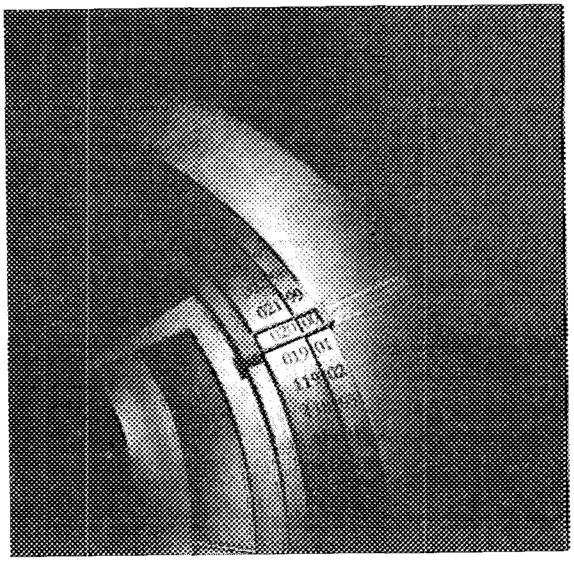
How to Design a 10,000-Year Clock

Danny Hillis

One of these days Danny Hillis will find the inner adult in himself. For now, Danny has a constant child-like curiousity about how things work, and a seriously playful manner in making new things. He's invented supercomputers, coded his business card into DNA, made a walking dinosaur for Disneyland, and, together with another boy wonder, Bran Farren, has gone into business as the appropriately named Applied Minds. In the past couple of years Danny has applied his mind to a clock. This project has all the hallmarks of a Danny Hillis idea; it's original, just barely feasible, and changes how others think of the world. —KK

OBVIOUSLY, NO ONE CAN GUARANTEE a 10,000-year lifetime for any clock. But the design of some clocks guarantees that they won't work for 10,000 years. For example, a clock that shows a four-digit year date will not work after the year 9999. I believe you can design a clock that, with continued care and maintenance, could reasonably be expected to display the correct time for the next 10,000 years. Whether or not it is reasonable that such a clock would actually receive care and maintenance for such a long time is another question, but even in this respect there are things we can design in to help it get that attention.

I chose 10,000 years as the plausible outer limit for the endurance of human-made things. We have technological artifacts such as fragments of pots and baskets that are at least 10,000 years old, so we have some precedent for a human artifact surviving this long.



While all clocks have design trade-offs, a 10,000-year clock has a unique set of design considerations:

A clock with a 10,000-year longevity implies that the mechanisms of the clock should move slowly, so that parts do not wear down, at least to the point of being inaccurate. After all, 10,000 years of tick-tocks is a lot of wear and tear. Even better would be to avoid ticking altogether, since a tick is really the bang of metal slamming into metal—something one would like to avoid over such a long run. If the clock must tick, it should do it infrequently. Longevity also implies that the design must withstand occasional earthquakes, and unusual extremes of outside weather, and if possible be kept clean and dry.

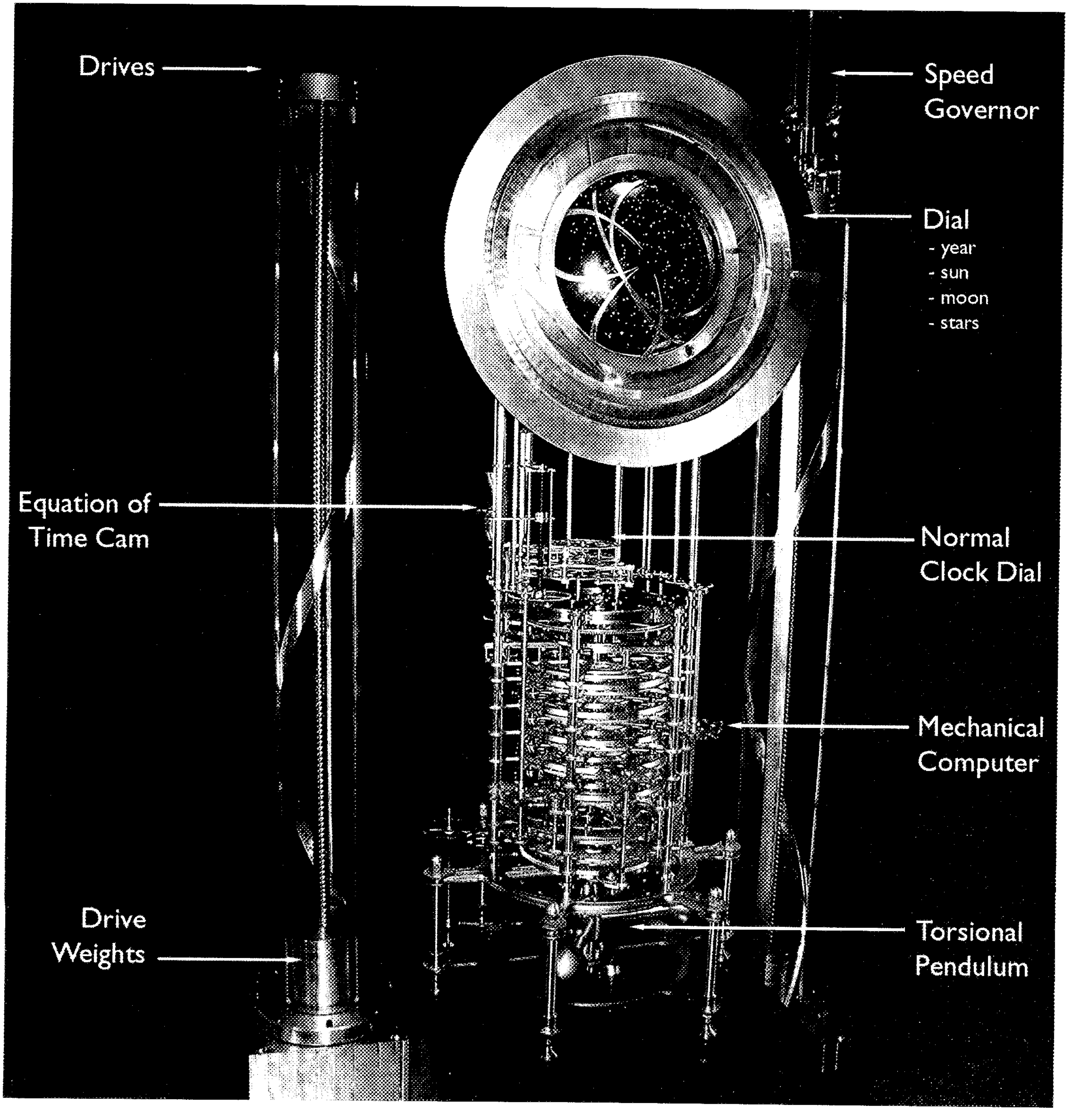
The corollary to longevity is maintainability. Most things last only if they are easy to care for and encourage stewardship. The greatest temptation in building something that will last a long time is the urge to build it using the newest technology. Paradoxically, the only technologies we are sure will work over a long time are…technologies that have been around for a long time already! The only technologies that can be relied upon to be around for a long time in the future are old ones that have been around a long time in the past. Electronics, for example, is not a safe bet for a 10,000-year duration, because on a 10,000-year time scale, it may be a passing fad. A prudent design demands the use of familiar materials, and proven, simple technology.

Another requirement for long-term maintainability is transparency. That is, it should be possible for an intelligent person to determine the operational principles of the clock by close inspection. This is another reason to rule out electronics, because if knowledge of electronics were lost for whatever reason, an electronic clock could not be understood without special tools; its operation and maintainance would not be transparent.

If the clock is ever stopped, it should be obvious how to restart it and set it to the right time. Diagnosing problems should be possible without special tools or esoteric knowledge, and it should be easy to build spare parts. Instruction manuals inevitably get lost (even in a few years!), so any information required to repair or restart the clock should be obvious from inspecting the clock itself. A major way to keep the technology transparent is to use simple technology and an open design that is understandable to anyone who comes upon it.

A study of history shows that things which last a very long time—such as great buildings—endure in part because they can be continually updated to meet current needs. The oldest clocks still going have been continually modified over time. In short, long-lived things evolve. Requirements change. New ideas are invented. The best designs accept changes with grace; those destined to be left behind are too rigid to modify. Therefore, the clock should be able to improve with time.

The final design requirement for a hundred-century clock is scalability. For aesthetic and technical reasons, we would like a build a very large clock, say something that is 40 feet high. But this is both expensive and difficult technically. One way to build a very big clock is to build a series of prototypes that start out small and



get bigger each time you build the next version. This allows you to do the initial experiments (and make mistakes) on a smaller, more affordable scale. But this also means coming up with a design that works both at the scale of a working model on a tabletop and at the scale of one weighing many tons. This is actually not easy to do because when small parts are made very large and massive they behave differently, even though they are the same shape.

Almost any clock has four components: 1) a display, 2) a timing element, 3) a converting mechanism, and 4) a power source. The display is the part that indicates the output of the clock to the users, the part you look at to see what time it is. This may be a dial with hands, a chime, or something more elaborate. The timing mechanism is usually some form of tuned oscillator, such as a pendulum, a balance wheel (which rotates back and forth), or a quartz crystal (which vibrates). The converting mechanism transfers the timing signals from the oscillator mechanism into the display. In most mechanical clocks and watches a "train" of gears does this transfer. Finally, any clock needs a source of power, such as a wound spring or a battery.

I considered many different options for the power source of the clock. Here are the ones I evaluated and why I rejected them, based on the design requirements above:

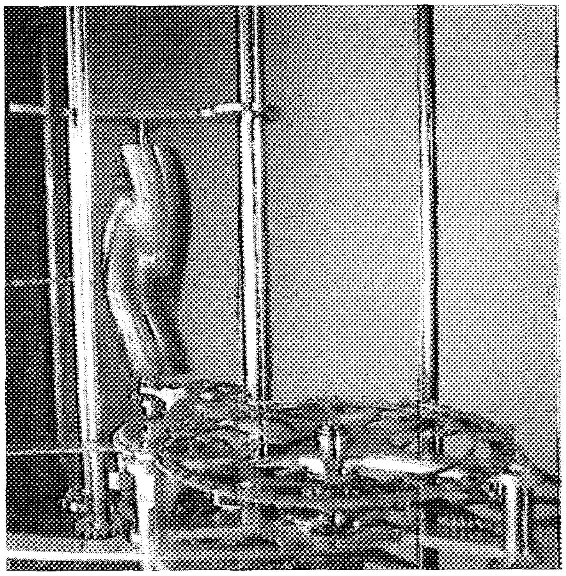
atomic power	*poor maintainability & transparency*
chemical power	*poor scalability*
solar electric cells	*poor maintainability & transparency*
very big spring	*poor scalability*
water flow	*exposure to water*
wind	*exposure to weather*
geothermal power	*poor scalability*
tidal gravitational changes	*poor scalability*
seismic and plate tectonics	*poor scalability*

Several systems based on temperature or pressure change seemed feasible, but in the end I decided the best system was to require regular human winding. This may seem an odd choice, but remember that the clock design already assumes regular human maintenance. Winding the clock fosters responsibility.

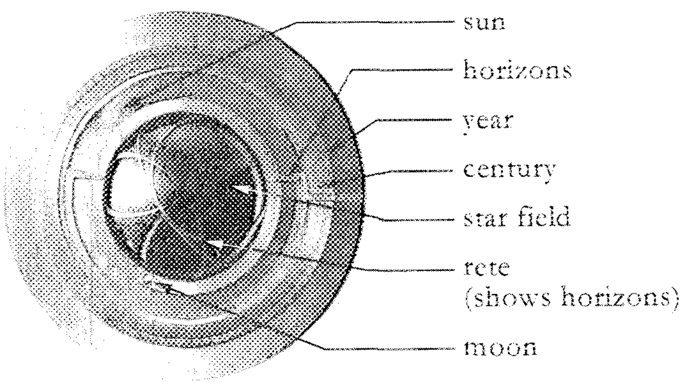
Over hundreds of years of clock making, inventors have devised scores of methods for timing clocks, providing me with a huge list of possible timing mechanisms. But for a 10,000-year clock I had to reject most of them for the following reasons:

pendulum *(inaccurate over the long term, requires lots of ticks)*,
balance wheel *(even more inaccurate)*,
a torsion pendulum *(potentially slower, but even less accurate)*,
water flow *(inaccurate and wet)*,
solid material flow, like sand *(inaccurate)*,
daily temperature cycle *(unreliable)*,
seasonal temperature cycle *(imprecise)*,
tidal forces *(difficult to measure)*,
Earth's rotating inertial frame *(difficult to measure accurately)*,
stellar alignment *(unreliable because of weather)*,
solar alignment *(unreliable because of weather)*,
atomic oscillator *(not transparent, difficult to maintain)*,
piezoelectric oscillator *(not transparent, difficult to maintain)*,
atomic decay *(difficult to measure precisely)*,
wear and corrosion *(very inaccurate)*,
rolling balls *(very inaccurate)*,
diffusion *(inaccurate)*,
tectonic motion *(difficult to predict and measure)*,
orbital dynamics *(difficult to scale)*,
tuning fork *(inaccurate)*,
pressure chamber cycle *(inaccurate)*,
inertial governor *(inaccurate)*,
human ritual *(too dependent on humans)*

After evaluating all these possibilities I concluded that no single source of timing met the requirements of a 10-millennium clock. Either the mechanism was accurate over a time, but could easily stop (unreliable), or it was reliable over the long haul, but not very accurate in the short term. My solution was to use a slightly unreliable timer to adjust a slightly inaccurate timer; these two imperfect timing mechanisms together produced something nearly perfect. Specifically, the current design uses solar alignment of the noon sun (accurate but unreliable) to adjust a slow-torsional-pendulum mechanical oscillator (reliable but inaccurate). The combination in the clock provides both reliability and long-term accuracy.



The Equation of Time. This piece is a physical representation of the shift over centuries of the Earth's tilt with respect to the stars. A pointer resting on the surface slides up over time while the Equation of Time rotates each year. In this manner the correct Earth time is maintained.



Choosing a display was also a tricky question. Many of the usual units displayed on clocks, such as hours and calendar dates, are likely to have little meaning 10,000 years from now. On the other hand, every human culture we know counts days, months, and years. There are also longer natural cycles, such as the 26,000-year precession of the Earth's axis. On the other hand, the clock is a product of our time, and it seems appropriate to pay some homage to our current arbitrary systems of time measurement. In the end, it seemed best to display both the natural cycles and some of the current cultural cycles. The center of the clock shows a star field, indicating both the daily rotation of the stars in the sky, and the 26,000-year precession as it migrates across the zodiac. Around this center circle is a ring showing the position of the sun and the moon in the sky, as well as the phase and angle of the moon. Encircling this is the ephemeral dial, showing the year according to our current Gregorian calendar system. But our current convention of using four digits is inadequate for a 10,000 span, so this clock has a five-digit display, indicating the current year as 02000. Not so prominent, hidden inside the clock, is a small conventional dial displaying the hours and minutes, in

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More information and pictures of the prototype can be seen at www.longnow.org. This essay was adapted from a note previously published in the *Horological Science Newsletter*.

case you actually wanted to know what time it was to the minute.

I considered various schemes for the part of the clock that converts time signals to display units. These included electronics, hydraulics, fluidics, and mechanics. One major problem with using a conventional set of gears is that gears have a ratio relationship between their input and output. Precisely how fast a big gear can turn a small gear depends on the accuracy of the ratio of their relative sizes. If their relative sizes are off a little, their speed, and thus the clock's timing, will be off. The required accuracy of the ratio increases with the amount of time the clock is measuring. For instance, if the ratio of gears of a clock produces 29.5 days per lunar month; that's okay for a short period of time, but over 10,000 years the number 29.5305882 is a much better choice. Achieving such precise ratios with gears is possible, but awkward.

The key innovation of the 10,000-year clock is that instead of gears it uses binary digital logic, implemented mechanically. (There are gears in the clock, but they are not used for counting.) Ordinary mechanical clocks take the timing signals from the oscillator, and use gears to count the ticks and then turn the clock's hands moving over numbers. In the 10KY clock, the counter is not a bunch of gears, but a simple digital computer. But this digital computer is mechanical, not electronic. To be more precise, the mechanism that converts the timing signal to the dial output is a digital differential analyzer, implemented with mechanical wheels and levers instead of the more usual electronics.

This mechanical-digital computer uses a 27-bit number representation, with each bit represented by a mechanical lever or pin that can be in one of two sliding positions (thus binary). There are about 300 bits in the machine. There is a complicated "adder" that slides over the bit pins and moves them (or not), almost like someone using an abacus. The adder tallies up the timing signals and delivers the result to other pins, which eventually—at the correct count—trigger the advance of the dial, or, every 1,000 years or so, the ringing of a gong.

Another advantage of the digital computer over the gear train is that it is more evolvable. For instance, the ratio of day to year depends on the Earth's rotation, which is slowing at a noticeable, but not very predictable, rate. This drift, for example, could be enough to throw off the phase of the moon by a few days over 10,000 years. The digital scheme allows the day/year ratio to be adjusted easily—just move some pins. To do this with gears would require re-engineering and re-cutting the gears, essentially making it unlikely to ever happen.

In 1999 we constructed a small prototype of this clock, approximately two meters tall. At midnight on New Year's Eve, at the conventional turn of the century, the date indicator on the face of the clock changed from 01999 to 02000. The chime struck twice, to ring in the second millennium. A small crowd of builders and supporters were on scene to celebrate this first chime. (It will be another 1,000 years before the descendant of this clock chimes again.) The prototype is currently on display at the London Science Museum in a permament exhibit where it stands among legendary prototypes of the past, such as Babbage's Difference Engine, and Watson and Crick's first model of the DNA molecule.

Alexander Rose has been my primary collaborator on this project. The other members of the design team for this prototype are David Munro, Elizabeth Woods, and Chris Rand.

While this prototype is currently functioning as a clock, not all its elements are completed. For instance, an early version of the solar sensor adjuster has been constructed and tested, but it is not yet integrated into the clock.

We are currently designing a second prototype, which will be about twice the size—18 feet tall. Some of the design details will shift as we improve it and increase its mass. We are aiming to build the great clock at 40 feet; its pendulum bobs alone would weigh about 200 pounds each. The rings holding the pins would be about 20 feet across. The fantasy is that you could walk inside the clock as it slowly, slowly, slowly counts the days toward the year 10,000.

Changing the World

Like much of my generation, I grew up believing that I should try to "change the world," presumably for the better. But I didn't know how to do this. Looking at how other people have changed the world I concluded there are five ways of doing it:

- Some people change the world by imposing their will on it.
- Some people change the world by discovering a truth.
- Some people change the world by changing people's minds.
- Some people change the world by creating things of great beauty.
- Some people change the world by making new tools for change.

Although I can admire all of these, the last mode of changing the world is the one that appeals to me the most. As a dramatic example of changing the world by making new tools, I include the creation of the Internet. I would also list something like building the rural credit system in Bangladesh as another example. Changing the world in this way can involve changing people's minds, and can entail imposing one's will to some extent, but it is mostly about enabling other people to change—by giving them tools to do so. This feels like progress.

The other appeal of tool creating is that change brought about this way is self-sustaining and self-correcting. By self-sustaining, I mean you can use tools to make other new tools. This gives enabling tools a self-amplifying effect that can gain importance with time. I like that. I feel this is a very different way to change the world from trying to impose your will on it, because when you do that the world tends to snap back after you stop trying, or after you leave. Also, enabling change through tools is self-correcting. People who try to change the world by imposing their will on it often cause unintended harm, because the consequences of the change are hard to predict. When the beneficiaries control the change themselves, they have a lot more opportunity for feedback. Thus, change of this sort has a better chance of being good.

I still want to change the world, but now I know how I want to do it: by making new tools for change.

—Danny Hillis