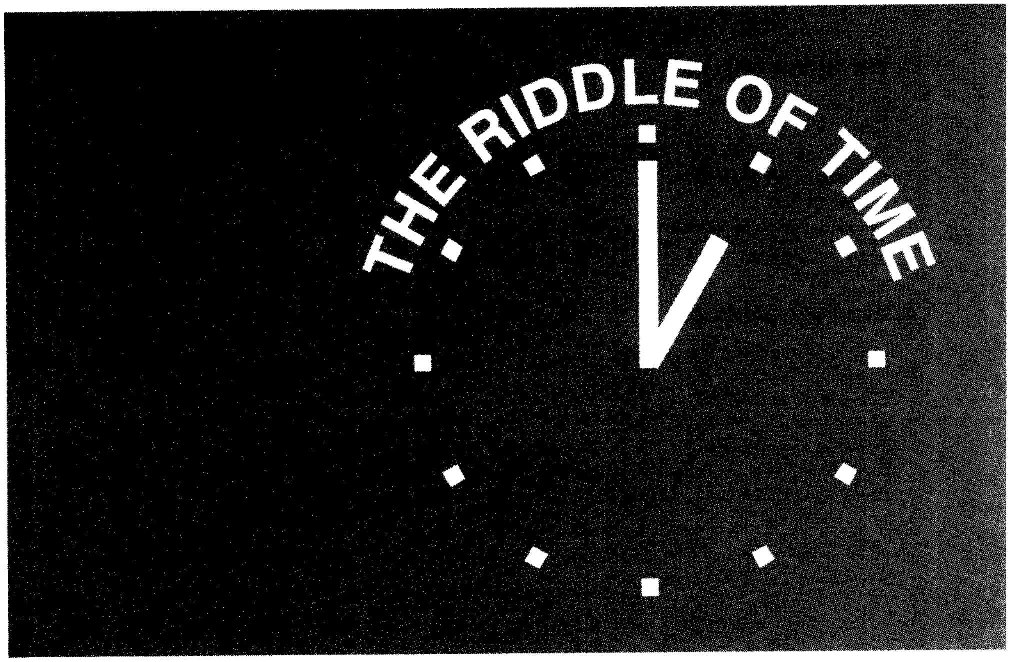

THE RIDDLE OF TIME

I. THE RIDDLE OF TIME

Chapter 1

THE RIDDLE OF TIME

- It's present everywhere, but occupies no space.
- We can measure it, but we can't see it, touch it, get rid of it, or put it in a container.
- Everyone knows what it is and uses it every day, but no one has been able to define it.
- We can spend it, save it, waste it, or kill it, but we can't destroy it or even change it, and there's never any more or less of it.

All of these statements apply to time. Is it any wonder that scientists like Newton, Descartes, and Einstein spent years studying, thinking about, arguing over, and trying to define time—and still were not satisfied with their answers? Today's scientists have done no better. The riddle of time continues to baffle, perplex, fascinate, and challenge. Pragmatic physicists cannot help becoming philosophical—even metaphysical—when they start pursuing the elusive concepts of time.

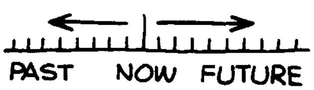
Much has been written of a scholarly and philosophical nature about time. But time plays a vital and practical role in the everyday lives of us all, and it is this practical role which we shall explore in this book.

THE NATURE OF TIME

LENGTH
MASS
TIME
TEMPERATURE

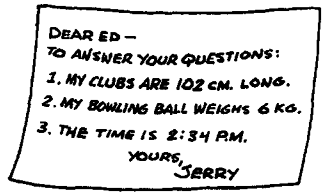
Time is a necessary component of many mathematical formulas and physical functions. It is one of several basic quantities from which most physical measurement systems are derived. Others are length, temperature, and mass. Yet time is unlike length or mass or temperature in several ways. For instance—

- We can see distance and we feel weight and temperature, but we cannot apprehend time by any of the physical senses. We cannot see, hear, feel, smell, or taste time. We know it only through consciousness, or through observing its effects.
- Time "passes," and it moves in only one direction. We can travel from New York to San Francisco or from San Francisco to New York, moving "forward" in either case. We can weigh the grain produced on an acre of land, beginning at any point, and progressing with any measure "next." But when we think of time, in even the crudest terms, we must always think of it as now, before now, and after now. We cannot *do* anything in either the past or the future—only "now."



- "Now" is constantly changing. We can buy a good meter stick, or a one-gram weight, or even a thermometer, put it away in a drawer or cabinet, and use it whenever we wish. We can forget it between uses—for a day or a week or 10 years—and find it as useful when we bring it out as when we put it away. But a "clock"—the "measuring stick" for time—is useful only if it is kept "running." If we put it away in a drawer and forget it, and it "stops," it becomes useless until it is "started" again, and "reset" from information available only from another clock.

- We can write a postcard to a friend and ask him how long his golf clubs are or how much his bowling ball weighs, and the answer he sends on another postcard gives us useful information. But if we write and ask him what time it is—and he goes to great pains to get an accurate answer, which he writes on another postcard—well, obviously before he writes it down, his information is no longer valid or useful.



This fleeting and unstable nature of time makes its measurement a much more complex operation than the measurement of length or mass or temperature. However, as we shall learn in Chapter 22, many of our basic measurement units are being turned into "time measurements."

WHAT IS TIME?

Time is a physical quantity that can be observed and measured with a clock of mechanical, electrical, or other physical nature. Dictionary definitions bring out some interesting points:

- **time**—A nonspatial continuum in which events occur in apparently irreversible succession from past through present to the future. An interval separating two points on this continuum, measured essentially by selecting a regularly recurring event, such as the sunrise, and counting the number of its recurrences during the interval of duration.

  American Heritage Dictionary

- **time**—1. The period during which an action, process, etc. continues; measured or measurable duration. . . 7. A definite moment, hour, day, or year, as indicated or fixed by the clock or calendar.

Webster's New Collegiate Dictionary

At least part of the trouble in agreeing on what time is lies in the use of the single word *time* to denote two distinct concepts. The first is *date* or *when* an event happens. The other is *time interval*, or the "length" of time between two events. This distinction is important and is basic to the problems involved in measuring time. We shall have a great deal to say about it.

DATE, TIME INTERVAL, AND SYNCHRONIZATION

We obtain the date of an event by counting the number of cycles, and fractions of cycles, of periodic events, such as the Sun as it appears in the sky and the Earth's movement around the Sun, beginning at some agreed-upon starting point. The date of an event might be 13 February 1961, 8h, 35m, 37.27s; *h*, *m*, and *s* denote hours, minutes, and seconds; the 14th hour, on a 24-hour clock, would be two o'clock in the afternoon.

In the United States literature on navigation, satellite tracking, and geodesy, the word "epoch" is sometimes used in a similar sense to the word "date." But there is considerable ambiguity in the word "epoch," and we prefer the term "date," the precise meaning of which is neither ambiguous nor in conflict with other, more popular uses.

Time interval may or may not be associated with a specific date. A person timing the movement of a horse around a race track, for example, is concerned with the minutes, seconds, and fractions of a second between the moment the horse leaves the gate and the moment it crosses the finish line. The *date* is of interest only if the horse must be at a particular track at a certain hour on a certain day.

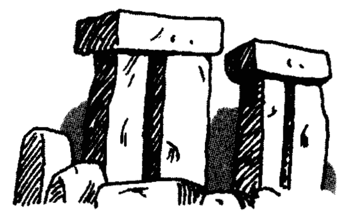
WHEN ?
HOW LONG ?
TOGETHER!

Time interval is of vital importance to *synchronization*, which means literally "timing together." Two military units that expect to be separated by several kilometers may wish to surprise the enemy by attacking at the same moment from opposite sides. So before parting, soldiers from the two units synchronize their watches. Two persons who wish to communicate with each other may not be critically interested in the date of their communication, or even in how long their communication lasts. But unless their equipment is precisely *synchronized*, their messages will be garbled. Many sophisticated electronic communications systems, navigation systems, and proposed aircraft-collision-avoidance systems have little concern with accurate dates, but they depend for their very existence on extremely precise synchronization.

The problem of synchronizing two or more time-measuring devices—getting them to measure time interval accurately and together, very precisely, to the thousandth or millionth of a second—presents a continuing challenge to electronic technology.

ANCIENT CLOCK WATCHERS

Among the most fascinating remains of many ancient civilizations are their elaborate time-watching devices. Great stone structures like Stonehenge, in Southern England, and the 4000-year-old passage grave of Newgrange, near Dublin, Ireland, that have challenged anthropologists and archaeologists for centuries, have proved to be observatories for watching the movement of heavenly bodies. Antedating writing within the culture, often by centuries, these crude clocks and calendars were developed by people on all parts of our globe.



In the Americas, Maya, Inca, and Aztec cultures developed elaborate calendars. As the Conquistadors explored the New World they were baffled by advanced city-states—many larger than those they knew in the Old World—with elaborate monuments and temples. Often these structures served as sophisticated calendars marking important religious holidays and significant dates for planting crops and other critical agricultural events. As in all great civilizations, time and its keeping reflected nature's order folded into society's organizations.

Cuzco, the capital city of the Incas, was itself a vast calendar. Throughout the city, lines of sight provided clear views of the Sun as it rose and set on important occasions. Later studies revealed 41 sightlines, all radiating from Coricancha, called the Temple of the Sun by the Spaniards.

In the Mayan civilization, whose classical period spanned the second through the tenth centuries, the day, embodied by the rising and setting Sun, was the basic unit of time. But to the Mayans the day was more than a building block to be divided and multiplied—it was time itself. Time began as the Sun appeared in the early morning sky and was swallowed up as the Sun disappeared at sunset in the western sky. The Mayan day also included the notion of cyclic time with time reversing direction at each sunrise and sunset.

AZTEC CALENDARS
1 YEAR = 260 DAYS
1 YEAR = 365 DAYS

Modern Mexico City lies on the ruins of the ancient Aztec capital, Tenochtitlán, established on an island in Lake Texcoco in 1325. Excavations of the buried city and other Aztec sites reveal that the Aztecs kept two calendars: one based on 260 days and the other on 365. They combined the two calendars to create a cycle 52 years long—possibly the average life span at the time. The end of one cycle and the beginning of the next was signaled by a celestial event—the passage of the Pleiades through a specific location in the nighttime sky. The passage signaled that the gods were pleased and would renew life's cycle for another 52 years.

Today, scientists are finding increasing evidence that even the less cosmopolitan Native Americans of the plains of North America were dedicated timekeepers. Stones laid out in formation, such as the Medicine Wheel in northern Wyoming, formerly thought to have only a religious purpose, are actually large clocks. Of course they had religious significance, also, for the cycles of life—the rise and fall of the tides, and the coming and going of the seasons—powers that literally controlled the lives of primitive peoples as they do our own, naturally evoked a sense of mystery and inspired awe and worship. Astronomy and time—so obviously beyond the influence or *control* of man, so obviously much older than anything the oldest man in the tribe could remember and as nearly "eternal" as anything the human mind can comprehend—were of great concern to ancient peoples everywhere.

CLOCKS IN NATURE

The movements of the Sun, Moon, and stars are easy to observe, and you can hardly escape being conscious of them. But there are countless other cycles and rhythms going on around us—and inside of us—all the time. Biologists, botanists, and other life scientists study but do not yet fully understand many "built in" clocks that regulate basic life processes—from periods of animal gestation and ripening of grain to migrations of birds and fish; from the rhythms of heartbeats and breathing to those of the fertile periods of female animals. These scientists talk about "biological time" and have written whole books about it.

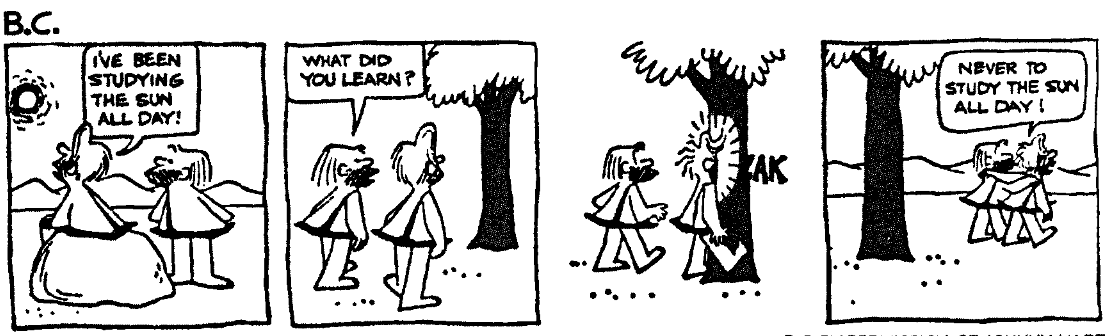
Geologists also are aware of great cycles, each one covering thousands or millions of years; they speak and write in terms of "geologic time." Other scientists have identified accurately the rate of decay of atoms of various radioactive elements—such as carbon-14, for example. So they are able to tell with considerable dependability the age of anything

that contains carbon-14. This includes *everything* that was once alive, such as a piece of wood that could have been a piece of Noah's Ark or the mummified body of a king or a pre-Columbian farmer.

In a later chapter we shall see how new dating techniques, made possible by the laser, have revolutionized our understanding of the Earth and our solar system.

KEEPING TRACK OF THE SUN AND MOON

Some of the stone structures of the earliest clock watchers were apparently planned for celebrating a single date—Midsummer Day, the day of the Summer solstice, when the time from sunrise to sunset is the longest. It occurs on June 21 or 22, depending on how near the year is to leap year. For thousands of years, the "clock" that consists of the Earth and the Sun was sufficient to regulate daily activities. Our ancient ancestors got up and began their work at sunrise and ceased work at sunset. They rested and ate their main meal about noon. They didn't need to know time any more accurately than this.



But there were other dates and anniversaries of interest and in many cultures calendars were developed on the basis of the cycles of the Sun, the Moon, and the seasons.

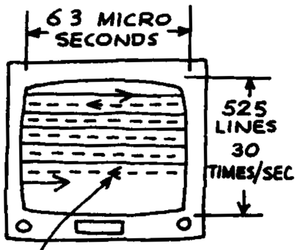
If we think of time in terms of cycles of regularly recurring events, then we see that timekeeping is basically a system of counting these cycles. The simplest and most obvious to start with is days—sunrise to sunrise, or more usefully, noon to noon, since the "time" from noon to noon is, for most practical purposes, always the same, whereas the hour of sunrise varies much more with the season.

You can count noon to noon with very simple equipment—a stick in the sand or an already existing post or tree, or even your own shadow. When the shadow points due North—if you are in the northern hemisphere—or when it is the shortest, the Sun is at its zenith, and it is noon. By making marks of a permanent or semipermanent nature, or by laying out stones or other objects in a preplanned way, you can keep track of and count days. With slightly more sophisticated equipment, you can count full moons—or months—and the revolutions of the Earth around the Sun, or years.

The Egyptians were probably the first to divide the day into smaller units. Archaeologists have investigated tall, slender monuments or obelisks, dating back to 3500 B.C., whose moving shadows doubtless provided an easy way to follow the course of the day. Later, more-refined obelisks are ringed with marker stones providing an even better accounting of the day.

By 1500 B.C., the Egyptians had developed portable shadow clocks, or sundials, which divided the sunlit hours into 10 segments with 2 more divisions for the morning and evening twilight hours.

Handsome sundials still decorate our gardens and buildings even though they have long been replaced by modern clocks and watches. Often these sundials are marked with scales allowing the observer to correct the "shadow time" for the season of the year. But even with the most advanced sundials there are problems to work out. One is that the cycles of the day, month, and year do not evenly divide into one another. It takes the Earth about 365¼ days to complete its cycle around the Sun, but the Moon circles the Earth about 13 times in 364 days. This gave early astronomers, mathematicians, and calendar makers some thorny problems to work out.



THINKING BIG AND THINKING SMALL—AN ASIDE ON NUMBERS

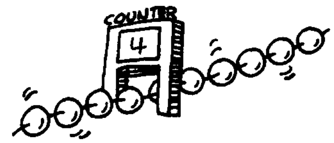
Some scientists, such as geologists and paleontologists, think of time in terms of thousands and millions of years. In their vernacular, a hundred years more or less is insignificant—too small to recognize or to measure. To other scientists, such as engineers who design sophisticated communication systems and navigation systems, one or two seconds' variation in a year is intolerable because it causes them all sorts of problems. They think in terms of thousandths, millionths, and billionths of a *second*.

The *numbers* they use to express these very small "bits" of time are very large. 1/1 000 000 of a second, for example, is one microsecond. 1/1 000 000 000 of a second is one nanosecond.

To keep from having to deal with these cumbersome figures in working out mathematical formulas, they use a kind of shorthand, similar to that used by mathematicians to express a number multiplied by itself several or many times. Instead of writing $2 \times 2 \times 2$, for example, we write 2^3, and say, "two to the third power." Similarly, instead of writing 1/1 000 000, or even 0.000 001, scientists who work with very small fractions express a millionth as 10^{-6}, meaning 0.1 multiplied by itself 6 times. A billionth of a second, or nanosecond, is expressed as 10^{-9} second, which is 0.1 multiplied by itself 9 times. They say, "ten to the minus nine power."

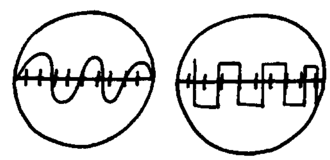
A billionth of a second is an almost inconceivably small bit—many thousands of times smaller than the smallest possible "bit" of length or mass that can be measured. We cannot think concretely about how small a nanosecond is; but to give some idea, the impulses that "trigger" the picture lines on the television screen come, just one at a time, at the rate of 15 750 per second. The whole picture "starts over," traveling left to right, one line at a time, the 525 lines on the picture tube, 30 times a second. At this rate it would take 63 000 nanoseconds just to trace out one line.

Millionths and billionths of a second cannot, of course, be *measured* with a mechanical clock at all. But today's electronic *devices* can count them accurately and display the count in usable meaningful terms.



Whether you are counting hours or microseconds, the principle is essentially the same. It's simply a matter of dividing units to be counted into identical, manageable groups. And since time moves steadily in a "straight line" and in only one direction, counting the swings or ticks of the timer—the *frequency* with which they occur—is easier than counting the pellets in a pailful of buckshot, for example. "Bits" of time, whatever their size, follow one another single file, like beads on a string; and whether we're dealing with 10 large bits—hours, for example—or 200 billion small bits, such as microseconds, all we need to do is to count them as they pass through a "gate," and keep track of the count.

The "hour" hand on a clock divides a day evenly into 12 or 24 hours—depending on how the clock face and works are designed. The "minute" hand divides the hour evenly into 60 minutes, and the "second" hand divides the minute evenly into 60 seconds. A "stop watch" has a finer *divider*—a hand that divides the seconds into tenths of a second.



When we have large groups of identical items to count, we often find it faster and more convenient to count by tens, dozens, hundreds, or some other number. Using the same principle, electronic devices can count groups of ticks or oscillations from a frequency source, add them together, and display the results in whatever way one may wish. We may have a device, for example, that counts groups of 9 192 631 770 oscillations of a cesium-beam atomic frequency standard, and sends a special tick each time that number is reached; the result will be very precisely measured one-second intervals between ticks. Or we may want to use much smaller bits—microseconds, perhaps. So we set our electronic divider to group counts into millionths of a second, and to display them on an *oscilloscope*.

Electronic counters, dividers, and multipliers make it possible for scientists with the necessary equipment to "look at," and to put to hundreds of practical uses, very small bits of time, measured to an accuracy of one or two parts in 10^{11}; this is about 1 second in 3000 years. Days, years, and centuries are, after all, simply units of accumulated nanoseconds, microseconds, and seconds.

Chapter

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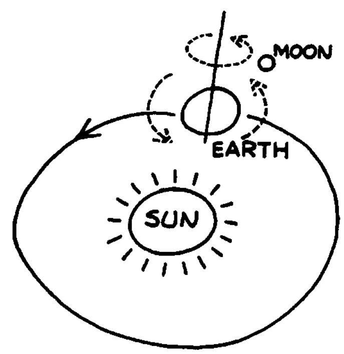
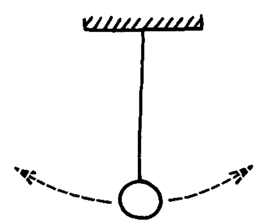
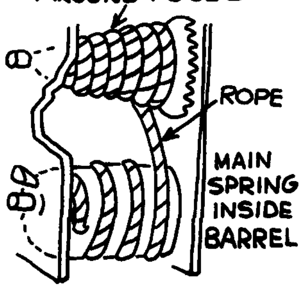
EVERYTHING SWINGS



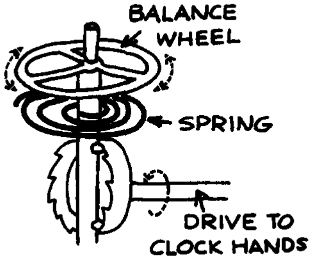
The Earth swings around the Sun, and the Moon swings around the Earth. The Earth "swings" around its own axis. These movements can easily be observed and charted from almost any spot on Earth. The observations were and are useful in keeping track of time, even though early observers did not understand the movements and often were completely wrong about the relationships of heavenly bodies to one another. The "swings" happened with dependable regularity, over countless thousands of years, and therefore enabled observers to predict the seasons, eclipses, and other phenomena with great accuracy, many years in advance.

When we observe the Earth's swing around its axis, we *see* only a part of that swing, or an arc, from horizon to horizon, as the Sun rises and sets. A big breakthrough in timekeeping came when someone realized that another arc—that of a free-swinging pendulum—could be harnessed and adjusted, and its swings counted, to keep track of passing time. The accuracy of the pendulum clock was far superior to any of the many devices that had preceded it—water clocks, hour glasses, candles, and so on. Furthermore, the pendulum made it possible to "chop up" or refine time into much smaller, measurable bits than had ever been possible before; one could measure—roughly, to be





AS MAIN SPRING UNWINDS, LEVERAGE BETWEEN BARREL AND FUSÉE CHANGES



sure—seconds and even parts of seconds, and this was a great advancement.

The problem of keeping the pendulum swinging regularly was solved at first by a system of cog wheels and an "escapement" that gave the pendulum a slight push with each swing, in much the same way that a child's swing is kept in motion by someone pushing it. A weight on a chain kept the escapement lever pushing the pendulum, as it does today in the cuckoo clocks familiar in many homes.

But then someone thought of another way to keep the pendulum swinging—a wound-up spring could supply the needed energy if there were a way to make the "push" from the *partially* wound spring the same as it was from a *tightly* wound spring. The "fusee"—a complicated mechanism that was used for only a brief period—was the answer.

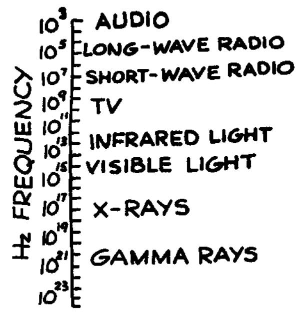
From this it was just one more step to apply a spring and "balance wheel" system directly to the pinions or cogs that turned the hands of the clock, and to eliminate the pendulum. The "swings" were all inside the clock, and this saved space and made it possible to keep clocks moving even when they were moved around or laid on their side.

But some scientists who saw a need for much more precise time measurement than could be achieved by conventional mechanical devices began looking at other things that swing—or vibrate or oscillate—things that swing much faster than the human senses can count. The vibrations of a tuning fork, for instance, which, if it swings at 440 cycles per second, is "A" above "Middle C" on our music scale. The tiny tuning fork in an electric wrist watch, kept swinging by electric impulses from a battery, hums along at several hundred vibrations or cycles per second.

As alternating-current electricity became generally available at a reliable 60 swings or cycles per second—or 60 hertz (50 in some areas)—it was fairly simple to gear these swings to the clock face of one of the most common and dependable timepieces we have today. For most day-to-day uses, the inexpensive electric wall or desk clock driven by electricity from the local power line keeps "the time" adequately.

But for some users of precise time, these common measuring sticks are as clumsy and unsatisfactory as a liter measuring cup would be for a merchant who sells perfume by the dram. These people need something that cuts time up with swings much faster than 60ths or 100ths of a second. The power company itself, to supply electricity at a constant 60 hertz, must be able to measure swings at a much faster rate.

Power companies, telephone companies, radio and television broadcasters, and many other users of precise time have long depended on the swings or vibrations of quartz crystal oscillators, activated by an electric current, to divide time intervals into *megahertz*, or millions of cycles per second. The rate at which the crystal oscillates is determined by the thickness—or thinness—to which it is ground. Typical frequencies are 2.5 or 5 megahertz (MHZ)—2½ million or 5 million swings per second.

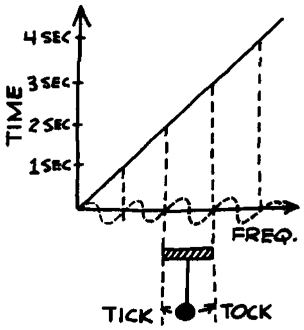


Incredible as it may seem, it is relatively easy to measure swings even much faster than this. What swings faster? Atoms do. One of the properties of each element in the chemistry Periodic Table of Elements is the set of rates at which its atoms swing or resonate. A hydrogen atom, for example, has a resonant frequency at 1 420 405 752 cycles per second, or hertz. A rubidium atom has one at 6 834 682 608 hertz, and a cesium atom at 9 192 631 770 hertz. These are some of the atoms most commonly used as measuring sticks for precise time—the "atomic clocks" maintained by television network master stations, some scientific laboratories, and others. Primary time standards, such as those maintained by the U.S. Naval Observatory or the National Institute of Standards and Technology (NIST), are "atomic clocks."

Everything swings, and anything that swings at a constant rate can be used as a standard for measuring time interval.

GETTING TIME FROM FREQUENCY

The Sun as it appears in the sky—or the "apparent Sun"—crosses the zenith or highest point in its arc with a "frequency" of once a day, and 365¼ times a year. A metronome ticks off evenly spaced intervals of time to help a musician maintain the time or *tempo* of a composition she



is studying. By moving the weight on its pendulums she can slow the metronome's "frequency" or speed it up.

Anything that swings evenly can be used to measure *time interval* simply by counting and keeping track of the number of swings or ticks-provided that we know how many swings take place in a recognized unit of time, such as a day, an hour, a minute, or a second. In other words, we can measure time interval if we know the *frequency* of these swings. A man shut up in a dungeon, where he cannot see the Sun, could keep a fairly accurate record of passing time by counting his own heartbeats—if he knew how many times his heart beats in one minute—and if he has nothing to do but count and keep track of the number.

The term *frequency* is commonly used to describe swings too fast to be counted mentally, and refers to the number of swings or cycles per second—called hertz (Hz), after Heinrich Hertz, who first demonstrated the existence of radio waves.

If we can count and keep track of the cycles of our swinging device, we can construct a time interval at least as accurate as the device itself—even to millionths or billionths of a second. And by adding these small, identical bits together, we can measure any "length" of time, from a fraction of a second to an hour—or a week or a month or a century.

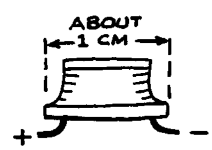
The most precise and accurate measuring device in existence cannot tell us the *date*—unless we have a source to tell us when to *start* counting the swings. But if we know this, and if we keep our swinging device "running," we can keep track of both time interval and date by counting the cycles of our device.

WHAT IS A CLOCK?

Time "keeping" is simply a matter of counting cycles or units of time. A clock is what does the counting. In a more strict definition, a clock also keeps track of its count and displays what it has counted. But in a broad sense, the Earth and the Sun are a clock—the most common and most ancient clock we have, and the basis of all other clocks.

When ancient peoples put a stick in the ground to observe the movement of its shadow from sunrise to sunset, it was fairly easy and certainly a natural step to mark off "noon" and other points where the shadow lay at other times of day—in other words, to make a sundial. Sundials can tell the time reliably when the Sun is shining. They are of no use at all when the Sun is not shining. So people made mechanical devices called clocks to interpolate or keep track of time between checks with the Sun. The Sun was a sort of "master clock" that served as a primary time scale by which the secondary mechanical clocks were calibrated and adjusted.

Although some early clocks used the flow of water or sand to measure passing time, the most satisfactory clocks counted the swings of a pendulum or of a balance wheel. Recently in the history of timekeeping, accurate clocks that count the vibrations of a quartz crystal activated by an electric current or the resonances of atoms of selected elements such as rubidium or cesium, have been developed. Since "reading" such a clock requires counting millions or billions of cycles per second—in contrast to the relatively slow 24-hour cycle of the Earth–Sun clock—an atomic clock requires much more sophisticated equipment for making its count. But given the necessary equipment, we can read an atomic clock with much greater ease, in much less time, and with many thousands of times greater precision than we can read the Earth–Sun clock.



METAL CAPSULE CONTAINING QUARTZ CRYSTAL USED IN WRIST WATCHES

A mechanism that simply swings or ticks—a clockwork with a pendulum, for example, without hands or face—is not, strictly speaking, a clock. The swings or ticks are meaningless, or *ambiguous*, until we not only count them but also establish some base from which to *start counting*. In other words, until we hook up "hands" to keep track of the count and put those hands over a face with numbers that help us count the ticks and oscillations and make note of the accumulated count, we don't have a useful device.

The familiar 12-hour clock face is simply a convenient way to keep track of the ticks we wish to count. It serves very well for measuring time interval, in hours, minutes, and seconds, up to a maximum of 12 hours. The less familiar 24-hour clock face serves as a measure of time interval up to 24 hours. But neither will tell us anything about the day, month, or year.

THE EARTH–SUN CLOCK

As we have observed, the spin of the Earth on its axis and its rotation around the Sun provide the ingredients for a clock—a very fine clock that we can certainly never get along without. It meets many of the most exacting requirements that the scientific community today makes for an acceptable standard:

AVAILABILITY

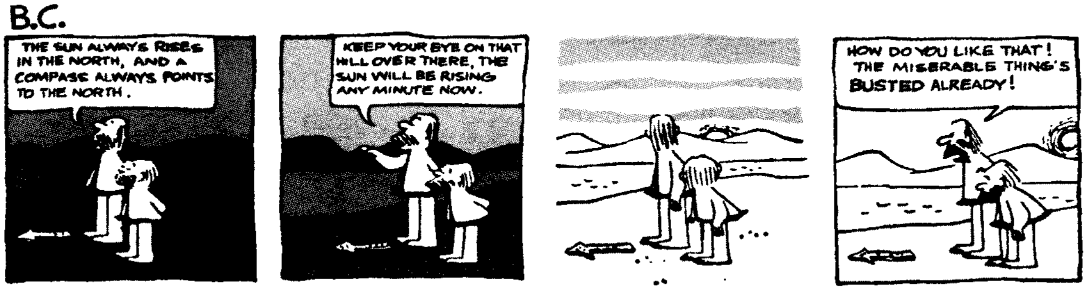
RELIABILITY

STABILITY

- It is *universally available*. Anyone, almost anywhere on Earth, can readily read and use it.
- It is *reliable*. There is no foreseeable possibility that it may stop or "lose" the time, as is possible with manufactured clocks.
- It has great overall *stability*. On the basis of its time scale, scientists can predict such things as the hour, minute, and second of sunrise and sunset at any part of the globe; eclipses of the Sun and Moon, and other time-oriented events hundreds or thousands of years in advance.

In addition, it involves no expense of operation for anyone; there is no possibility of international disagreement as to "whose" Sun is the authoritative one, and no responsibility for keeping it running or adjusted.

Nevertheless, this ancient and honored timepiece has some limitations. As timekeeping devices were improved and became more common—and as the study of the Earth and the universe added facts and figures to those established by earlier observers—it became possible to measure



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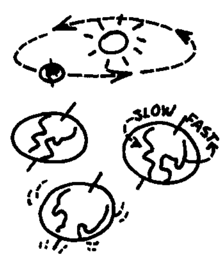
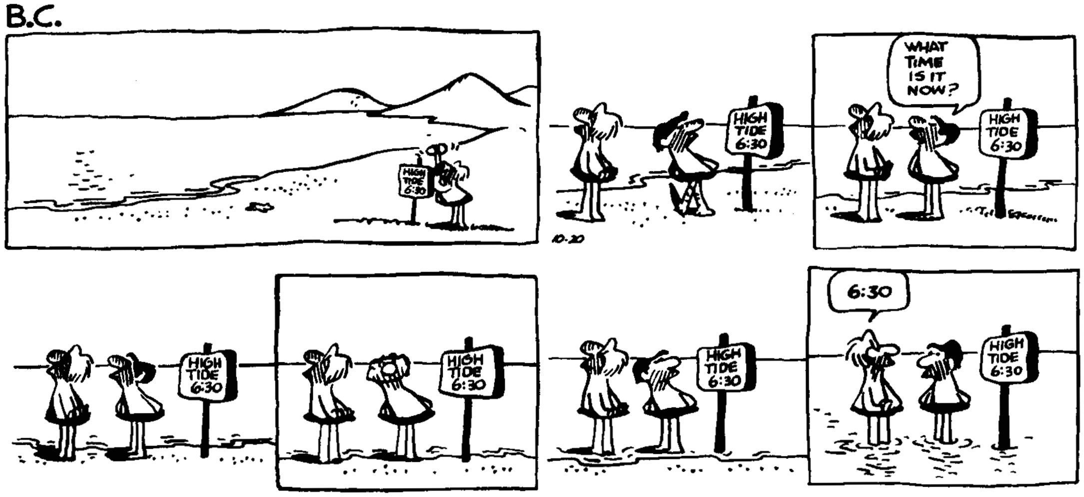
precisely some of the phenomena that had long been known in a general way, or at least suspected. Among them was the fact that the Earth–Sun clock is not, by more precise standards, a very stable timepiece.

- The Earth's orbit around the Sun is not a perfect circle but is elliptical, so the Earth travels faster when it is nearer the Sun than when it is farther away.
- The Earth's axis is tilted to the plane containing its orbit around the Sun.
- The Earth spins at an irregular rate around its axis of rotation.
- The Earth wobbles on its axis.



For all of these reasons the Earth–Sun clock is not an accurate clock. The first two facts alone cause the day, as measured by a sundial, to differ in time, as we reckon it today, by about 15 minutes a day in February and November. These effects are predictable and cause no serious problem, but there are also significant, unpredictable variations.

Gradually, clocks became so much more stable and precise than the Earth–Sun clock as time scales for measuring short time intervals that solar time had to be "corrected." As mechanical and electrical timepieces became more common and more dependable, as well as easier to use, nearly everyone looked to them for the time and forgot about the Earth–Sun clock as the master clock. People looked at a clock to see what time the Sun rose, instead of looking at the sunrise to see what time it was.



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METER STICKS TO MEASURE TIME

If we have to weigh a truckload of sand, a bathroom scale is of little use. Nor is it of any use for finding out whether a letter will need one postage stamp or two. A meter stick is all right for measuring centimeters—unless we want to measure a thousand or ten-thousand meters—but it won't do for measuring accurately the thickness of an eyeglass lens.

Furthermore, if we order a bolt 5/16 of an inch in diameter and 8-3/16 inches long—and our supplier has only a *meter* stick, he will have to use some arithmetic before he can fill our order. His *scale* is different from ours. Length and mass can be chopped up into any predetermined sizes anyone wishes. Some sizes are easier to work with than others, and so have come into common use. The important point is that everyone concerned with the measurement agrees on what the *scale* is to be. Otherwise a liter of tomato juice measured by the juice processor's scale might be different from the liter of gasoline measured by the oil company's scale.

Time, too, is measured by a scale. For practical reasons, the already existing scale, set by the spinning of the Earth on its axis and the rotation of the Earth around the Sun, provides the basic scale from which others have been derived.

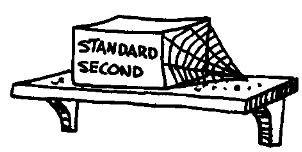
WHAT IS A STANDARD?

The important thing about measurement is that there be general agreement on exactly what the *scale* is to be and how the basic *unit* of that scale is to be defined. In other words, there must be agreement upon the *standard* against which all other measurements and calculations will be compared. In the United States, the standard unit for measuring length is the meter. The basic unit for measurement of mass is the kilogram.

The basic unit for measuring time is the second. The second multiplied evenly by 60 gives us minutes, or by 3600 gives us hours. The length of days, and even years, is measured by the basic unit of time, the second. Time intervals of less than a second are measured in 10ths, 100ths, 1000ths—on down to billionths of a second and even smaller units.

Each basic unit of measurement is very exactly and explicitly defined by international agreement; each nation directs a government agency to make *standard units* available to anyone who wants them. In our country, the National Institute of Standards and Technology, a part of the Department of Commerce with headquarters in Gaithersburg, Maryland, provides the primary standard references for ultimate calibration of the many standard weights and measures needed for checking scales in drug and grocery stores, the meters that measure the gasoline we pump into our cars, the octane of that gasoline, the purity of the gold in our jewelry or dental repairs, the strength of the steel used in automobile parts and children's tricycles, and countless other things that have to do with the safety, efficiency, and comfort of our everyday lives.

The National Institute of Standards and Technology is also responsible for making the second—the standard unit of time interval—available to many thousands of time users everywhere—not only throughout the land, but to ships at sea, planes in the air, and vehicles in outer space. This is a tremendous challenge, for the standard second, unlike the kilogram, cannot be sent in an envelope or box and put on a



shelf for future reference, but must be supplied constantly, ceaselessly from moment to moment-and even counted upon to give the date.

HOW TIME TELLS US WHERE IN THE WORLD WE ARE

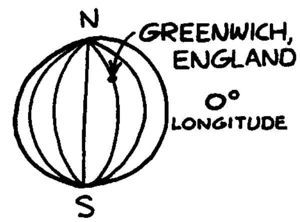
One of the earliest, most important, and universal needs for precise time information was—and still is—as a basis for place location. Navigators of ships at sea, planes in the air, and small pleasure boats and private aircraft depend constantly and continuously on-time information to find out where they are and to chart their course. Many people know this, in a general way, but few understand how it works.

Ancient people discovered long ago that the Sun and stars could aid them in their travels, especially on water where there are no familiar "signposts." Early explorers and adventurers in the northern hemisphere were particularly fortunate in having a pole star, the North Star, that appeared to be suspended in the northern night sky; it did not rotate or change its position with respect to Earth as the other stars did.

These early travelers also noticed that as they traveled northward, the North Star gradually appeared higher and higher in the sky. By measuring the elevation of the North Star above the horizon, then, navigators could determine their distance from the North Pole—and conversely, their distance from the equator. An instrument called a sextant helped to measure this elevation very accurately. The measurement is usually indicated in *degrees of latitude*, ranging from 0 degrees latitude at the equator to 90 degrees of latitude at the North Pole.

Measuring distance and charting a course east or west, however, presented a more complex problem because of the Earth's spin. But the problem also provides the key to its solution.

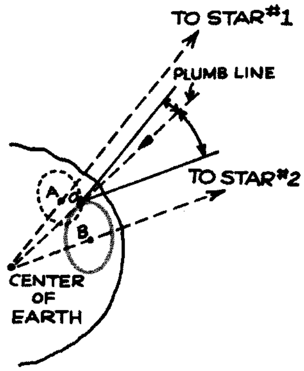
For measurements in the east-west direction, the Earth's surface has been divided into lines of *longitude*, or meridians; one complete circuit around the Earth equals 360 degrees of longitude, and all longitude lines intersect at the North and South Poles. By international agreement, the line of longitude that runs through Greenwich, England, has been labeled the zero meridian, and longitude is measured both east and west from this meridian to the point where the measurements meet at 180 degrees, on the opposite side of the Earth from the zero meridian.



At any point on Earth, the Sun travels across the sky from east to west at the rate of 15 degrees in 1 hour, or 1 degree in 4 minutes. So if a navigator has a very accurate *clock* aboard his ship—one that can tell him very accurately the time at Greenwich or the zero median—he can easily figure his longitude. He simply gets the time *where he is* from the Sun. For every four minutes that his clock, showing Greenwich time, differs from the time determined locally from the Sun, he is one degree of longitude away from Greenwich.

At night he can get his position by observing the location of two or more stars. The method is similar to obtaining latitude from the North Star. The difference is that whereas the North Star appears suspended in the sky, the other stars appear to move in circular paths around the North Star. Because of this, the navigator must know the *time* in order to find out where he is. If he does not know the time, he can read his location with respect to the *stars*, as they "move" around the North Star, but he has no way at all to tell where he is *on Earth*! His navigation charts tell him the positions of the stars at any given *time* at every season of the year; so if he knows the time, he can find out where he is simply by referring to two or more stars, and reading his charts.

The principle of the method is shown in the illustration. For every star in the sky there is a point on the surface of



the Earth where the star appears directly overhead. This is Point A for Star #1 and Point B for Star #2 in the illustration. The traveler at Point 0 sees Star #1 at some angle from the overhead position. But as the illustration shows, all travelers standing on the black circle will see Star #1 at this same angle. By observing Star #2, the traveler will put herself on another circle of points, the gray circle; so her location will be at one of the two intersection points of the gray and the black circles.

She can look at a third star to choose the correct intersection point; more often, however, she has at least some idea of her location, so she can pick the correct intersection point without further observation.

The theory is simple. The big problem was that until about 200 years ago, no one was able to make a clock that could keep time accurately at sea.

BUILDING A CLOCK THAT WOULDN'T GET SEASICK

During the centuries of exploration thousands of miles across uncharted oceans, the need for improved navigation instruments became critical. Ship building improved, and larger, stronger vessels made ocean trade—as well as ocean warfare—increasingly important. But too often ships laden with priceless merchandise were lost at sea, driven off course by storms, with the crew unable to find out where they were or to chart a course to a safe harbor.

Navigators had long been able to read their latitude north of the equator by measuring the angle formed by the horizon and the North Star. But east-west navigation was almost entirely a matter of "dead reckoning." If only they had a *clock* aboard that could tell them the time at Greenwich, England, then they could easily find their position east or west of the zero meridian.

It was this crucial need for accurate, dependable clocks aboard ships that pushed inventors into developing better and better timepieces. The pendulum clock had been a real breakthrough and an enormous improvement over any timekeeping device made before it. But it was no use at all at sea. The rolling and pitching of the ship made the pendulum inoperative.

In 1713 the British government offered an award of £20 000 to anyone who could build a chronometer that would serve to determine longitude within half a degree. Among the many craftsmen who sought to win this handsome award was the English clock maker, John Harrison, who spent more than 40 years trying to meet the specifications. Each model became a bit more promising as he found new ways to cope with the rolling sea, temperature changes that caused intolerable expansion and contraction of delicate metal springs, and salt spray that corroded everything aboard ship.

ROLLING SEA
TEMPERATURE
SALT SPRAY

When finally he came up with a chronometer that he considered nearly perfect, the government commission was so afraid that it might be lost at sea that they suspended testing it until Harrison had built a second unit identical with the first, to provide a pattern. Finally, in 1761 Harrison's son William was sent on a voyage to Jamaica to test the instrument. In spite of a severe storm that lasted for days and drove the ship far off course, the chronometer proved to be amazingly accurate, losing less than 1 minute over a period of many months and making it possible for William to determine his longitude at sea within 18 minutes of arc, or less than of one-third of one degree. Harrison claimed the £20 000 award, part of which he had already received, and the remainder was paid to him in various amounts over the next two years—just three years before his death.

Harrison's difficulty in receiving his just award was more political than technical. As he built ever-improved versions of his chronometer, astronomers pursued an astronomical solution to the longitude problem. Their idea was to

CLOCK IN THE SKY...
- LENGTHY CALCULATIONS

HARRISON'S CLOCK...
- RELATIVELY SIMPLE CALCULATIONS

JUPITER

GALILEO DISCOVERED FOUR MOONS

replace Harrison's chronometer with a "clock" in the sky. The idea was an old one going back to at least 1530. The concept was simple, but in practice it was well beyond the measurement skills of the astronomers of that era. We can understand the method by describing a version proposed by Galileo Galilei in 1610.

Galileo was the first to point the newly invented telescope to the heavens. Among the bewildering things Galileo observed were four moons of Jupiter. In his usual meticulous fashion, Galileo determined the orbits of the moons and was soon able to predict the times at which the moons disappeared behind Jupiter's disk—eclipsed by Jupiter. Here was a clue to a clock in the sky. Galileo reasoned that a navigator equipped with a table of Jovian moon eclipse times could calibrate his local clock. If, for example, an eclipse of one of the moons occurred at 9:33 in the morning Greenwich time, then the navigator could watch for the eclipse, note the time the eclipse occurred relative to his local clock, and correct it accordingly. Since the eclipses of the moons occurred fairly often it would not be necessary to wait long periods of time to make clock corrections. That was the idea anyway.

There were practical problems. First, the navigator needed a telescope to make the necessary observations. That in itself was not a big obstacle, but sighting Jupiter's moons on the heaving deck of a ship rolling in high seas was a different matter. Further the observations needed to be made at night, and the sky might be overcast. All in all, the clock in the sky did not look like a promising solution to ship navigation. Nevertheless, the method and variations on it worked well enough on land for cartographers to make the first truly accurate maps of the world.

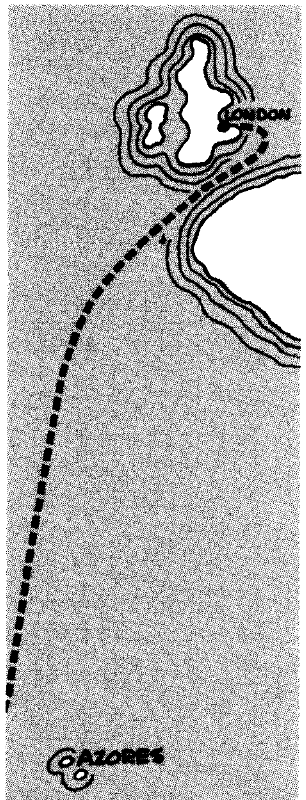
By Harrison's time, astronomers had made much progress in mapping the skies. The clock in the sky continued to look encouraging, although the necessary computations required several hours while, with Harrison's clock, the computations were relatively simple and could be done in a matter of minutes.

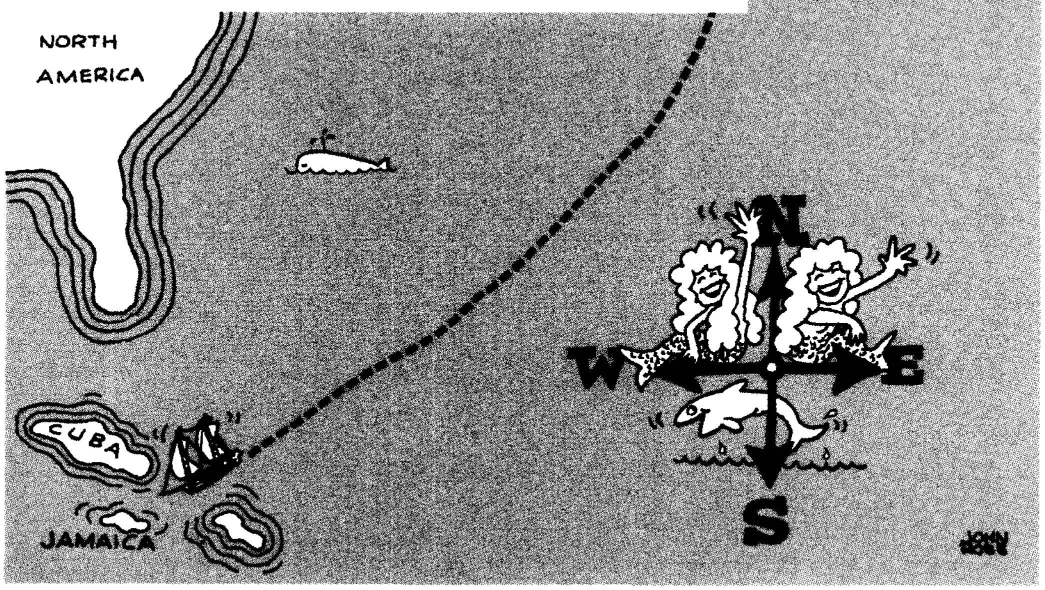
Unfortunately for Harrison, one of the members of the prize committee was a strong advocate of the astronomical method and was the Astronomer Royal to boot. Finally, Harrison appealed directly to King George III, who, sympathetic to Harrison's plea, applied pressure on Parliament to award the balance of the prize money. Technically, Harrison never did receive the full prize since he never received the approval of the prize committee.

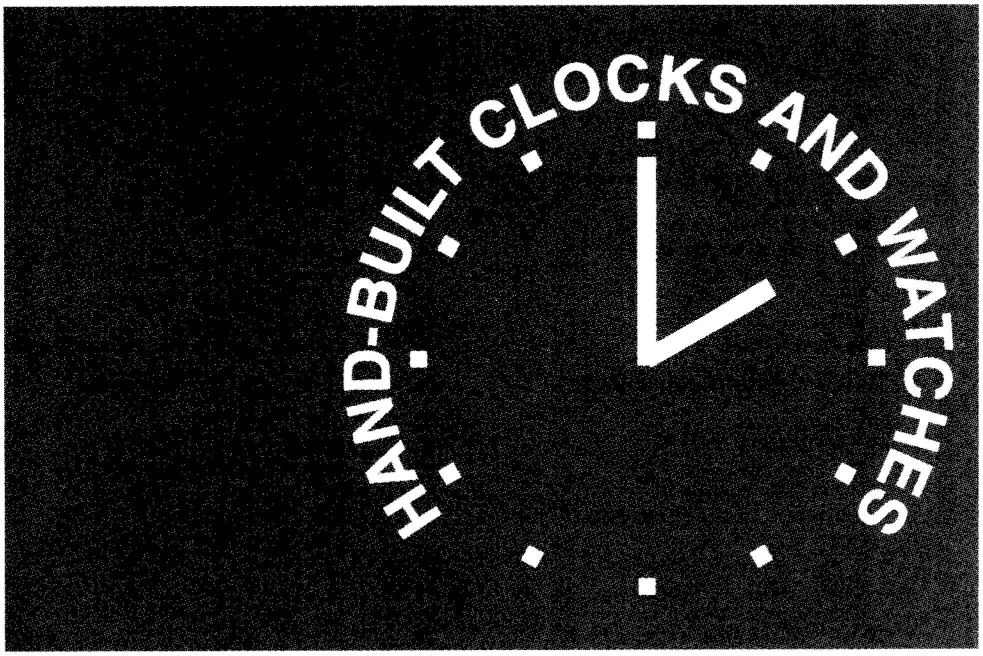
To this day, the struggle between the astronomers and the clock makers continues—although in a considerably friendlier fashion. We shall take up this matter again when we discuss the atomic definition of the second.

For more than half a century after Harrison's chronometer was accepted, an instrument of similar design—each one built entirely by hand by a skilled horologist—was an extremely valuable and valued piece of equipment—one of the most vital items aboard a ship. It needed very careful tending, and the one whose duty it was to tend it had a serious responsibility.

Today there may be almost as many wrist watches as crew members aboard an ocean-going ship—many of them more accurate and dependable than Harrison's prized chronometer. But the ship's chronometer, built on essentially the same basic principles as Harrison's instrument, is still a most vital piece of the ship's elaborate complement of navigation instruments.






HAND-BUILT CLOCKS AND WATCHES

II.

HAND-BUILT CLOCKS AND WATCHES

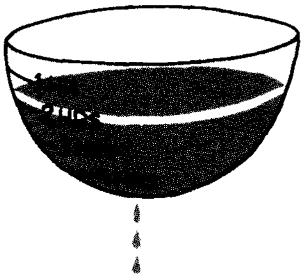
Chapter 3

EARLY CLOCKS

Three young boys, lured by the fine weather on a warm spring day, decided to skip school in the afternoon. The problem was knowing when to come home, so that their mothers would think they were merely returning from school. One of the boys had an old alarm clock that would no longer run, and they quickly devised a scheme: The boy with the clock set it by a clock at home when he left after lunch at 12:45. After they met they would take turns as timekeeper, counting to 60 and moving the minute hand ahead one minute at a time!

Almost immediately two of the boys got into an argument over the rate at which the third was counting, and *he* stopped counting to defend his own judgment. They had "lost" the time—crude as their system was—before their adventure was begun, and spent most of their afternoon alternately accusing one another and trying to estimate how much time their lapses in counting had consumed.

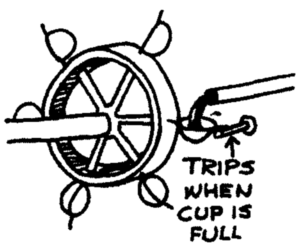
"Losing" the time is a constant problem even for timekeepers much more sophisticated than the boys with their old alarm clock. Regulating the clock so that it will "keep" time accurately, even with high-quality equipment, presents even greater challenges. We have already discussed some of these difficulties, in comparison with the relatively simple keeping of a device for measuring length or mass, for example. We've talked about what a clock is and have mentioned briefly several different kinds of clocks. Now let's look more specifically at the components common to all clocks and the features that distinguish one kind of clock from another.



SAND AND WATER CLOCKS

The earliest clocks that have survived to now were built in Egypt. The Egyptians constructed both sundials and water clocks. The water clock in its simplest form consisted of an alabaster bowl, wide at the top and narrow at the bottom, marked on the inside with horizontal "hour" marks. The bowl was filled with water that leaked out through a small hole in the bottom. The clock kept fairly uniform time because more water ran out between hour marks when the bowl was full than when it was nearly empty and the water leaked out more slowly.

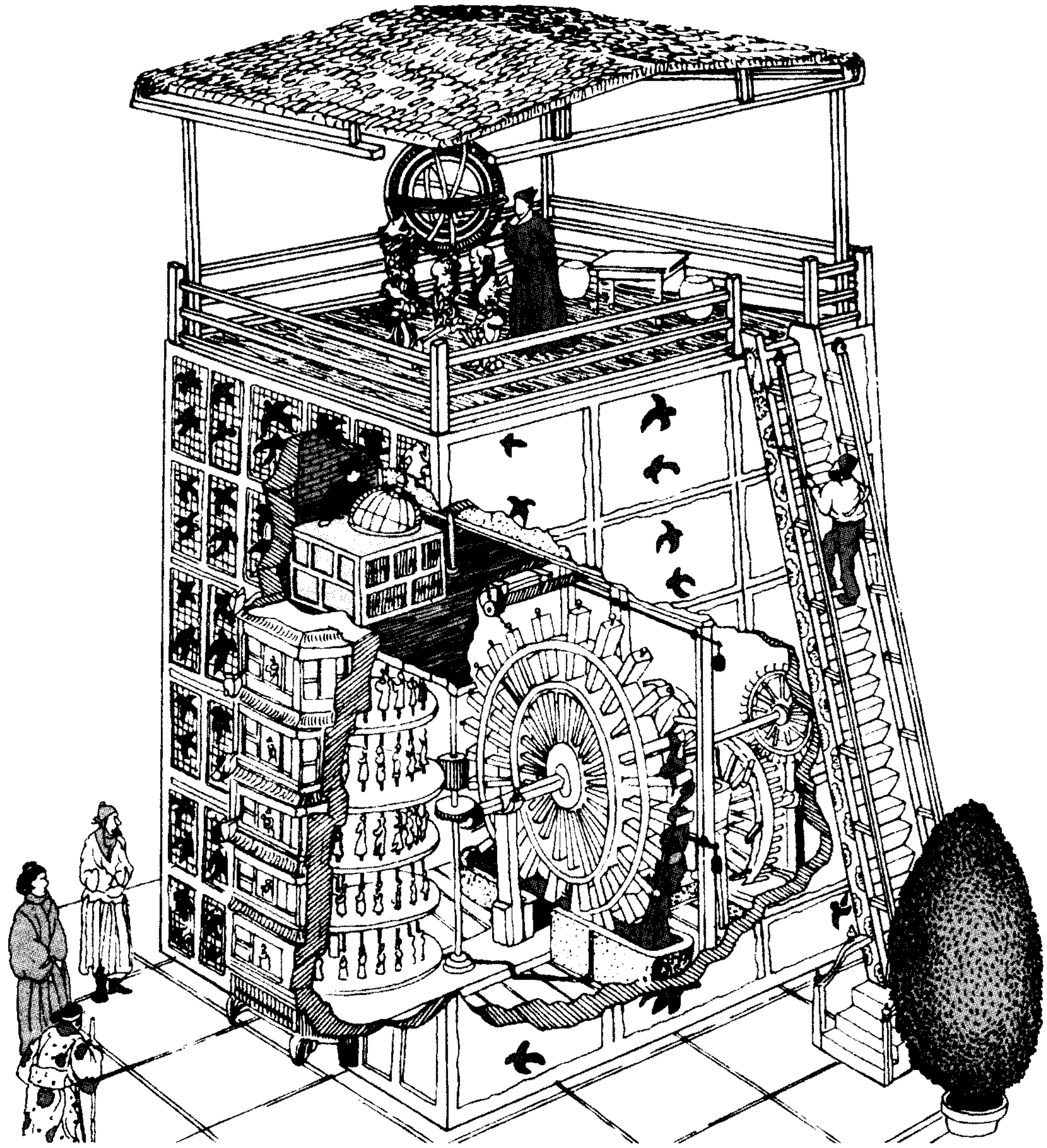
The Greeks and Romans continued to rely on water and sand clocks. Sometime between the 8th and 11th centuries A.D. the Chinese constructed a clock that had some of the characteristics of later "mechanical" clocks. The Chinese clock was still basically a water clock, but the falling water powered a water wheel with small cups arranged at equal intervals around its rim. As a cup filled with water it became heavy enough to trip a lever that allowed the next cup to move into place; thus the wheel revolved in steps, keeping track of the time.



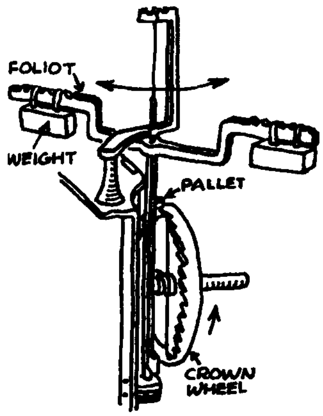
EARLY CHINESE WATER CLOCK

Many variations of the Chinese water clock were constructed, and it had become so popular by the early 13th century that there was a special guild for its makers in Germany. But aside from the fact that the clock did not keep very good time, it often froze in the western European winter.

The sand clocks introduced in the 14th century avoided the freezing problem. But because of the weight of the sand, they were limited to measuring short intervals of time. One of the chief uses of the hour glass was on ships. Sailors threw overboard a log with a long rope attached to it. As the rope played out into the water, they counted knots tied into it at equal intervals, for a specified period of time as determined by the sand clock. This gave them a crude estimate of the speed—or "knots"—at which the ship was moving.

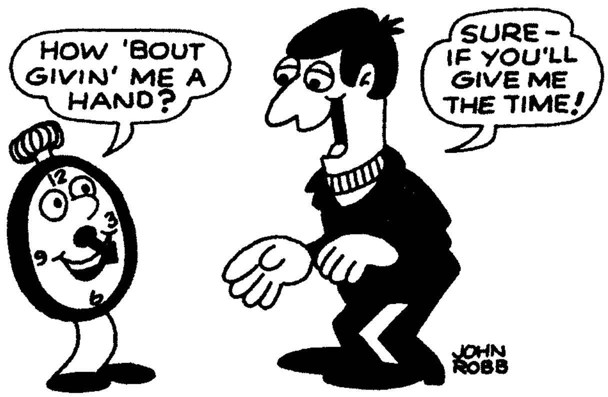


14TH CENTURY CHINESE WATER CLOCK



MECHANICAL CLOCKS

The first mechanical clock was built probably sometime in the 14th century. It was powered by a weight attached to a cord wrapped around a cylinder. The cylinder in turn was connected to a notched wheel, the *crown wheel*. The crown wheel was constrained to rotate in steps by a vertical mechanism called a *verge escapement*, which was topped by a horizontal iron bar, the *foliot*, with movable weights at each end. The foliot was pushed first in one direction and then the other by the crown wheel, whose teeth engaged small metal extensions called *pallets* located at the top and bottom of the crown wheel. Each time the foliot moved back and forth, one tooth of the crown wheel was allowed to escape. The rate of the clock was adjusted by moving the weights in or out along the foliot.

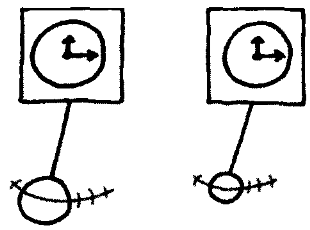


Since the clock kept time accurately within about 15 minutes a day, it did not need a minute hand. No two clocks kept the same time because the period was very dependent upon the friction between parts, the weight that drove the clock, and the exact mechanical arrangement of the parts of the clock. Later in the 15th century the weight was replaced by a spring in some clocks, but this was also unsatisfactory because the driving force of the spring diminished as the spring unwound.

The Pendulum Clock

As long as the period of a clock depended primarily upon a number of complicated factors such as friction between the parts, the force of the driving weight or spring, and the skill of the craftsman who made it, clock production was a chancy affair, with no two clocks showing the same time, let alone keeping accurate time. What was needed was some sort of periodic device whose frequency was essentially a property of the device itself and did not depend primarily on a number of external factors.

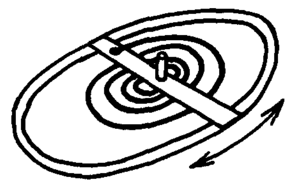
A pendulum is such a device. Galileo is credited with first realizing that the pendulum could be the frequency-determining device for a clock. As far as Galileo could tell, the period of the pendulum depended upon its length and not on the magnitude of the swing or the weight of the mass at the end of the string. Later work showed that the period does depend slightly upon the magnitude of the swing, but this correction is small as long as the magnitude of the swing is small.



Apparently Galileo did not get around to building a pendulum clock before he died in 1642, leaving this application of the principle to the Dutch scientist Christian Huygens, who built his first clock in 1656. Huygens' clock was accurate within 10 seconds a day—a dramatic improvement over the foliot clock.

The Balance-Wheel Clock

At the same time that Huygens was developing his pendulum clock, the English scientist Robert Hooke was experimenting with the idea of using a straight metal spring to regulate the frequency of a clock. But it was Huygens who, in 1675, first successfully built a spring-controlled clock. He used a spiral spring, whose derivative—the "hair spring"—is still employed in watches today. We have already told the story of John Harrison, the Englishman who built a clock that made navigation practical. The rhythm of Harrison's chronometer was maintained by the regular coiling and uncoiling of a spring. One of Harrison's chronometers gained only 54 seconds during a five-month voyage to Jamaica, or about one-third second per day.



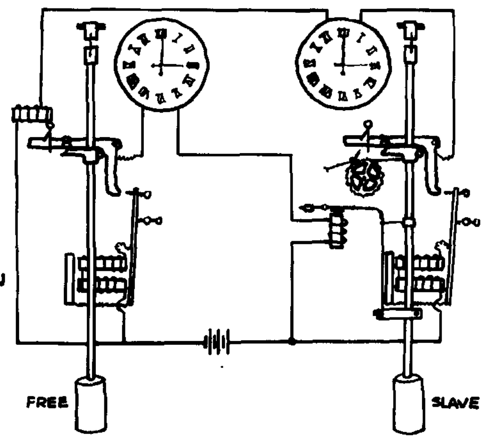
Further Refinements

The introduction of the pendulum was a giant step in the history of keeping time. But nothing material is perfect. Galileo correctly noted that the period of the pendulum depends upon its length; so the search for ways to overcome the expansion and contraction of the length of the pendulum caused by changes in temperature was on. Experiments with different materials and combinations of metals greatly improved the situation.

As the pendulum swings back and forth it encounters friction caused by air drag, and the amount of drag changes with atmospheric pressure. This problem can be overcome by putting the pendulum in a vacuum chamber, but even with this refinement there are still tiny amounts of friction that can never be completely overcome. So it is always necessary to recharge the pendulum occasionally with energy, but recharging slightly alters the period of the pendulum.

Attempts to overcome all of these difficulties finally led to a clock that had two pendulums—the "free" pendulum and the "slave" pendulum. The free pendulum was the frequency-keeping device, and the slave pendulum controlled the release of energy to the free pendulum and counted its swings. This type of clock, developed by William Shortt, kept time within a few seconds in five years.

SCHEMATIC DRAWING OF AN EARLY TWO-PENDULUM CLOCK. THE SLAVE PENDULUM TIMES THE RELEASE OF ENERGY VIA AN ELECTRIC CIRCUIT TO THE FREE PENDULUM, THUS AVOIDING A DIRECT MECHANICAL CONNECTION BETWEEN THE FREE AND SLAVE PENDULUM.



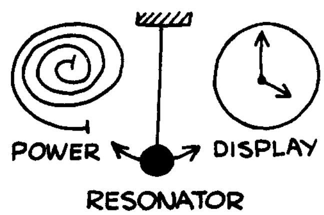
THE SEARCH FOR EVEN BETTER CLOCKS

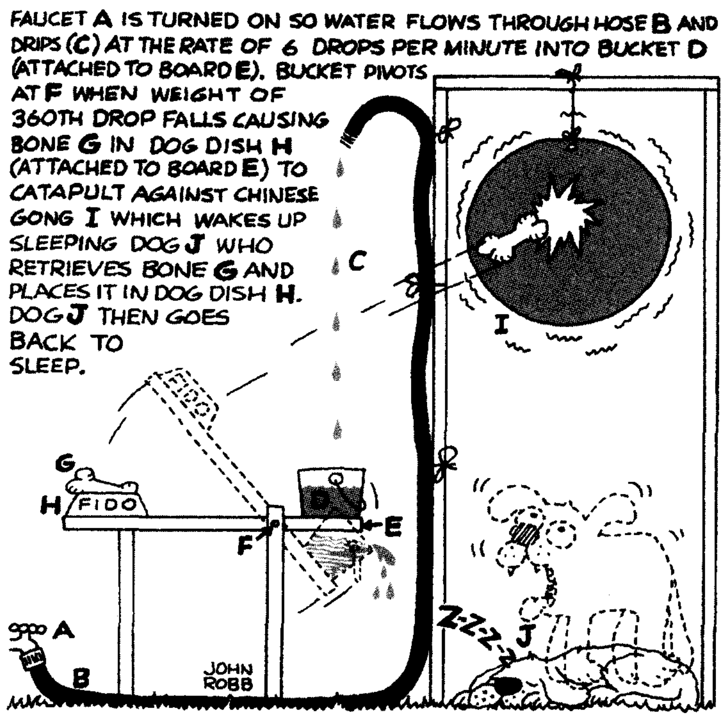
If we are to build a better clock, we need to know more about how a clock's major components contribute to its performance. We need to understand "what makes it tick." So before we begin the discussion of today's advanced atomic clocks, let's digress for a few pages to talk about the basic components of all clocks and how their performance is measured.

From our previous discussions we can identify three main features of all clocks:

- We must have some device that will produce a "periodic phenomenon." We shall call this device a *resonator.*
- We must sustain the periodic motion by feeding energy to the resonator. We shall call the resonator and the energy source, taken together, an *oscillator.*
- We need some means for counting, accumulating, and displaying the ticks or swings of our oscillator—the hands on the clock, for example.

All clocks have these three components in common.





HOUR CLOCK

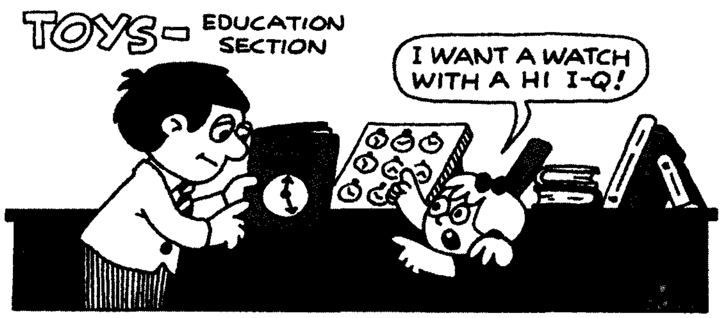
Chapter 4

"Q" IS FOR QUALITY

An ideal resonator would be one that, given a single initial push, would run forever. But of course this is not possible in nature; because of friction everything eventually "runs down." A swinging pendulum comes to a standstill unless we keep replenishing its energy to keep it going.

Some resonators, however, are better than others, and it is useful to have some way of judging the relative merit of various resonators in terms of how many swings they make, given an initial push. One such measure is called the "Quality Factor," or "*Q*." *Q* is the number of swings a resonator makes until its energy diminishes to a few percent of the energy imparted with the initial push. If there is consider-

Q=QUALITY FACTOR



TYPE	Q
INEXPENSIVE BALANCE WHEEL WATCH	1000
TUNING FORK WATCH	2000
QUARTZ CLOCK	$10^5 - 10^6$
RUBIDIUM CLOCK	10^6
CESIUM CLOCK	$10^7 - 10^8$
HYDROGEN MASER CLOCK	10^9

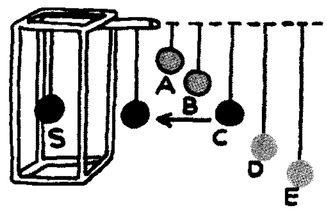
able friction, the resonator will die down rapidly, so resonators with a lot of friction have a low Q, and vice versa. A typical mechanical watch might have a Q of 100, whereas scientific clocks have Q's in the millions.

ACCURACY
STABILITY

One of the obvious advantages of a high-Q resonator is that we don't have to perturb its natural or *resonant* frequency very often with injections of energy. But there is another important advantage. A high-Q resonator won't oscillate at all unless it is swinging at or near its natural frequency. This feature is closely related to the *accuracy* and *stability* of the resonator. A resonator that won't run at all unless it is near its natural frequency is potentially more *accurate* than one that could run at a number of different frequencies. Similarly, if there is a wide range of frequencies over which the resonator can operate, it may wander around within the allowed frequency range, and so will not be very *stable*.

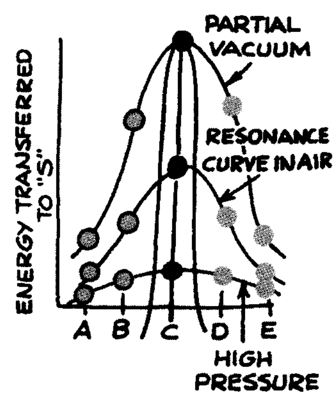
THE RESONANCE CURVE

To understand these implications better, consider the results of some experiments with the device shown in the sketch. This is simply a wooden frame enclosing a pendulum. At the top of the pendulum is a round wooden stick to which we can attach the pendulums of various lengths shown in the sketch.



Let's begin by attaching pendulum C to the stick and giving it a push. A little bit of the swinging motion of C will be transmitted to the pendulum in the frame, which we shall call S. Since S and C have the same length, their *resonant frequencies* will be the same. This means that S and C will swing with the same frequency, so the swinging energy of C can easily be transferred to S. The situation is similar to pushing someone on a playground swing with the correct timing; we are pushing always *with* the swings, never working against them.

After a certain interval of time we measure the amplitude of the swings of S, which is also a measure of the energy that has been transferred from C to S. The sketch shows this measurement graphically; the black dot in the middle of the graph gives the result of this part of our experiment.



Now let's repeat the experiment, but this time we'll attach pendulum D to the stick. D is slightly longer than S, so its period will be slightly longer. This means that D will be pushing S in the direction it "wants" to swing part of the time, but at other times S will want to reverse its direction before D is ready to reverse. The net result, as shown on our graph by the gray dot above D, is that D cannot transfer energy as easily as could C.

Similarly, if we repeat the experiment with pendulum E attached to the stick, there will be even less transference of energy to S because of E's even greater length. As we might anticipate, we obtain similar diminishing in energy transfer as we attach pendulums of successively *lesser* length than S. In these cases, however, S will want to reverse its direction at a rate *less* than that of the shorter pendulums.

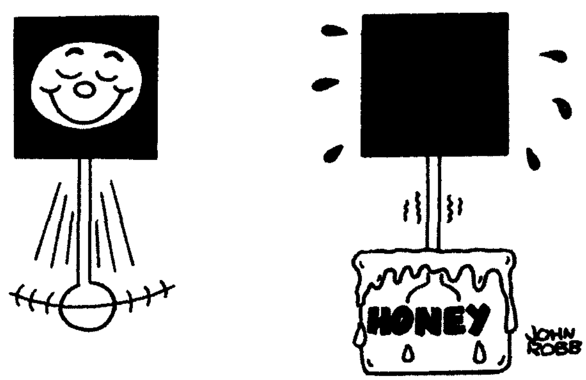
The results of all our measurements are shown by the second, or middle, curve on our graph; and from now on we shall call such curves *resonance* curves.

We want to repeat these measurements two more times, first, with the frame in a pressurized chamber, and second with the frame in a partial vacuum. The results of these experiments are shown on the graph. As we might expect, the resonance curve obtained by doing the experiment under pressure is much flatter than that of the experiment performed simply in air. This is true because, at high pressure, the molecules of air are more dense, so the pendulum experiences a greater frictional loss because of air drag. Similarly, when we repeat the experiment in a partial vacuum, we obtain a sharper, more peaked resonance curve because of reduced air drag.

These experiments point to an important fact for clock builders: the smaller the friction or energy loss, the sharper and more peaked the resonance curve. Q is related to frictional losses; the lower the friction for a given resonator, the higher the Q. Thus we can say that high-Q resonators have sharply peaked resonance curves and that low-Q resonators have low, flat resonance curves. Or to put it a little differently, the longer it takes a resonator to die down, or "decay," given an initial push, the sharper its resonance curve.

ENERGY BUILD-UP AND THE RESONANCE CURVE —AN ASIDE ON Q

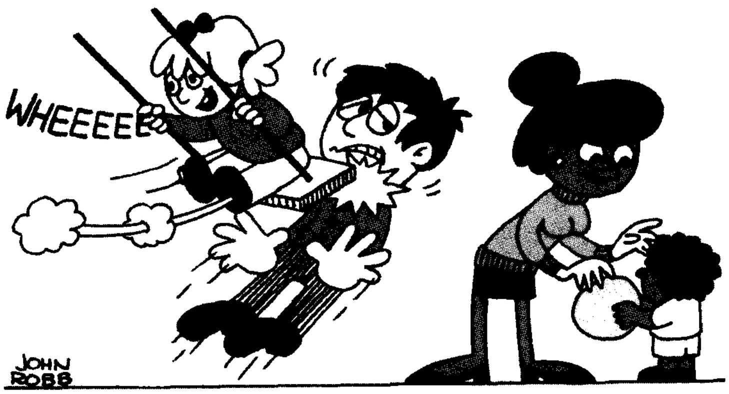
Why do resonators with a long "decay" time resist running at frequencies other than their natural frequency? A pendulum with a high Q may swing for many minutes, or even hours, from just a single push, whereas a very low-Q pendulum—such as one suspended in honey—may hardly



make it through even one swing after an initial push; it would need a new push for every swing and would never accumulate enough energy to make more than the single swing.

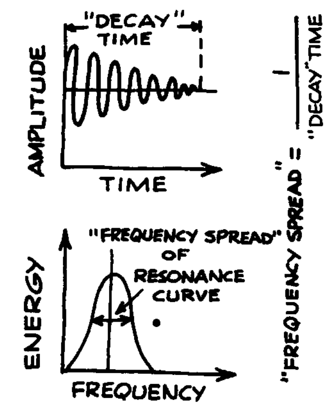
But if we push the high-Q pendulum occasionally in step with its own natural rhythm or frequency, it accumulates or stores up the energy imparted by these pushes. Thus the energy of the pendulum or oscillator may eventually greatly *exceed* the energy imparted by a single push or injection. We can observe this fact by watching someone jumping on a trampoline. As the jumper matches her muscular rhythm to that of her contact with the trampoline, it tosses her higher with each jump; she stores up the energy she puts into it with each jump.

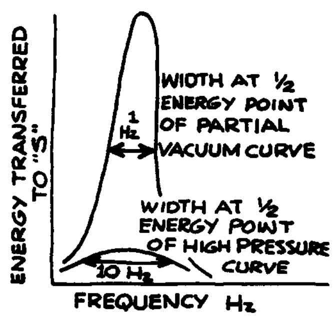
The same principle governs a person swinging on a playground swing. He "pumps up" by adding an extra shot of energy at just the right moment in the swing's natural rhythm or frequency. When he does this, the swing carries over extra energy from his pushes. The rhythm of the swing becomes so strong, in fact, that it can resist or "kick back" at the energy source if it applies energy at the wrong time-as anyone who has pushed someone else in a swing well knows!



In just such a way, a high-*Q* resonator can accumulate or pile up the energy it receives from its "pusher," or oscillator. But a low-*Q* resonator cannot accumulate appreciable energy; instead, the energy will constantly "leak out" at about the same rate it is being supplied, because of friction. Even though we feed the resonator with energy at its natural frequency, the amplitude will never build up. On the other hand, if we replenish its energy at a rate other than the natural frequency, the resonator won't have accumulated appreciable energy at its natural frequency to resist pushes at the wrong rate.

Thus the shape of the resonance curve is determined by the Q of the resonator that is being pushed or driven by some other oscillator, and the transferral of energy from the oscillator to the driven resonator depends upon the similarity between the natural frequency of the resonator and the frequency of the oscillator.





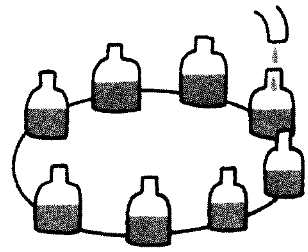
THE RESONANCE CURVE AND THE DECAY TIME

We have already observed that resonators with a high Q or long decay time have a sharp resonance curve. Careful mathematical analysis shows that there is an exact relation between the decay time and the sharpness of the resonance curve, if the sharpness is measured in a particular way. This measurement is simply the *width* of the resonance curve, in hertz, at the point where the *height* of the curve is half its maximum value.

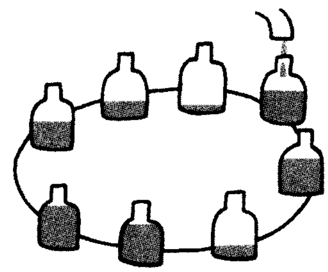
To illustrate this principle we have redrawn the two resonance curves for our resonator in a pressure chamber and in a partial vacuum. At the half-energy point of the high-pressure curve, the width is about 10 hertz, whereas for the partial vacuum curve the width is about 1 hertz at the half-energy point. With this measurement of width the mathematical analysis shows that the width of the resonance curve at the half-energy point is just the reciprocal of the decay time of the resonator. As an example, let's suppose it takes a particular resonator 10 seconds to die down, or decay. Then the width of its resonance curve at the half-energy point is one over 10 seconds, or 0.1 hertz.

We can think of the width of the curve at the half-energy point as indicating how close the pushes of the driving oscillator must be to the natural frequency of the resonator before it will respond with any appreciable vibration.

ACCURACY, STABILITY, AND Q



ALL BOTTLES HALF FULL



EACH BOTTLE CONTAINS DIFFERENT AMOUNT

Two very important concepts to clockmakers are *accuracy* and *stability*; and, as we suggested earlier, both are closely related to *Q*.

We can understand the distinction between accuracy and stability more clearly by considering a machine that fills bottles with a soft drink. If we study the machine we might discover that it fills each bottle with almost exactly the same amount of liquid, to better than one-tenth of an ounce. We would say the filling *stability* of the machine is quite good. But we might also discover that each bottle is being filled to only half capacity—but very precisely to half capacity from one bottle to the next. We would then characterize the machine as having good stability but poor *accuracy*.

However, the situation might be reversed. We might notice that a different machine was filling some bottles with an ounce or so of extra liquid, and others with an ounce or so less than actually desired, but that *on the average* the correct amount of liquid was being used. We could characterize this machine as having poor *stability*, but good *accuracy* over one day's operation.

Some resonators have good stability, others have good accuracy; the best, for clockmakers, must have both.

High Q and Accuracy

We have seen that high-*Q* resonators have long decay times and therefore sharp, narrow resonance curves—which also implies that the resonator won't respond very well to pushes unless they are at a rate very near its natural or resonant frequency. Or to put it differently, a clock with a high-*Q* resonator essentially won't run at all unless it's running at its resonant frequency.

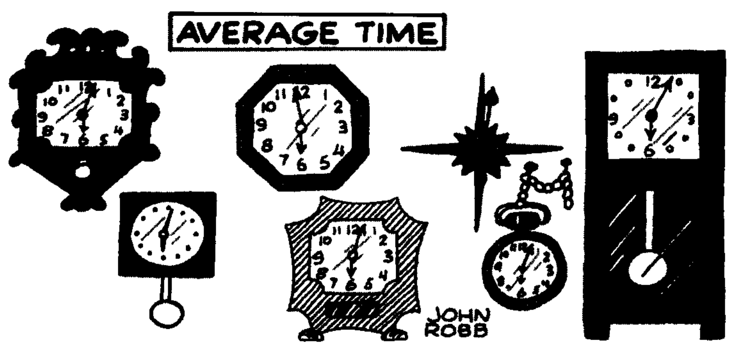
Today, the second is defined in terms of a particular resonant frequency of the cesium atom. So if we can build a resonator whose natural frequency is the natural frequency of the cesium atom—and furthermore, if this resonator has an extremely high *Q*—then we have a device that will *accurately* generate the second according to the definition of the second.

High Q and Stability

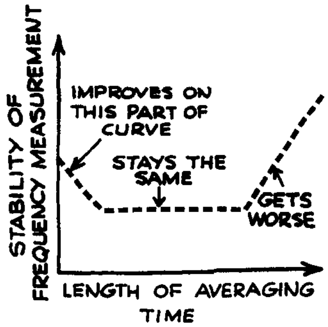
We saw that a low-stability bottle-filling machine is one that does not reliably fill each bottle with the same amount of liquid and further, that good stability does not necessarily mean high accuracy. A resonator with a high-Q, narrow resonance curve will have good stability because the narrow resonance curve constrains the oscillator to run always at a frequency near the natural frequency of the resonator. We could, however, have a resonator with good stability but whose resonance frequency is not according to the definition of the second—which is the natural frequency of the cesium atom. A clock built from such a resonator would have good stability but poor accuracy.

Waiting to Find the Time

In our discussion of the bottle-filling machine, we considered a machine that did not fill each bottle with the desired amount, but that on the average over a day's operation used the correct amount of liquid. We said such a machine had poor stability but good accuracy averaged over a day. The same can be said of clocks. A given clock's frequency may "wander around" within its resonance curve so that for a given measurement the frequency may be in error. But if we average many such measurements over a long time—or average the time shown by many different clocks at the same time—we can achieve greater accuracy—assuming that the resonator's natural frequency is the correct frequency.



It may appear that clock error can be made as small as desired if enough measurements were averaged over a long time. But experience shows that this is not true. As we first begin to average the measurements, we find that the fluctuations in frequency decrease, but then beyond some point the fluctuations no longer decrease with averaging, but remain rather constant. And finally, with more measurements considered in the averaging the frequency stability begins to grow worse again.



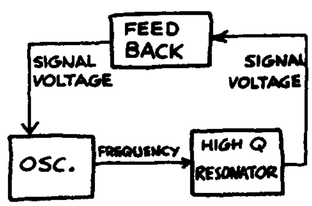
The reasons that averaging does not improve clock performance beyond a certain point are not entirely understood. One reason, called "flicker" noise, has been observed in other electronic devices—and interestingly enough, even in the fluctuations of the height of the Nile River.

PUSHING Q TO THE LIMIT

You may wonder whether there is any limit to how great Q may be. Or in other words, whether clocks of arbitrarily high accuracy and stability can be constructed. It appears that there is no fundamental reason why Q cannot be arbitrarily high, although there are some practical considerations that have to be accounted for, especially when Q is very high. We shall consider this question in more detail later, when we discuss resonators based upon atomic phenomena, but we can make some general comments here.

Extremely high Q means that the resonance curve is extremely narrow, and this fact dictates that the resonator will not resonate unless it is being driven by a frequency very near its own resonant frequency. But how are we to generate such a driving signal with the required frequency?

The solution is somewhat similar to tuning in a radio station—or tuning one stringed instrument to another. We let the frequency of the driving signal change until we get the maximum response from the high-Q resonator. Once the maximum response is achieved, we attempt to maintain the driving signal at the frequency that produced this response. In actual practice this is done by using a "feedback" system of the kind shown in the sketch.



We have a box that contains our high-Q resonator, and we feed it a signal from our other oscillator, whose output frequency can be varied. If the signal frequency from the oscillator is near the resonant frequency of the high-Q resonator it will have considerable response and will produce an output signal voltage proportional to its degree of response. This signal is fed back to the oscillator in such a way that it controls the output frequency of the resonator. This system will search for that frequency from the oscillator which produces the maximum response from the high-Q resonator, and then will attempt to maintain that frequency.

In the next chapter, where we discuss resonators based upon atomic phenomena, we shall consider feedback again. With a fair notion of what Q is all about and how it describes the potential stability and accuracy of a clock, we are in a position to understand a number of other concepts introduced later in this book.