The correct criterion is reversibility and bounded cost. A reversible action whose cost is bounded can be delegated even when the stakes are high, because being wrong is cheap and can be undone: pause a discharge, divert an intake, issue an advisory, close a valve, hold a release. What must wait for people is the part that cannot be undone, or that trades one protected value against another. The distinction matters because environmental harm is heavy-tailed: a few events carry most of the damage, and those are exactly the ones that will still involve human judgment.

To see how much each lever is worth I simulated 200,000 disturbances with heavy-tailed stakes (lognormal, $\sigma = 2$, under which the largest 1% of events carry 38% of the total stakes and the largest 10% carry 77%), harm accruing in proportion to stakes times the time spent deciding, a one-hour machine path and a one-year human path. Two policies were varied: the share of decisions, by count, delegated to the loop; and whether rung 1 takes a reversible containment action on the events that still wait for people, cutting their growth rate while the decision is pending.

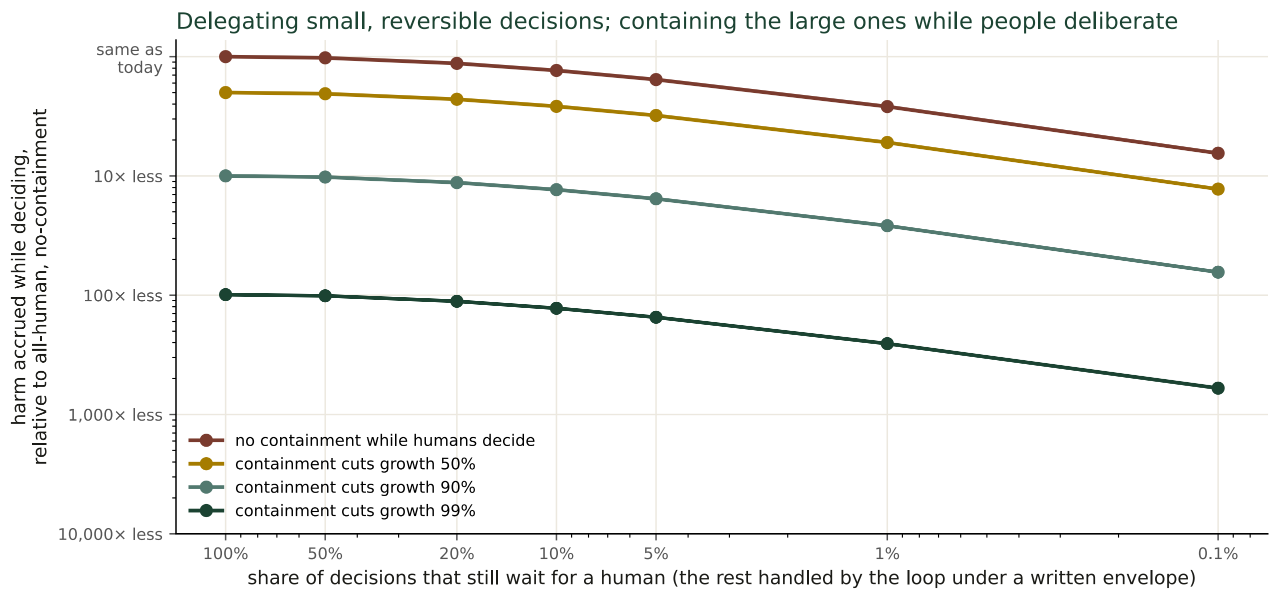


Figure 10. Harm accrued while deciding, relative to today's all-human, no-containment baseline, as the share of decisions still waiting for a human falls. Delegation alone (top line) helps little in a heavy-tailed world, because the harm lives in the events people still decide. Containment while people deliberate (lower lines) is the larger lever, and the two multiply.

containment on events that still wait for people	50% of decisions delegated	90% delegated	99% delegated	99.9% delegated	100% delegated
none (deliberate while it grows)	1.0×	1.3×	2.6×	6×	8,760×
rung 1 cuts growth 50%	2×	2.6×	5×	13×	8,760×
rung 1 cuts growth 90%	10×	13×	26×	64×	8,760×
rung 1 cuts growth 99%	101×	129×	255×	601×	8,760×

Table 4. Reduction in harm-weighted decision latency (baseline ÷ policy), from the simulation described above. The 8,760× column is the ratio of one year to one hour and is the ceiling for this parameter choice; the interesting cells are the ones where people still decide 1–10% of cases.

Decide while clamped. The second lever converts human latency from a period during which harm accumulates into a period during which harm is held. The committee is as slow as it ever was; it is no longer the thing bleeding. That is also how the fast human-era loops actually worked. Elk River's do-not-use order was a reversible, bounded-cost action taken in hours by someone who already had the authority; the irreversible questions, liability, the tank farm's future, the standard, took years, and could, because the water was already off. Medicine calls the same thing triage: the emergency room stabilizes before the specialist decides, and nobody thinks the specialist should be rushed.

> IN PLAIN TERMS
>
> A hospital does not convene a committee to decide whether to stop a bleed. It stops the bleed, and then convenes the committee about the surgery. The regulatory era convened the committee first, while the patient bled. The loop that can now be built stops the bleed in seconds, and the committee can take all the time it needs.

Why now, and not before. Rung 1 has been buildable since 1975 wherever a sensor sat at the point of action, which outside the fence line was nowhere, because there were no sensors in the river. Rung 2 needs a machine that can infer the state of a watershed or an airshed well enough to choose among playbooks, and that did not exist at environmental scale before the models of 2022–25. Both rungs need instant notification and override, which the fiber provides. The legal instruments for pre-delegation are old and already in use: a permit limit is a decision made in advance; a safety instrumented system shuts a plant down without asking anyone; emergency orders and automated warnings are delegated authority. What is new is the range of decisions a machine can competently hold and the density of sensing that lets the ladder exist outdoors. Three things had to be true at once, and they became true in the same decade.

What it does not mean. Not every decision should be fast. Rung 4 is slow by design; deliberation about what to protect is a feature, not a latency to be engineered away. Delegation moves the human decision from the case to the rule, which is harder and done once: people must write the envelopes, thresholds and playbooks in advance, with the precision a machine can execute, and that is the bottleneck Section 7 names. And the automation record is specific about how delegated decisions fail: an envelope that was not bounded, an action that could not be undone, a single sensor allowed to trigger an irreversible act, an override that took too long, a decision nobody could audit, an authority nobody had been assigned. Aviation's automation accidents are almost all failures of one of those conditions, not of the idea, and the conditions are the design brief for every rung below the line.

06 · WHAT THE MACHINE ERA DOES NOT FIX

New limits replace the old ones; they are different, not absent

FALSE ALARMS AT SCALE

A million sensors, each tuned for one false alarm per decade, produce 274 false alarms a day

Network-scale detection has to set its threshold for the network, not the sensor. The penalty is logarithmic: holding the whole million-sensor field to one false alarm per day raises each detector's threshold enough to slow detection by about 2.5×, not by orders of magnitude (computed from the same CUSUM relation used in Section 2b). Spatial correlation does the rest: a real plume moves through neighbouring sensors in sequence; noise does not.

OUT-OF-DISTRIBUTION FAILURE

A model trained on the record may fail on the unprecedented

Learned forecasters beat physics on the large majority of standard targets; the open question is performance on events unlike anything in the training record. The dossier already flags this. The defensible position is to keep physics-based models as a check and to measure skill specifically on unprecedented extremes, because that is where the loop matters most.

SPOOFING AND CORRELATED FAILURE

A sensor that can be trusted can be lied to

The human era's inference stage could be jammed by argument; the machine era's sense stage can be jammed by a tampered sensor or a shared software fault. Redundancy of modality (satellite plus in-situ plus model) is the equivalent of the scientist's independent replication, and it has to be designed in.

VARIETY

Ashby: only variety can destroy variety

A fast loop with one actuator regulates one thing. A planet perturbed across chemistry, climate, land and biology needs a response repertoire as large as the disturbance repertoire. Speed is necessary and not sufficient; the actuator stage, which the loop cannot compress past the mechanics of matter, is also the stage that has to be made various.

THE GOAL

The loop cannot produce its own reference

Every regulator in history had its goal set by the thing it protected: the cell, the organism, the community. The machine loop is the first where the thing setting the goal and the thing running the loop are different kinds of system. That is not a flaw to be engineered away; it is the design. It does mean that the question of whose goal, stated precisely enough to be encoded, is now the whole of the political problem rather than part of it.

ENERGY

Inference is cheap per bit and expensive in aggregate

Hardware runs about a billion times above the Landauer floor, so the thermodynamic ceiling is nowhere near; the practical constraint is grid capacity for inference at continental scale, which the corpus counts elsewhere. The loop that strains the grid is the loop that closes; what it is pointed at is the open question.

07 · WHAT THE HISTORY PREDICTS

Five claims that follow from the record

1. **Latency falls only where decision and action are pre-delegated.** This held for 50 years inside the fence line and failed for 50 years outside it. Expect the same boundary to govern the AI era, and expect the boundary, not the model, to be the variable worth tracking. The useful measure of progress is the share of decisions handled on rungs 1–2 of the ladder, and the share of the remainder that are contained while people deliberate.
2. **The next pole is institutional, and it is measurable.** With sensing and inference at machine speed, the loop's latency is the sum of decide and act. Both can be timed per disturbance class and published, the way hurricane track error is published. A regulator that does not know its own loop time cannot shorten it, and a regulator that routes every decision through one channel cannot shorten it by more than that channel allows.
3. **Containment first is worth more than delegation alone.** Because harm is heavy-tailed, handing the loop 90% of decisions by count buys little if the large events still wait uncontained; letting rung 1 hold the large events reversibly while people decide buys ten to a hundred times, and the two levers multiply (Table 4).
4. **Noise engineering replaces noticing.** The regulatory era's long pole was being sure; the machine era's is not being wrong a thousand times a day. The false-alarm budget, the out-of-distribution test set, and modality redundancy are the new sensing problem.
5. **Bigger will no longer mean slower.** For the first time, a planetary regulator can be faster than a municipal one. That inverts the intuition behind subsidiarity in environmental law, which assumed local loops were the fast ones.
6. **The reference stays human, and its precision becomes the bottleneck.** A goal that can be argued in a hearing is not yet a goal that can be encoded in a threshold, an envelope, or a playbook. Translating the one into the other, in advance and once, is the work the loop cannot do for us, and it is where the regulatory era's decades go next.

For four billion years, bigger meant slower. *This is the first regulator for which it doesn't.*

The loop is not new. A bacterium ran all four stages before there was oxygen to breathe. What is new is the substrate of the middle two stages and the deletion of the handoffs between minds, and the consequence is that a loop the size of a planet can now close faster than a loop the size of a committee. The committee keeps the decisions that deserve it, and stops holding the ones that never did. What we point it at is the only question that was ever open.

08 · METHODS, SOURCES, CAVEATS

What was computed, what was looked up, and what is contested

Computations in this document

- **Delay experiment (Fig. 2).** Euler integration, $dt = 10^{-3}$ T, plant $T \cdot dx/dt = -x + u(t-\tau) + d$, $u = -3x$, unit step disturbance at t = 1. Critical delay from the Nyquist crossing condition, $\tau_{crit} = (\pi - \arctan\sqrt{(K^2-1)})/\sqrt{(K^2-1)} = 0.676$ T. Peak deviations: 0.25 (τ = 0.05 T), 0.43 (0.45 T), 1.41 and growing (0.75 T) versus 1.0 uncontrolled.
- **Detection experiment (Fig. 3, Table 1).** Page's CUSUM with reference value $\delta/2$; threshold from Siegmund's approximation $ARL_0 \approx 2[\exp(\delta b) - 1 - \delta b]/\delta^2$, $b = h + 1.166$; 300 Monte-Carlo trials per cell for detection delay; threshold verified by direct simulation of the false-alarm run length (target 3,650 samples, measured 3,709). False-alarm budget fixed at one per ten years of wall-clock for every sampling interval.
- **Era latencies and care speed (Figs. 5–6, Table 3).** Order-of-magnitude ranges; geometric mean used for the scale plot; log–log slope 1.25 fitted on body, village, nation and Montreal (1.48 on the first three alone; 1.22 if the planet point is set at the nation's years-to-decades range instead of Montreal's 13 years). Diffusion times re-derived from $\tau = L^2/D$ with $D = 10^{-9}$ m²/s.
- **Case decomposition (Figs. 7–8).** Stage boundaries: onset = first large-scale release or use; detection/attribution = first published causal attribution or official recognition; decision = first binding rule or treaty; effect = ban, phase-out completion, delisting or measured reversal. Alternative boundaries (e.g., Farman 1985 instead of Molina–Rowland 1974 for ozone) shorten the decide segment and lengthen the sense-plus-infer segment; they do not change the ranking of the three stages.
- **Decision-ladder experiment (Fig. 10, Table 4).** 200,000 disturbances with stakes S ~ lognormal(0, σ = 2); harm per event = S × time spent deciding; machine path 1 hour, human path 1 year. Delegation by count quantile of S; containment modelled as rung 1 cutting the growth rate of human-decided events by a fraction c from hour one. Reported as baseline harm ÷ policy harm. Under this distribution the largest 1% of events carry 38% of stakes and the largest 10% carry 77%. Sensitivity: with the top 10% carrying 39% (lognormal σ = 1) delegation alone at 90% is worth 2.6×; at 51% (Pareto α = 1.5) 2.0×; at 76% (σ = 2) 1.3×. The more the stakes concentrate in the tail, the less delegation alone is worth, and 90% containment dominated in every case tested (26×, 19×, 13×).
- **Network false alarms.** 10^6 detectors × (1 alarm / 3,652 days) = 274 per day; holding the network to one per day requires per-detector ARL_0 of 3.65×10^8 samples at daily sampling, raising $\ln(ARL_0\delta^2/2)$ from 7.5 to 19.0, a 2.5× longer detection delay at δ = 1.

Sources verified for this analysis

- Zheng & Meister, "The unbearable slowness of being: why do we live at 10 bits/s?", *Neuron* (2024): ~10 bit/s behavioural throughput against ~10^9 bit/s sensory intake; estimates "reliable to within a factor of 2". Disputed: a published rebuttal argues the inner brain runs faster than 10 bit/s. Used here as a 10–50 bit/s range.

- Coupé, Oh, Dediu & Pellegrino, *Science Advances* (2019): 39.15 ± 5.10 bit/s across 17 languages.
- Koch et al., "How much the eye tells the brain," *Current Biology* (2006): ~10^7 bit/s per optic nerve. Cowan (2001): ~4 chunks of working memory.
- Walker, Hays & Kasting (1981); Archer (2005, 2009); Colbourn et al., *Global Biogeochemical Cycles* (2015): silicate-weathering e-folding ~240 kyr (170–380); Kaufhold et al., *Biogeosciences* (2025): 80–160 kyr depending on scenario.
- NHC Forecast Verification Reports (2020, 2022, 2024) and the Commerce OIG report OIG-25-007-A: 24–72 h track errors down 60–70% since 1990; 72 h forecast now as accurate as 48 h in 2010.
- Honeywell and trade histories: TDC 2000 announced November 1975, the first distributed control system.
- Lead: Patterson, *Archives of Environmental Health* (1965); EPA phase-down regulations 1973; EPA press release, January 29, 1996, concluding the phase-out. Minamata: discharge from 1932; recognition May 1956; methylmercury suspected July 1959; discharge ended and state designation 1968 (Japan Ministry of the Environment chronology).
- NICT press releases (2024–25): 402 and 430 Tb/s in a single standard fiber; 1.02 Pb/s over 1,808 km in 19-core fiber.
- GraphCast (*Science* 2023), Pangu-Weather (*Nature* 2023), GenCast (*Nature* 2024), Aurora (*Nature* 2025), as cited in the corpus manuscript; Landauer (1961); Ashby, *An Introduction to Cybernetics* (1956); Page (1954) and Lorden (1971) for change detection; Åström & Murray, *Feedback Systems*, for the delay results.

Caveats

- The loop is a modelling simplification. Real protection is many coupled loops with shared sensors and actuators; the stage decomposition is productive, not ontological. The corpus says this already and should keep saying it.
- All era latencies are order-of-magnitude. The claims that survive are the ones that span several orders, which is all of them.
- The 10 bit/s figure is contested; the argument here needs only that human decision throughput is tens of bits per second, not thousands, and that is not contested.
- "Latency was infinite for four billion years" is best restated as "there were feedbacks but no regulator," which is both more accurate and harder to argue with.
- The machine-era entries are projections of an architecture that exists at plant scale and is being built at environmental scale; the fence-line row is the precedent, not a promise.
- The decision ladder is a design, not a forecast. Its gains depend on envelopes being bounded, actions reversible, sensors redundant, overrides instant and authority assigned; the simulation assumes all five and the automation record shows what happens when one is missing.

Prepared as a working analysis for the jedanderson.org latency corpus, August 2026. Figures 2–8 and 10 were generated from the computations described above; Figures 1 and 9 are schematic. Colours follow the corpus: rust for the human era, green for the machine era, sage for physical floors.