Limits on Interstellar Messages

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1.0. Introduction

While SETI experiments designed to find radio and optical signals intentionally sent from other worlds have been conducted for more than four decades, there has never been a sustained, deliberate broadcasting effort. Arguments against a transmitting project range from the practical (cost) and the philosophical (our communication technology is less than a century old, so we should listen first), to the paranoid (it might be dangerous to betray our location with a signal). A summary of some of the arguments for and against terrestrial broadcasting efforts is given by Ekers, Cullers, Billingham, and Scheffer (2002).

Although we are not beaming signals to other star systems ourselves, there has nonetheless been considerable thought given to how we might reply to, or even initiate, any extraterrestrial communication. Various suggestions (Vakoch 1998) have included encoding our message with mathematics, music, or graphics. The last has some precedent in the pictorial messages affixed to the Pioneer 10 and 11 spacecraft, as well as the analog records carried by Voyager 1 and 2. In addition, a simple graphic was also used in the first, deliberate high-powered transmission to deep space, the Arecibo broadcast (Staff of the Arecibo Observatory 1975).

Irrespective of coding schemes, one might argue that exercises in message construction for replies are superfluous, given that mankind has long been transmitting information to the stars inadvertently. Indeed, high-powered broadcasting at frequencies above ~100 MHz will traverse the ionosphere and continue into space. The earliest television signals have already reached several thousand star systems. However, the strength of TV signals at light-years' distance will be low, given the small gain of the transmitting antennas. For VHF broadcasts, the maximum effective radiated power is between 100 and 300 kilowatts, and for UHF is 5 megawatts. At 100 light-years, these will produce signals of flux density no more than 10^{-33}–10^{-31} watts/m^2-Hz, even in the very narrow parts of the band where the carriers are located. The best SETI experiments today are seven orders of magnitude too poor to be able to detect a comparable signal. And note that retrieving the video components of a TV broadcast would require ~10^4 greater antenna collecting area than required to find the carriers.

Our military radars, thanks to their higher-gain antennas, produce more detectable emissions, but cover only a fraction of the sky at any one time. Finally, it has been pointed out that high-powered terrestrial broadcasting is likely to be a transitory activity, as improved technology will soon encourage us to use either optical fibers or low-power, highly targeted transmissions to disseminate information and entertainment.

In other words, to assume that leakage automatically generates a "reply from Earth" to any SETI signal we might receive is unrealistic. Consequently, it's useful to seriously consider the general nature of signals intended for deliberate communication between star systems, as these might (1) elucidate the construction of any future replies to extraterrestrial transmissions, and (2) help to gauge what sort of signals our SETI experiments might discover. In this chapter, we consider some realistic limits on information content that can be easily sent across interstellar distances via light or radio, and suggest what might be reasonable signaling strategies.

2.0. Information Content

Leaving aside for the moment the ostensible content of an interstellar message, be it a photograph, mathematics, music, or plain text, one can ask how much information can be sent in a reasonable time between galactic star systems that are separated by hundreds, or possibly thousands of light-years' distance. In the case of electromagnetic signaling (radio or light), this depends on (1) distance, (2) transmitter power, (3) transmitting beam size and receiver collecting area, and (4) the chosen frequency. In this chapter, we do not consider the bodily transmission of information, although as pointed out by Rose and White (2004) actually rocketing highly compressed inscribed data (which in the case of genetic material can reach densities of ~10^{24} bits/kg) to deliberately chosen recipients could convey a great deal of information at low cost. Physical conveyance of data also has the advantage that the signal is not transient—it does not require that the recipient be monitoring the communication when it arrives. On the other hand, electromagnetic signaling is fast, and—if the information conveyed is limited—can be an inexpensive way to reach very large numbers of target star systems, as will be shown below.

We are interested in estimating a reasonable *maximum* data rate for interstellar communications, on the assumption that a society only modestly more advanced (a few centuries) than ours would have the technology to construct the requisite transmitting apparatus. We can then compute the likely size of messages, a parameter that will directly influence the type of information that is sent.

2.1. Data Communication at Microwave Frequencies

Since most SETI is conducted at microwave frequencies—both because the Galaxy is highly transparent in this part of the band, and also because natural "marker" frequencies such as that of neutral hydrogen (1,420 MHz) and the hydroxyl radical (1,612, 1,665 and 1,667 MHz) delimit this spectral region—it is instructive to compute the amount of information, and the requisite power, that can be conveyed in this spectral regime.

Common radio practice is that a broadcast will use a bandwidth that is ~5 percent of the carrier frequency, or in this case, ~70 MHz. The amount of information C (bits/second) that can be conveyed with a channel of bandwidth W is given by Shannon (1948)

$$C = W \log_2 (1 + P/N), \qquad [1]$$

in which P/N is the signal power-to-noise ratio at the receiver = T_A/T_S, where T_A and T_S are respectively the antenna temperature produced by the source and the receiving system temperature. So for circumstances in which this ratio is 1, we have C = W, or 70 megabits/second.

Note that for most SETI experiments, W~1 Hz, and P/N is less than one, but these efforts are intended to find carriers or very slowly pulsed signals, both of which have extremely low information transmission rates. If sufficient transmitter power and/or antenna gain are available to produce a P/N ~1, and if the entire 70 MHz can be recorded by those receiving the signal with high temporal resolution (~10 nanoseconds), then in the course of a day, 750 gigabytes of information could be received, and in a year, 270 terabytes.

To get some idea of how feasible this is, consider the transmitter power required to produce $T_A/T_S = 1$. We have

$$T_A = A_R S_v / 2\kappa \qquad [2]$$

where A_R is the collecting area of the receiving antenna, κ is Boltzmann's constant, and S_v is the incident flux density (watts/m^2-Hz).

If we define P_T as the transmitter power over a band W, and additionally assume that this power is uniformly distributed over that band, then equation [1] becomes

$$C = W \log_2 (1+ [P_T\ A_R A_T\ ]/[\pi \kappa W \lambda^2 D^2 T_R]\ ), \qquad [3]$$

where A_T is the transmitting antenna area, T_R is the system temperature of the receiver, D is the distance between sender and receiver, and λ is the wavelength. As example, consider Arecibo-sized (7×10^4 m^2 area) transmitting and receiving antennas separated by D = 100 light-years, with λ=21 cm, and T_R = 5 K. To achieve a signal-to-noise P/N = 1 requires a transmitter power density of 1 kilowatt/Hz, or 70 gigawatts over the entire 70 MHz band. The latter figure is considerable, approximately 0.5 percent of the total energy generation on Earth today, but permits a data rate of ~10 megabytes/sec, roughly comparable to that of a high-definition television signal. There are, however, several ways that an extraterrestrial transmitting society could reduce the power demand, by using (1) a larger transmitting antenna, (2) a reduced bandwidth, or (3) a reduction in the data rate, either by sending less information, or by taking longer to send it. Note that scheme (3) has some small benefit from the slow, logarithmic dependence on power implied by equation [3].

We have assumed Arecibo-sized transmitting and receiving antennas. This is, of course, merely an anthropocentric guess. There are already plans to build a radio telescope on Earth whose maximum dimension is 1 km. At the transmitting end, an Arecibo-sized antenna used at 21 cm wavelength has a beam that is ~4,000 AU in size at 100 light-years. This is enormously larger than the zone within which one expects to find Earth-like worlds. It seems more reasonable to suppose that an advanced society bent on sending deliberate signals would focus its transmissions to cover no more than the habitable zone of the target star, defined to be of radius R_H. If we postulate that they have optimized their broadcasting effort in this fashion, equation [3] then becomes independent of distance, and

$$C = W \log_2 [1 + P_T A_R/(2\pi\kappa W R_H^2 T_R)],$$

or, solving for P_T

$$P_T = 2\pi\kappa W R_H^2 T_R / A_R (2^{C/W} - 1). \qquad [4]$$

Assuming we have a 1 km diameter receiving antenna, and using other parameters as in our example above, the power requirement drops so that only 4 kilowatts is required to transmit ~10 Megabytes/sec, assuming R_H = 2 AU, which delimits a zone larger than the orbit of Mars in our own solar system. While this optimization is logical, and rewarded by a dramatic drop in power cost, the transmitting antenna is now impressively large (a filled aperture of 300 km size for targets at 100 light-years). Nonetheless, this optimized approach gives us an estimate of the lower limit on the required power.

We have assumed that only a small fraction of the microwave band would be modulated, as this is typical practice. However, Jones (1995) has pointed out that optimal encoding could make use of the entire free-space microwave window from 1–10 GHz. If this is done, the gain in information transfer rate would be ~10^2 over our example, with a concomitant increase by the same factor in required power. Note also that interstellar scattering will smear high-frequency signal components, and this will require special transmission schemes if broadcasts are made over long distances in the galactic plane (Shostak 1995).

2.2. Data Communication at Optical Frequencies

Optical communication using pulsed light is both feasible and is being looked for by SETI practitioners. For distances extending over many hundreds of light-years or more, scattering by the interstellar medium argues for the use of infrared wavelengths. However, at wavelengths ⩾1 micron, dispersion will broaden individual pulses, limiting the maximum number of pulses that can be sent per second. The amount of the dispersion is (Taylor and Cordes, 1993)

$$\Delta t = 4.1 \times 10^{15}\ \mathrm{DM}\ \lambda^2 c^2\ \mathrm{sec}, \qquad [5]$$

where a typical value for the dispersion measure DM = 30 sec^{-1} over ~1 kpc distance. This limits pulse repetition rates to 10^{12} sec^{-1} at 1 micron wavelength, and 10^{10} sec^{-1} at 10 microns. We will assume one bit per pulse because of the slow increase in data rate with power implied in the Shannon formulation [1] and its derivative, equation [4]. Clearly, if energy cost is no object, higher bit rates than those we consider could be achieved.

Suppose, as above, an optimized system that targets a star's habitable zone. We further assume that the incoming flux of photons in one pulse width τ (seconds) at the receiving end must be ~10 times that produced during time τ by the transmitting society's own star, of luminosity L_*. If we send C binary bits/sec (one bit per pulse), with a duty cycle for "on" bits of 50 percent, the required power is

$$P_T = C\tau\ L_*\ R_H{}^2/D^2 \qquad [6]$$

The necessary power *decreases* with distance D because in this simplified calculation we have assumed that the only noise source is light from the transmitting society's star. This has the counterintuitive result that targeting distant stars requires less power, which is true if the habitable zone strategy is used. Using [6], with $\tau = 10^{-10}$ sec, an information rate of $C = 10^{10}$ bits/sec, D = 100 light-years, $R_H = 2$ AU, and a solar-type star with infrared luminosity $L^* \sim 10^{26}$ watts, then $P_T = 10^{13}$ watts. Reducing the bit rate proportionately reduces the power required, and if only one bit per second is sent, only 1 kilowatt is necessary to signal stars at 100 light-years.

There is a minimum power requirement for signaling in the optical: the level necessary to produce one photon per pulse ("on" bit) in the receiving device, assuming that there is no noise introduced by the transmitter's home star. This might be the case, for instance, if the distance D is great enough so that the star delivers $<<\tau^{-1}$ photons/sec to the receiver's mirror, or if the transmitter is located far enough from the home star to be cleanly resolved by the receiver.

The minimum power required is

$$P_{Tmin} = \pi C \; R_H^2 \; hc/(A_R\lambda), \qquad [7]$$

where h is Planck's constant and A_R is, once again, the area of the receiving mirror. Assuming λ = 10 microns, R_H = 2 AU, and a 100 m diameter receiving mirror, $P_{Tmin} = 7 \times 10^9$ watts for $C = 10^{10}$ bits/sec.

Note that from [6] and [7], we can deduce that beyond a distance of

$$D = [\tau \; L_* \; A_R \; \lambda/(\pi hc)]^{1/2}, \qquad [8]$$

the power requirement given by [6] reaches the minimum level, and no further decrease occurs. For a data rate of $C = 10^{12}$ bits/sec at λ = 1 micron, and our example parameters, this happens at D = 120 light-years. For C = 10^{10} bits/sec at λ = 10 microns, the minimum power applies for distances greater than D = 3,700 light-years.

2.3. Radio versus Optical

In Figure 23.1 we plot the required power for radio (both 5% bandwidth, and full microwave window) and two optical regimes as a function of distance.

The straightforward considerations above have shown that data rates from 10^7 to 10^{12} bits/sec can be straightforwardly achieved in the radio and optical. The power requirements as given in Figure 23.1 are considerable, particularly for optical, although one should bear in mind that these values are somewhat dependent on our assumptions about the size of the transmitting and receiving apparatus. For all but the nearest stars, the required powers are less than the current energy production on Earth (1.5×10^{13} watts), and much less than the Earth's insolation (2×10^{17} watts, above the atmosphere). These facts suggest that advanced societies could muster the energy required for transmitting at the given bit rates.

One aspect of Figure 23.1 worth noting is that full spectrum microwave transmissions have a bit rate comparable to 10 micron optical, but achieve this with four to eight orders of magnitude less power. However, against this energy efficiency, one must weigh the greater instrumental and decoding

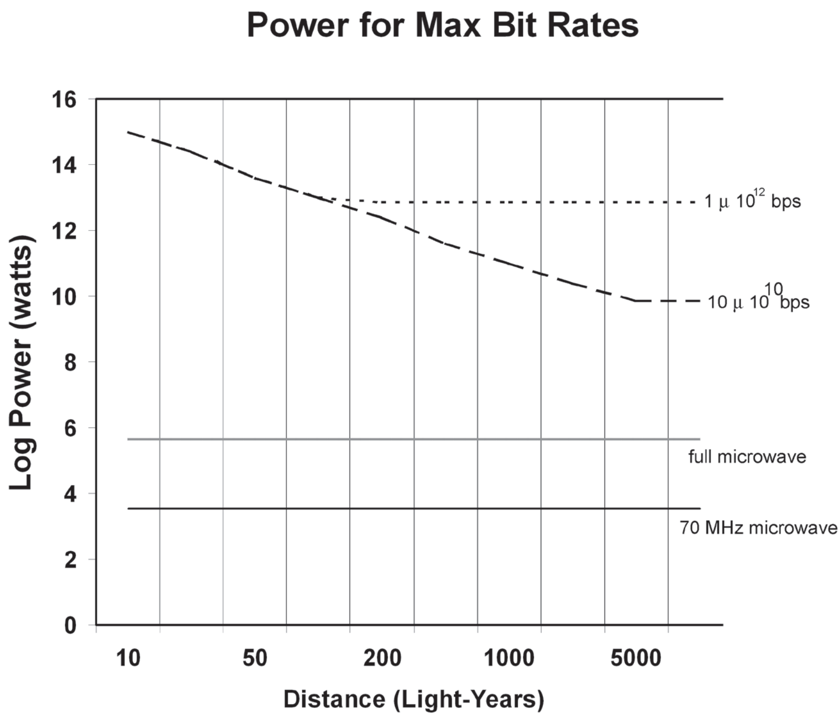

Figure 23.1. Minimum power levels required for high bit-rate transmissions. There are four regimes plotted, and all assume that the senders are beaming to a circle of radius 2 AU centered on the target star: (a) Microwave with a fully modulated 70 MHz bandwidth, having a data rate of 7 10^7 bits/sec, (b) microwave using the spectrum from 1–10 GHz, conveying 10^{10} bits/sec (c) a 10 m pulsed laser with 10^{-10} sec pulses sending 10^{10} bits/sec, and (d) a 1 m laser with 10^{-12} sec pulses and a data rate of 10^{12} bits/sec. The radio examples assume a 1 km diameter receiving antenna. Note that the power required in the optical regime flattens with distance once the influence of noise introduced by the luminosity of the home star (assumed to be $L_* = 10^{26}$ watts) drops to less than 1/10th photon per pulse width collected by a 100 m diameter receiving mirror (assumed in these examples). For comparison, terrestrial power generation is currently ~1.5 10^{13} watts.

challenges of the microwave scheme. To put information into 9 GHz bandwidth requires ingenuity both in the design of hardware and in the encoding scheme to minimize the effects of dispersion. In addition, we have assumed that all transmitters will target a star's habitable zone. At 1,000 light-years, the necessary transmitting antenna aperture in the radio, which will vary across the 9 GHz spectrum, is 5×10^3 km (nearly one-half

Earth's diameter) at the lowest part of the band. For 10 micron optical, the transmitting mirror would only need be 160 m in diameter to properly target the habitable zone of a star 1,000 light-years' distant. These differences in implementation requirements, in situations where energy is cheap, might easily favor the use of optical.

3.0. Possible Messages

With data rates in hand, we can trivially compute the total information conveyed for any broadcast length. The types of messages we routinely encounter in daily intercourse are usually formulated, decoded, and understood in a few days at most. However, such short messages may not be appropriate for a deliberate transmission intended to reach other societies. If there are 1,000–100,000 civilizations (Dick 1996) spread throughout the Milky Way, then their average separation is hundreds to a few thousand light-years. The round-trip message times will probably lead senders to assume they are engaged in one-way communication. They will want to send everything at once, since interaction with the communicant may not occur. This encourages long messages.

But messages shouldn't be *too* long, as virtually no one will chance to pick up the signal just as the message begins, but will "tune in" somewhere in the middle. Consequently, repetition will be necessary, and should occur at intervals that are short compared with the time that the recipients will be devoting to a single listening project. On Earth, this time is usually less than a human lifetime, suggesting message lengths of no more than a few years.

In considering what message might be encoded by interstellar signaling, it is worth remarking that our own efforts at interstellar communication have been extremely modest, a fact that may influence how we have thought about message content in general. The Pioneer 10/11 and Voyager 1/2 messages contained pictorial information about our appearance, culture, and location, as well as some music and verbal greetings in the case of the Voyager probes. The Voyager message was inscribed on a mechanical record, of ~10 megabytes carrying capacity. The earlier Pioneer plaques were engraved, and a bit map rendition of that graphic is ~600 kilobytes in size. The 1974 Arecibo message, which was sent digitally at about 1 byte/sec, comprised 210 bytes.

The data that our current radio SETI experiments could receive are also very limited. Project Phoenix, for example, a highly sensitive radio scrutiny of ~750 nearby star systems, could recognize narrow-band signals that pulsed every few seconds, and could collect no more than ~10 bytes in a single observation of a target star system. On the other hand, today's optical SETI experiments could, in principle, record short (ten minute) bursts of nanosecond pulses, at 10^8 bytes/sec, making for a total recordable message of ~75 gigabytes.

The limitations of the radio efforts, in particular, have seduced us into assuming that highly efficient encoding schemes would be necessary for interstellar messaging. However, this might be analogous to extrapolating Samuel F. B. Morse's carefully weighed message in 1844, "What hath God wrought?"—the first telegraphic message between cities—to present-day communication. Given the very large size of messages that could be sent by a modestly advanced civilization, as calculated above, it may be unnecessary to be overly concerned about either encoding schemes or specifics of content, but rather rely on redundancy in the transmitted information to provide the key to understanding by the recipient.

In the face of the fact that large information transfers are possible, let us consider what sorts of messages might be sent, based on current human activity. Among SETI researchers, it is occasionally (and usually offhandedly) said that altruistic societies will transmit their "Encyclopedia Galactica." Our own encyclopedias could be sent in a matter of seconds. A more ambitious project would be to transmit the contents of a major library. The content of the Library of Congress is ~1.4×10^{14} bytes (U.C. Berkeley School of Information Management and Systems, 2003) and could be sent in under an hour with the highest speed optical signaling link. The iconic information repository in contemporary times is the World Wide Web, and the estimated amount of immediately accessible data on servers in 2003 was comparable to that in the collections of the Library of Congress (U.C. Berkeley School of Information Management and Systems 2003), although the Web is growing rapidly (doubling time in the 1990s was less than six months).

These and other possible "messages" are listed in Table 23.1. What we see is that, even at radio wavelengths, we can send content as extensive as the Library of Congress in a half-year's time or less. On the other hand, the amount of *new* data currently being stored on magnetic media is about 5×10^{18} bytes per year (U.C. Berkeley School of Information Management and Systems 2003). While this may be only a temporary phenomenon, there's little doubt that information is growing at a prodigious rate. Our fastest channel, a 10^{12} bits/sec optical link, could just barely keep up with this new information flow. In a few years' time, it will obviously be unable to do so. The implication is that, while we might be able to broadcast a comprehensive "Encyclopedia Terrestria," the annual updates will require editing, and the editing will become more severe with time.

Nonetheless, Table 23.1 encourages us to think that, with transmitting times of a year or less, a society could send enormously rich content, with enough redundancy to facilitate decoding (in the same way that anyone

Table 23.1. Size of Sample Messages and Transmission Time for Various Modes.

Message	Size (bytes)	Microwave Radio Narrow-band	Microwave Radio Wide-band	Optical 10^{10} bps	Optical 10^{12} bps
Arecibo 1974 Message	2×10^2	2×10^{-5} sec	2×10^{-7} sec	2×10^{-7} sec	2×10^{-9} sec
Pioneer plaque	6×10^5	6×10^{-2} sec	5×10^{-4} sec	5×10^{-4} sec	5×10^{-6} sec
Voyager record	10^7	1 sec	0.01 sec	0.01 sec	10^{-4} sec
Human DNA	10^9	2 min	1 sec	1 sec	8×10^{-3} sec
Encyclopedia Britannica	5×10^9	10 min	5 sec	4 sec	4×10^{-2} sec
Library at Alexandria	$\sim 7 \times 10^{11}$	1 day	10 mins	10 mins	6 secs
A human memory	3×10^{12}	4 days	40 mins	40 min	25 sec
New books in 1 year	5×10^{12}	1 week	1 hour	1 hour	40 sec
Library of Congress (17 million books)	2×10^{14}	6 months	1 day	1 day	20 min
World Wide Web (2003)	2×10^{14}	7 months	2 days	2 days	20 min
E-mail in 1 year	4×10^{17}	1,500 yrs	10 yrs	10 yrs	1 month
New information generated in one year (2002)	5×10^{18}	20,000 yrs	140 yrs	130 yrs	1 yr
Memory content of all human beings	2×10^{22}	70 million yrs	0.6 million yrs	0.5 million yrs	5,000 yrs

Some table entries are based on information found in U.C. Berkeley School of Information Management and Systems (2003), and in Reupke (1992).

receiving the Library of Congress would eventually be able to figure out English). However, there is the serious problem of knowing where to broadcast the information, especially since, as we have seen, the power requirements for high bit-rate transmissions are substantial, making multiple targeting expensive. It is well and good to say that the Web can be sent in two days, but if one is compelled to sequentially target every star in the Galaxy, the transmitting project will last a billion years, and the chances that someone is listening when the broadcast reaches their planet is small.

One means to ameliorate this unfavorable approach is to use advanced astronomical information. Extraterrestrial societies that are only a century or two beyond our own will possibly have long lists of planets whose atmospheres give evidence for biology, as Earth's has for ~2 billion years. This would tell them which target stars have worlds with life. However, technological societies might only inhabit a planet for a tiny fraction of its biological history, and thus even for those transmitting societies with lists of fecund worlds, the number of possible signaling targets could still be large ($>10^6$).

These facts incline us to suggest that only three strategies seem appropriate for a transmitting society:

1. Develop very large energy sources (10^{17} watts or more, for optical transmissions) and construct a device capable of *simultaneously* targeting millions of likely worlds. If the energy of a star (~10^{26} watts) can be harnessed (e.g., via a Dyson sphere), then continuous broadcasts in the optical could be made in all directions.
2. Transmit only to those star systems from which signals have already been heard, confirming the presence of intelligent recipients. In this case, it is highly unlikely that the Solar System is now on anyone's target list, as Earth's leakage signals have only reached to ~60 light-years.
3. Transmit short messages sequentially, but repeatedly. As example, imagine a society that "pinged" a million star systems once a day (~0.1 seconds per ping). That would be adequate to daily convey the equivalent of the Encyclopedia Britannica to each of these systems using 1 micron infrared as the carrier and one bit per pulse. Needless to say, the message could be different each time.

The relative ease and economy of approach (3) suggests that it is a good candidate for the type of transmission that might be made to star systems for which the senders have no direct proof of technically competent listeners;

in other words, systems like our own, as judged by any extraterrestrials more than ~60 light-years distant. It also suggests that SETI researchers should consider looking for stars whose infrared luminosity regularly spikes.

In conclusion, we have seen that instrumentation that is technologically feasible, coupled to power sources that an advanced society will surely command, would be able to transmit, in a year's time or less, quantities of information comparable to the largest collections on Earth. However, unless the transmitting society is so advanced that it can afford both the instruments and the energy necessary to broadcast simultaneously to vast numbers of stars, it will most likely adopt the strategy of sending short, frequently repeated messages. In the case of optical signaling, these could be gigabytes in size. It seems reasonable to suspect that, until we make our presence known to others, we will have to make do with the fact that other worlds might be sending us only an encyclopedia's worth of information daily.

Note

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