Episode Book

EPISODE #5887

Gears That Did Calculus: Mechanical Computers

PUBLISHED	12 October 2026 at 09:18 UTC
DURATION	25:29
LISTEN	myweirdprompts.com/episode/mechanical-computing-history-22020/
HOSTS	Corn, Herman, Hilbert
SCRIPT MODEL	deepseek-flash
VOICES	chatterbox-regular (chatterbox-local)
PIPELINE	V5.4
SOURCES	14 cited by the research (listed at the end)
BOOK GENERATED	19 October 2026 at 17:41 UTC

SYNOPSIS

Before electronics, gears and cams were doing calculus. This episode traces mechanical computing from the Antikythera mechanism — a shoebox of bronze gears that predicted eclipses — through Vannevar Bush's room-filling differential analyzers and the three-thousand-pound Ford Mark One that aimed battleship guns into the 1990s. Along the way: how a gear ratio becomes an equation, why the moon forced ancient engineers into epicyclic gearing, what a spinning disc integrator actually computes, and the surprising ways analog computing is still alive today doing things digital machines can't.

TRANSCRIPT



Corn

Daniel's been reading about the history of computing, and he's noticed something about the way we tell it. We go from the abacus to the mechanical calculator to, boom, ENIAC, as if the whole mechanical era was just a waiting room.



Herman

A stepping stone.



Corn

And his point is that the actual mechanical machines got serious. So he wants the high point. The Antikythera mechanism as the ancient precursor, then the fire-control computers on battleships, the Ford Mark One specifically, and Vannevar Bush's differential analyzers. How did gears and cams and shafts actually do the math. What was the most sophisticated thing anyone ever built that way, how did it stack up against what replaced it, and did mechanical computing actually die, or is it still hiding somewhere doing something electronics can't.



Herman

That last part is the one that surprised me when I went back through this, because it's not a nostalgia question. There is a live research field there.



Corn

Start with the mechanism, then. Because I've read about the Antikythera thing for years and I still don't understand how a gear train knows where the moon is.



Herman

That's the right place to start, because it's the purest case. No electronics, no power source except a hand, and it's doing something we'd now call simulation. Second century BC, bronze, recovered off a wreck near Antikythera in nineteen oh one. Roughly thirty five gears in a wooden case about the size of a shoebox, and the largest gear has two hundred and twenty three teeth.



Corn

Two hundred and twenty three.



Herman

That number isn't arbitrary. It's the Saros cycle. Two hundred and twenty three synodic months is the period over which solar and lunar eclipses repeat. So you cut a gear with exactly that many teeth and you've baked the eclipse cycle into the geometry. Turn the crank and the machine tells you when the next one is.



Corn

So the gear ratio is the equation.



Herman

The gear ratio is the equation. That's the whole idea of mechanical computing, and it never changed. A ratio of teeth is a multiplication. If one gear has twice the teeth of the one driving it, it turns half as fast, and you've just divided by two, permanently, in metal. You want to add? A differential gear takes two inputs and outputs their average, so if you double that output you get the sum. You want a function that isn't a simple ratio, something with a curve in it? You machine a cam, and the shape of the cam is the function.



Corn

The answer is stored in the shape of the part.



Herman

Stored in the shape of the part. And the Antikythera does the clever version of this, because the moon doesn't move at a constant speed. It speeds up near perigee and slows near apogee, and a plain gear train can't do that. So they used epicyclic gearing, gears mounted on a carrier that itself rotates, and the output speed varies in exactly the way the moon's does. Earliest known use of that trick.



Corn

That's the part that gets me. Not the eclipse prediction, that's arithmetic. The variable moon is the one where somebody had to sit down and decide the mechanism would imitate the sky rather than approximate it.



Herman

And then the moon phase display uses a differential to combine the sun position and the moon position and show you the illuminated fraction. And the eclipse predictions are glyphs, little marks, in fifty one of those two hundred and twenty three cells. Thirty eight lunar eclipses, twenty seven solar, with the time of day encoded.



Corn

Fifty one out of two hundred and twenty three cells.



Herman

Fifty one out of two hundred and twenty three is what survives legibly. There may have been more.



Corn

So it's a calendar, an almanac, and an orrery in one box, and nothing of comparable gear complexity turns up again for about fifteen hundred years.



Herman

The fourteenth century astronomical clocks. That's the gap.



Corn

Somebody built that and then the technique just... goes quiet. For fifteen centuries. What happened?



Herman

The honest answer is we don't know. We don't have the workshop, we don't have the intermediate versions, we don't have the treatise that would have described how to cut a gear like that. It's possible there were more and they were bronze and they got melted down, because bronze is valuable and a broken machine is scrap metal. The Antikythera survived because it sank.



Corn

Best-preserved computer in history because it drowned.



Herman

That's roughly the situation, yes.



Corn

Move forward. Skip the stuff everyone knows, the adding machines and the difference engines. Get to Bush.



Herman

The differential analyzer is the machine that makes the mechanical era look like a computing era rather than a machining era. Bush starts it in nineteen twenty eight with a student named Harold Hazen, it solves its first problems in nineteen thirty, and it fills a room. Gears and shafts driven by electric motors, and eighteen long rotating shafts running the length of the machine that you can interconnect.



Corn

And the heart of it is the thing Hannibal Ford also used. The integrator.



Herman

The integrator is the key device of mechanical computing, and it's worth understanding because once you have it, you have calculus in hardware. It's a spinning disc with a small wheel or ball riding on it. The disc turns at constant speed. Where the ball sits on the disc



Herman (continued)

sets how fast the output shaft turns. Near the rim, the surface is moving fast, so the output is fast. Near the center, the surface is barely moving, so the output is slow. Push the ball across the disc and you're continuously changing the rate.



Corn

So the output is the integral of where you put the ball.



Herman

The output is the integral of that input, yes. And you can chain them. Bush's machine had six integrators, and with six of them it could solve an arbitrary sixth order differential equation. Approximately. That's not a calculator. That's a machine that takes a physical process described as a differential equation and simulates it.



Corn

What did it actually get used for?



Herman

Power networks, seismology, ballistics. Bush modeled transmission networks on it. And the technique spread, because the design was published and people copied it. Britain, Europe, the Soviets, Australia. Somebody in Manchester built a working differential analyzer out of Meccano.



Corn

Meccano.



Herman

Meccano. Douglas Hartree and Arthur Porter, nineteen thirty five. It was less accurate than Bush's, and it cost about a hundred dollars against twenty five thousand for the real one.



Corn

The toy version was competent. I want to meet those two.



Herman

Here's the detail I like. The integrator's output shaft is too weak to drive anything downstream. You can't just attach it to the next stage, it stalls. So Hazen had to invent a torque amplifier out of these contra-rotating capstans, and the amplifier itself introduced a small error, so he had to add what they called frontlash units to correct it. It's a chain of mechanical fixes on top of mechanical fixes.



Corn

That's not a computer at that point. That's a machine that has to be humored.



Herman

It has to be maintained the way a lathe is maintained. And reconfiguring it for a new problem took days. You physically unbolt shafts and re gear them. Changing the program meant changing the machine.



Corn

Which is the thing everybody waves away when they say the mechanical era was a stepping stone. It wasn't that the math was primitive. It's that the program was made of metal, and you can't email metal.



Herman

That's the bottleneck. And it's worth saying that this is where the analog approach has a genuine advantage that people forget. An analog machine represents a quantity as a continuously varying thing, so it doesn't round. There are no dropped least significant digits. Every digit is there, it just may not be accurate at that resolution, because of backlash and wear and temperature. Digital throws the low digit away on purpose and guarantees the rest.



Corn

Two different religions of error.



Herman

Analog error is smooth and continuous. Digital error is quantized and bounded.



Corn

So Bush's analyzer, for all that it needed days of setup, could do something electronic machines of the time couldn't do at all.



Herman

The comparison with ENIAC is where I want to be careful, because I don't have a clean head-to-head number. What I can say is that the differential analyzers at Aberdeen were too slow to produce the artillery tables that were needed, and that shortfall is part of what pushed people toward the electronic machine. But the analog approach wasn't failing at accuracy. It was failing at throughput.



Corn

And the thing ran until nineteen fifty four.



Herman

The larger Rockefeller-funded version ran until nineteen fifty four. And during the war it was doing things nobody outside the lab knew about. Firing tables, radar antenna profiles. It's been called the most important computer in existence in the United States at the end of the war, and that's a machine built out of shafts.



Corn

Now do the battleship one. Because this is the one I want to understand.



Herman

The Ford Mark One. Developed by Hannibal Ford and William Newell, and it's the machine that took the integrator and turned it into a weapon system. It's part of the Mark thirty seven fire control system, deployed from the second World War through nineteen ninety one.



Corn

Nineteen ninety one. The Gulf War.



Herman

The Missouri and the Wisconsin bombarding Iraqi positions. That's the last combat use of the mechanical era systems. And I want to be precise about that, because the wording matters. The ships were firing with these analog computers and spotting the fall of shot with drones.



Corn

They were using a nineteen thirty machine to aim at a target, and the drone was just telling them where the shell went.



Herman

The computer did the aiming. The aircraft observer did the correcting, which is the same job a human spotter did in nineteen forty three. The system is roughly three feet wide, four feet tall, six feet long. Over three thousand pounds. It lives deep in the ship, in a compartment called the plotting room, well below the waterline, because nothing that weighs that much and needs that much precision belongs anywhere that moves violently.



Corn

Three thousand pounds of arithmetic sitting under the armor.



Herman

And what it's doing is hard. Inputs come in from the director up on top, which is measuring the target's bearing, range and elevation. There's a gyroscopic stable element measuring the ship's roll and pitch. There's a pitometer log for the ship's speed through the water. There's an anemometer for the wind. And the machine combines all of it to compute the lead angle, where to point the gun so the shell and the target arrive at the same place.



Corn

And it has to correct for gravity drop, wind, the spin of the shell.



Herman

The Magnus effect of the spinning shell, yes. Parallax, because the director and the gun aren't in the same place. The Coriolis effect, because the shell is in flight for a long time and the earth turns underneath it. And the machine has no memory. That's the part I keep coming back to. It tracks current events only. There's no stored history of where the target has been.



Corn

Then how does it predict where a moving target will be?



Herman

The integrator is the crystal ball. You feed in the target's bearing and range as a continuously changing input. The integrator converts that rate of change into a predicted future position. It's not remembering the past, it's differentiating and extrapolating in real time, continuously, on an X, Y and Z axis at once.



Corn

So it doesn't know where the ship was. It knows how fast the situation is changing.



Herman

And the hardware for that is this disc about six inches across, half an inch thick, spinning at constant speed. That's the time constant of the whole machine, that constant rotation is how the fire control computer knows what a second is. There's a one-inch ball pressed against it at about six pounds of force by a carriage. Move the ball off center and you get an output proportional to the rate of change of the coordinate. When the coordinate stops changing, the carriage recenters the ball and the output goes to zero.



Corn

So the machine's sense of time is a spinning plate and its sense of change is how far off center a ball is sitting.



Herman

That's the physical implementation, yes.



Corn

How long does it take to solve?



Herman

Up to thirty seconds to work out a new moving target's course and speed from the moment of acquisition. A few seconds to re solve after a course change.



Corn

Thirty seconds is a long time in a gunnery engagement.



Herman

It was long, and the Mark One A version from the mid thirties fixed part of that. It added elevation rate computation, and it raised the maximum target speed the machine could handle. The original spec topped out around two hundred knots. They raised it to four hundred and fifty, then to six hundred and fifty for the jet age. And the way you raise the limit on a mechanical computer is you change gear ratios and double the mechanical



Herman (continued)

stop.



Corn

The software update is a machinist.



Herman

The software update is a machinist with a gear cutter. And the Mark One A is the Navy's first dual purpose computer, surface and anti-aircraft in one machine. Paired with the five inch thirty eight gun it's considered the finest anti-aircraft fire control system of the war.



Corn

What's the reliability like? Because I'd assume a machine with that many moving parts is a nightmare.



Herman

The Navy's own documentation says no scheduled maintenance, recommended or performed.



Corn

That can't be right.



Herman

That's the line in the documentation. Gene Slover, who worked on these, wrote that looking inside the Mark One was like looking into a fine mechanical watch, and then asked how anyone could have put together something like that and made it work, especially in nineteen thirty.



Corn

That's the sentence of the episode for me. Not because it's sentimental. Because the man who maintained it is the one saying he doesn't understand how it was built.



Herman

There's a line from a Navy captain, David Boslaugh, about the effort to digitize the Iowa class fire control. They studied it and concluded that digitizing the computer would improve neither the reliability nor the accuracy of the system, and recommended don't bother.



Corn

They ran the numbers and the electronic version wasn't better.



Herman

The electronic version wasn't better, on that problem, at that time. Which is the point of Daniel's question, really. On a continuous ballistic problem, the analog machine wasn't a lesser ancestor. It was a peer, and in some respects it stayed a peer for decades.



Corn

So why did they stop?



Herman

Cost. Not accuracy. The Navy abandoned analog fire control because of what it cost to put a ship like that to sea. The comparison that gets made is that you could crew ten of the modern destroyers for the cost of putting one Iowa back out there. And the modern gun, with a GPS guided shell, has a circular error of about fifty meters. The Iowa's mechanical system, with a two thousand seven hundred pound shell, was around eighty meters, at thirty miles.



Corn

Fifty versus eighty.



Herman

Fifty versus eighty, and one of those systems is digital, guided, and expensive per round, and the other one is a shaft of steel computed by a spinning plate.



Corn

So a machine built in the nineteen thirties gets within thirty meters of a GPS guided shell at thirty miles. And people call that thing primitive.



Herman

They call it primitive because the story we tell starts with the transistor as the beginning of real computing. But the transistor didn't make the math possible. It made the math cheap.



Corn

Say that again.



Herman

The transistor made the math cheap, and cheap is the thing that changed the world. There were mechanical machines that could do the computation. There was never a mechanical machine that could do it for everybody.



Corn

Which is why the era ended, and why I'd like to push on the part of Daniel's question about whether it's actually over. Because if analog had genuine advantages, something should have kept it alive.



Herman

Something did, in a niche, and the niche is where electronics don't survive. Mechanical logic gates are being built now for environments where a chip is not an option. High temperature, radiation, no power available, and no electromagnetic signature.



Corn

No electromagnetic signature. Meaning you can't detect it.



Herman

Meaning there's nothing radiating for anyone to find. There's work on silicon carbide electromechanical computing that operates at five hundred degrees Celsius. That's not a laboratory curiosity for its own sake. That's downhole instrumentation, that's reactor environments, that's things that go into places where a conventional processor fails in minutes.



Corn

And the manufacturing has caught up to the old idea.



Herman

That's the bit that's new. In twenty nineteen there's a demonstration of additively manufactured micro mechanical logic gates. 3D printed buckling flexures that implement the full set. Not, and, or, nand, nor. No electronics, no reset needed between operations. The micro scale element is thirty eight by thirty eight by three micrometers, with flexures eight hundred nanometers across. Estimated operation in the megahertz range.



Corn

So you print a logic gate. You don't fabricate it.



Herman

You print it, and it's a flexure, which means it works by bending. It's a switch made of a shape rather than a junction. And there's a scheme from twenty eighteen, Merkle and others, that's Turing complete using only rigid links and rotary joints. Locks and balances. And it's reversible, which means in theory it could dissipate arbitrarily little energy.



Corn

That's the Landauer thing.



Herman

That's the Landauer limit. There's a minimum energy cost to erasing a bit, about two point nine times ten to the minus twenty one joules at room temperature. And modern processors are roughly nine orders of magnitude less efficient than that limit. So if you're thinking about the floor of what computation costs, reversible mechanical logic is interesting, because it doesn't have to erase.



Corn

That's a long way from the Mark One. Same idea though. Compute by moving something instead of by pushing electrons.



Herman

And the broader research case is that computation can be a material property. That's the framing in the big review. A structure or a material that processes information as part of what it is, alongside its strength or its stiffness. There's work on soft machines that compute autonomously with no external power, because the computation is in the way the material deforms.



Corn

So a hinge that decides something.



Herman

A hinge that decides something, and holds the decision in its shape. And the origami work is the same family. Reconfigurable mechanical circuits, you fold the thing to change the logic.



Corn

Here's what I want to put to you, because I think the framing is what Daniel is really asking. The way we tell this history makes the mechanical era look like a stage of childhood. But the Antikythera mechanism and the Mark One are four hundred million times apart in gear count and they're doing the same kind of work. The gap isn't capability. The gap is that one of them was a one off and the other was a production line.



Herman

That's the through line. The mechanical era didn't fail. It got industrialized right when the electronic machine showed up, and then it lost the industrialization argument.



Corn

Which is why the one that lasted longest was the one bolted to a battleship, where you cannot plug in a replacement.



Herman

That's not a coincidence. The Mark One survived into the nineties because the alternative required a supply chain the ship didn't have. You can maintain a mechanical computer at sea with a machinist and a set of gauges. You cannot maintain a chip fab at sea.



Corn

So the last mechanical computers were the ones that lived where the electronic ones couldn't follow.



Herman

And that's the actual answer to Daniel's last question. The niche was never about doing the math better. It was about doing the math in a place where the other option doesn't work.



Corn

Say the MEEMS part again, because I want to know how close this is to being a product.



Herman

I don't know how close it is, honestly. That's the gap. There was a Nature review in twenty twenty one that's the field's survey, and a run of papers since, including origami circuit reconfiguration last November. But I looked for a modern mechanical computer you can buy and I couldn't find one. There's no product. The work is at the laboratory stage.



Corn

So it's a research field, not an industry.



Herman

A research field with good papers and no catalog. If it becomes an industry it'll be because of the environments where nothing else works, not because somebody wants to compute mechanically for its own sake.



Corn

That's the part I'd want Daniel to take away. The Antikythera mechanism isn't a curiosity. It's the first case of somebody deciding the answer would live in the shape of the machine.



Hilbert

So the thing about the Mark One is the plotting room had a rating whose entire job was the integrators.



Hilbert

Not the whole computer. The integrators. Six of them. His rate was Fire Controlman, and he owned those six plates and their balls, and the rest of the machine belonged to other people.



Corn

How many did you have?



Hilbert

I had four of them. Surplus, out of a yard sale in Alameda, nineteen eighty eight. I keep them on the shelf above the tape machine, next to the splicing block. The trick is the ball has to be trued every so often, and there's a little jig for it, and if you don't true the ball the output drifts and you don't find out until the shot is long.



Corn

What did the jig look like?



Hilbert

It looked like a jig.



Herman

So the drift was the failure mode you'd see in the field.



Hilbert

The drift was the pitfall. The parts failure you saw was the ball, if it sat in one spot too long, because the plate keeps spinning and the ball develops a flat. The man I bought them from, his name was Pete Ostrander, he'd been a Fire Controlman on the Wisconsin, and he sold them because his wife told him to. He wanted nine hundred for the lot and I gave him nine hundred.



Corn

I want to be clear that you own four integrators.



Hilbert

They're not integrators on their own. They're the disc and the carriage. An integrator is the pair.



Corn

So you own four halves of four integrators.



Hilbert

No.



Herman

What did Pete do with his after he left the Navy?



Hilbert

He worked at a nursery. He ran the irrigation. Whole thing was gate valves and timers and he hated it.



Corn

Because nothing in it needed a man to true a ball.



Hilbert

Nothing in it needed anything.



Herman

There's a paper from a few years back, on mechanical logic, that argues computation could be a material property. That make sense to you, given the plates?



Hilbert

If the plate is spinning, it's already computing. You just haven't asked it anything yet.



Corn

Which means the answer was sitting in the metal the whole time and nobody asked.



Hilbert

Pete asked it. He just didn't want to hear the answer anymore.



Herman

The thing he told us about the ball is the thing that matters, which is that the accuracy was never the machine's spec, it was whoever kept the ball round.



Corn

That's the whole episode, honestly. The Mark One's reputation was maintained by a man with a jig.



Herman

That's the piece the histories leave out, because the histories talk about the design and the design was beautiful, and the design wasn't what made it work.



Corn

It never is.



Herman

One thing for the cutting room floor, since we got far enough into this. The Antikythera mechanism may not be finished. There's a gear in it, sixty three teeth, that nobody can account for. And there's no surviving gearing for the five classical planets, which the literary sources say such a machine would have had. So the most famous mechanical computer in history might be a fragment of something that showed all five planets moving.



Corn

Sixty three teeth with nowhere to go.



Herman

Every reconstruction people have proposed has to find a job for it, and so far nobody's proposal has convinced everyone.



Corn

That's the right place to leave it. Daniel's question started as a question about gears and it turns out the answer is that the machine was never the point. The person truing the ball was the point, and that doesn't get written down.



Herman

Which is why the story jumps from the abacus to ENIAC. Nobody puts a jig in the footnote.



Corn

Thanks to Hilbert Flumingtop for producing, and for the four halves of four integrators on the shelf. If this was your kind of episode, go back for episode eighteen, Beyond the GPU; episode twenty, Architectural AI; and episode thirteen, AI. This has been My Weird Prompts.



Herman

The human AI collaboration podcast.



Corn

Send us your own prompt on Telegram at t dot me slash MWP listener bot. We'll be back soon.

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