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Toward a "Digital Noah's Archive" (DNA)

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Abstract

Visions for the future range from utopian to dystopian, with at least one instance suggesting that human progress will take forms none of us can imagine. Lacking any Delphic oracle, it seems prudent to prepare for the worst even while hoping for the best. In this paper we propose applying a novel, archival, silver-based medium to preserve the data of our global heritage for the long-term future. This media, Write Once Read Forever (WORF), is currently at the point of productization. WORF is distinguished by a stable, dense, data media requiring minimum maintenance and no continuous energy input for centuries-long and potentially millennia storage. As there are many risks to our civilization, our proposal is that multiple digital copies of a "Digital Noah's Archive" (or a DNA Ark)—encompassing our historical and current knowledge base—be placed in outer space away from Earth's fraught and currently unsustainable environment, as well as copies on our planet. Space, however, presents challenges of its own, so WORF media are currently being tested by NASA on the International Space Station to confirm its resistance to hostile space environments including ionizing radiation. These proposed, multiple, comprehensive Arks containing WORF data would expand on the sparse information about human existence on Earth as preserved in NASA's Pioneer and Voyager analog plaques launched to outer space in the 1970s.

1. Background

A unique, optical data storage media, specially formulated by Creative Technology, LLC, (CTech) will be tested by NASA on the International Space Station (ISS) [1] for a minimum of 6 months during 2019 to establish sufficient data on the media's resistance to space radiation [2]. We term this media *Write Once, Read Forever* (WORF) since it does not require recopying, continual maintenance, or energy inputs for multi-century (or potentially millennia) storage under normal ambient conditions. This makes WORF a data storage solution for long-term space missions, such as proposed Lunar and Mars colonies.

The experiment, termed by NASA "Hardened Extremely Long-Life Information in Optical Storage" (HELIOS), will determine whether the hostile space environment—specifically ionizing gamma and cosmic rays, solar plasma eruptions, micrograviy, and the stresses of the launch itself—will degrade WORF media. Currently data on the ISS stored on conventional media has to be continually refreshed because of radiation corruption [3, 4, 5, 6].

2. The Digital Noah's Archive (DNA Ark)

While the NASA HELIOS mission is intended to test WORF media primarily for ISS data storage and long space missions, the results of this experiment could make a space-based archive—a "Digital Noah's Archive" (or a DNA Ark)—viable in order to preserve the entirety of human DNA and that of select species, plus our historical and current knowledge base for future use. Our proposal is that multiple digital copies of a DNA Ark—preserved using archival WORF data media—be placed in outer space away from Earth's fraught and currently unsustainable environment, as well as copies on our planet, and perhaps the Moon or other planets of our solar system.

Risks currently faced by our civilization include: hegemonic [7]; misuse of resources [8, 9]; wrong turns of humans re-engineering humans [10, 11, 12]; a global natural disaster [13]; mass starvation due to loss of critical species in our food chain [14, 15] or lack of water [16]; and microbiological pandemics [17, 18]. Such apocalyptic fears "have been expressed at the highest intellectual and moral levels," as Oliver Sacks has noted [19] citing the Astronomer Royal, Martin Rees, "not a man given to apocalyptic thinking"; Rees gives our civilization a 50-50 chance of surviving the 21st Century [20].

The cataclysmic events of the First World War spurred several long-term, classic sci-fi, pseudo-history dismal projections for the human race. Olaf Stapledon's 1930 novel, *Last and First Men* [21], is one such grim vision, presciently predicting much of the 20th Century's dire events—a Second World War, mass migrations, human-induced planetary devastation—and beyond, imagining humanoid evolution in fits and starts over 10+ billion years (!). A more contemporary novel, Neal Stephenson's *Seveneves* [22], uses the ISS as the core to construct a space-base "Cloud Ark"—strikingly similar to our proposed DNA Ark—containing a "Human Genetic Archive" and human community with sufficient data to preserve our species and its culture after an apocalyptic event makes life on Earth impossible for 5000 years.

However, without projecting to the end of time or even millennia, the estimated multi-century lifetimes for WORF media —based on the re-use of proven and tested silver-based technologies that have already stood the test of time for almost two centuries [23] —should be sufficient to serve as a basis for our proposed Ark. And even if our species does not disappear or self-destruct, there is a clear benefit of having a sustainable, long-term preservation medium to store our total information database for our species' survival. For this we cannot count on the Internet or the Cloud to save all our data.

A comprehensive media container in space—a radiation-resistant, stable, and immutable WORF-based Ark—would expand on the sparse information about human existence on Earth as recorded on NASA's Pioneer 10 and 11 plaques, launched to outer space in 1972 and 1973 [24], and NASA's 1977 Voyager "Golden Record" [25].

3. Deciphering the Ark's Data

Hominids have survived several near extinctions over millions of years [26, 27, 28]. Though we have survived, we know little of anything of the technology and technics homo sapiens used to get to this stage since very little "meta-data" has been recorded until recently. Even where we have striking artifacts of our past—such as Stonehenge, the Pyramids, Easter Island's Moai statues [29], and the Inca's mysterious quipu (khipu) data storage system [30] —we can only guess about the technologies that were used to create them and the social implications for their people.

Co-incident meta-documentation is critical for future comprehension of our digital Ark. A recent archeological survey noted that the "behavioral and social sciences use archeological data in framing foundational arguments…," and such evidence "frequently undergirds debate on contemporary issues" [31], yet without decipherable, written texts we often have only vague, contentious, concepts of what the archeological data really indicates. The quipu is a case in point: the Incas contrived a color coded data system using string and knots—remarkably similar to our superimposed WORF color permutations (discussed in Sect. 6 and the Appendix on WORF matrices) [32, 33] —yet archeologists today have only an inkling about what information the quipu strings may encode; the literature does not even recognize the likelihood that these intricate strings may store data in a complex mathematical notation beyond binary (base 2) [34].

4. WORF on the ISS: the *HELIOS* experiment

It was enlightening and impressive for CTech's personnel to work with the NASA launch team covering a variety of technical disciplines to assure our mission's success. Since the HELIOS payload shares its space with astronauts on the station, CTech has had to complete a comprehensive safety review to assure the complete protection of the ISS onboard crew.

As of this writing, the HELIOS payload, in a sealed, packed case, has been scheduled to launch to the ISS from NASA's Kennedy Space Center (KSC) at Cape Canaveral, FL, in April 2019. To prevent additional radiation exposure that would occur when flying in an airplane at high altitudes, the sealed HELIOS payload has been delivered via ground transport from CTech's lab to NASA's Johnson Space Center (JSC) near Houston, TX, for incorporation into SpaceX's Dragon Capsule launch cargo module. After splashdown, expected by Fall 2019, the payload will return, again via ground transport, to CTech's labs for analysis. As a control, an exact duplicate packed and sealed case, containing equivalent WORF media, will remain at CTech's labs for comparison when the payload is returned to Earth.

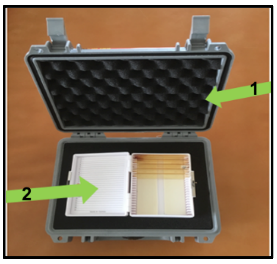

*Figure 1. Two stages of safety for the HELIOS payload: a foam-lined Pelican Model No. 1120 case (**1**) containing two Pelco Model 2306-1 standard microscope slide cases (**2**), each containing 25 WORF slides. The cases have minimal radiation resistance.*

The HELIOS WORF media payload consists of 50 conventional microscope glass slides (~1 x 25 x 75 mm); each slide rests in an individual foam slot enclosed in two microscope slide cases, which are further contained in a foam-lined Pelican case (Fig. 1), offering two stages of safety containment and protection from launch vibration and other stresses. The Pelican case is sealed, labeled not to be opened for the duration of the experiment, including in-orbit, until it is returned to CTech's labs.

The payload will be placed in the ISS "BEAM" (the Bigelow Expandable Airlock Module [35]), which has minimal protection from external space radiation; this module is attached to the ISS "Tranquility" node [36]. To more precisely quantify the amount of radiation exposure experienced in orbit as compared to the control, one radiation dosimeter is on the inside of the HELIOS Pelican case, and another dosimeter is inside the ground control case.

5. WORF archival media

WORF data media contains superimposed [37] optical wavelengths, or colors, in the form of metallic silver "standing waves" embedded in a stable, hardened silver halide (AgX) suspension, an emulsion specially formulated by CTech. No fading dyes are applied to generate the colors—the emulsion itself is monochromatic. We term these WORF data locations "worfels." WORF media is atypical in that its multiplexed wavelengths can store data as non-binary digital states (*see Appendix for details*), as well as color visual images, plus human-readable instructions for constructing reading and decoding apparatus (Fig. 2). Extant silver media similar to WORF has been proven resistant to deterioration for centuries in normal ambient environments [38, 39], is immutable after processing (*i.e.*, not hackable—important for security), and is antimicrobial [40] resisting fungus and destructive microbiota.

(A series of papers presented at previous IS&T's Archiving Conferences[41, 42, 43] describe in detail WORF's archival media and its patented process for storing high density data in normal ambient environments for the long term without continual maintenance or replication.)

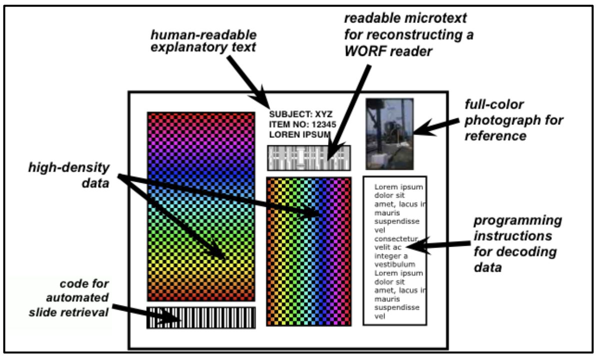

Figure 2. Example of one possible WORF slide illustrating data, human readable microtext, indexing codes, a full-spectrum color image, and instructions for building a reader and decoding the data. WORF media is agnostic: other formats — different sizes, shapes, disks, credit cards, thumbnail-sized chips, etc. — are feasible

The HELIOS WORF Media

The HELIOS slides have been coated with identical AgX WORF emulsions. Identical test patterns, consisting of selected WORF standing-wave wavelengths, are embedded in the emulsion on each end of each slide via controlled exposure and the WORF chemical process (Fig. 3). All the exposed WORF media for the HELIOS payload and ground control have been processed in CTech's chemistry lab under similar conditions to reduce the number of variables, though some exposure times were deliberately varied.

For security reasons the test patterns on the HELIOS mission contain no meaningful data, just nonrepresentational spectra and spectral combinations. Selected spectral information for each target has been recorded for all the payload and ground control slides using CTech's purpose-built, semi-automated spectrometer. Using the same spectrometer, after the payload

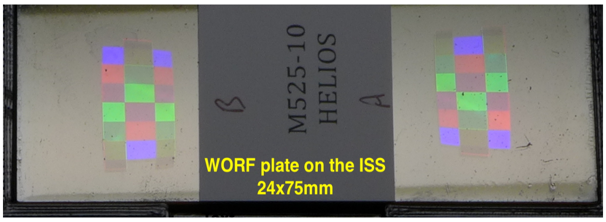

Figure 3. Embedded wavelengths on sample WORF test slide #M525-10. Red, green and blue rectangles are single wavelength, while the magenta, yellow and cyan rectangles are superimposed wavelength combinations. Note, this photograph is not an accurate representation of the colors as detected by CTech's spectrometer reader

returns to ground, the media's spectra will be compared to the control to determine if any measurable changes have taken place from the payload's exposure to the space environment, as well as any changes on the ground control slides over the mission's elapsed time. In addition to these processed media, there are several slides in each package with exposed latent target images but not yet processed; these will be processed and spectra analyzed after the payload is returned. There are also a few WORF-coated slides in the packages unexposed (and unprocessed); these are intended to be exposed with the same targets, processed and analyzed at the end of the mission.

6. Preserving our History.

Even without considering the extinction events outlined in Sect. 2, we find that our civilization's history is disappearing. Until recently, memory institutions—those involved with preserving culture—depended on the known preservation technologies from cuneiform, papyrus, paper and more recently the long-term, if not loved, technology of microfilm [44]. The last two decades have seen a transition from proven, if faulty, physical media to the more problematic digital file. Indeed, "storage is neither simple nor cheap" [45]: digital files cannot be left alone for long periods of time; digital files are energy intensive to store, and must be constantly maintained and checked for data degradation, which itself is an energy-intensive process. Many institutions, having created large archives of digital media are now experiencing trouble keeping data. As the director of the Museo Galileo in Florence, Italy, Paolo Galluzzi, recently told the *New York Times*:

> "We want to be sure that our archives will be accessible in 300 years.… At first we thought that digital would last forever, but it turns our it's much less durable than a book, which can last centuries." [46]

The Digital Preservation Network (DPN) [47] —the large-scale consortial effort to create a sustainable digital repository — recently announced that it was "sunsetting" operations after only a few years [48]. Yet, the "longevity" goal for DPN data was a mere 20 years total, hardly a long-term solution. There are few other options to save digital files. The trend has been to depend on commercial products such as large consolidated services in the "cloud". Outsourcing basic cultural infrastructure to marketplace storage solutions exposes the invaluable data to increased risks. Physical storage hosted by a corporate entity is no guarantee of safety. Amazon AWS FAQs states their retention policy is as follows:

> "Although AWS has a number of internal controls and procedures to prevent loss, damage or disclosure of your data, AWS is not responsible for damages associated with loss or inadvertent disclosure of data, or the loss, damage or destruction of your storage device. You should always retain a back-up copy of your data." [49] [emphasis added]

This is not a preferred strategy for long term safekeeping. Further extracting data from these services in the future can become both complex and expensive. Data, if retained, may be held hostage to a fee anytime in the future, or the data may only be read on a proprietary appliance which may not be available in the future [50], or 'open access' software, heretofore depended on for systems' maintenance, may be withdrawn without notice [51]. And, current proposals for free access to published scientific information is also controversial; while much research has been publicly funded, and open access would be beneficial to the scientific community, the costs to maintain quality including peer review and professional training by academic societies, plus public outreach, need to be covered somehow [52].

Considering the flaws of the current long term preservation environment, WORF seems well-suited as a more permanent solution for dark storage.

Sustainable Data for the Future.

Multiple cycles of fabrication, experimentation, and analysis have refined WORF since 2016 [53]. We recognize that a DNA Ark will have to contain potentially yottabytes of data (1 followed by 24 zeros), so high density storage is important. For this reason we have investigated using WORF's ability to write and read superimposed wavelengths for innovative data encodings beyond binary. Applying permutation matrices offers intense data density, and unlike existing data storage media, allows data to be extracted in parallel. *Details of this encoding is in the Appendix*.

Not only do we need to store the data of our knowledge base in a sustainable medium, the data has to be readable in the long-term future. The challenge is two-fold: 1) the mechanism for reading the data has to be simple enough to replicate; and, 2) the data has to be in a format that will be readily recognizable as data or information.

If the encoding is proprietary or requires obsolete devices to read, the Ark may be useless in the future. Hence while we are offering WORF as a solution for media sustainability that fits these two criteria, we are asking the readers of this paper to think about:

a) how will WORF wavelength permutations be recognizable as data, utilizing WORF's unique feature set which can display instructions for reading and decoding on the same media as data [54];

b) how should WORF data be managed and indexed for ready retrieval;

c) what mechanism should be described in detail to decipher the 10's of thousands of formats already in existence for digital data [55]; and,

d) where and how many of the Arks should be placed on Earth, in space, and possibly on other planets or moons for use by future human generations, or possibly discovered by extraterrestrials.

When is Everybody?

Why send an Ark into outer space for possible use by an alien civilization? Why not just save the relevant data on Earth for our own use? And if there are billions of exo-planets in the universe capable of sustaining life forms [56] why haven't we been contacted by aliens? Two possibilities: as *The Economist* has speculated, "One chilling idea is that technological civilisations [sic] destroy themselves before they can make their presence known" [57]; and also, "Any technologically sophisticated alien civilisation casting a radio-telescope glance our way a mere 200 years ago would have seen nothing.... [so] the probability of two technological civilisations existing contemporaneously within a few hundred light-years of each other is, in effect, zero…" Therefore, 'where is everybody?' can be better restated as '*when is everybody*?' [58, 59].

Nevertheless, by sending our several Arks into the galaxy for discovery at a future time, we enhance the chances that our civilization will at least eventually be recognized, even assuming no advanced alien species exist within the same time period as ours [60].

7. Conclusions

Besides obvious external threats to our civilization, many other threats to humankind may originate from within, such as future wrong turns in humans re-engineering humans. A digital archival "Ark" which can last millennia in outer space could act as a "Time Machine" to unwind such errors.

Yet, the way we currently store data is clearly unsustainable. It can only fail: our data system and network is energy intensive as we enter an era where energy generation itself is the problem; the current costs for keeping data forever ignores the necessity for continual re-copying; the income stream for storing data is not directly associated with storing data but in marketing directed advertising, selling personalized profiles, etc.; the incentive for storing most data in the cloud is that a small portion can be monetized in the future, but as that income chain gets broken accountants or investors will surely cut their losses by eliminating services.

WORF has been specifically designed to solve the long-term storage of data. WORF technology dramatically reduces operational costs for Tier 3 and 4 archiving [61]: read and write hardware is comprised of readily available, low-cost components; the media, being monochrome, is no more expensive than film; and, CTech's patented technology enables very high data density using multi-level, color-based permutations for unique non-binary encoding.

We propose, that as a novel and robust storage medium WORF is the only mechanism that can preserve information for a long time without power, dramatically reduced maintenance, and sustainable beyond that of contemporary data media, even on Earth after a nuclear attack, solar flares, or earthquake-induced electromagnetic pulse (EMP). In fact, WORF media—stabilized silver in a hardened emulsion—should survive merely by leaving it unattended in a drawer for eons.

So, even without postulating total species extinction or natural disaster, a properly constructed and annotated Ark could prevent an almost total loss of our heritage and data due to the inability to maintain archives within the vicissitudes of business cycles, personnel and institutional turnover.

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Appendix — WORF *M*-ary Arithmetic, Permutations & Matrices

Initially we proposed to encode WORF media beyond simple binary using *M*-ary arithmetic—where an enumeration of the set of available colors (*e.g.,* red, orange, green, blue) encode 1,2,3,4 (or as bits, 00, 01, 10, 11) at each worfel (data locattion)—a straightforward approach to data storage [62]. To dramatically increase density, consider using a selectable set of k multiplexed wavelengths (a "worflet") chosen from a larger palette (N) of *all* wavelengths which can be written and successfully disambiguated when read back with WORF reader technology.

As writing a wavelength is an idempotent—*i.e.,* unchanged or unaltered—matrix operation with WORF, the number of k-wavelength combinations (S) in the set is given by the formula:

S = N!/((N-k)!*k!) [63, 64]

where k! indicates the product of the integer k with all natural numbers less than k, a factorial (so, 4! = 4*3*2*1, or 24).

For 4 worflet wavelengths per worfel, *selected from a palette of 32 different wavelengths*, (32!/((32-4)!*4!)), and noting that 32! = (32*31*30*29*28!) gives (32*31*30*29)/24, or *35,960 distinct states* [65]. (An analogous use of the formula for drawing a hand of 5 playing cards from a 52-card deck gives 2,598,960 distinct hands. [66])

Thus, a 1 cm^2 WORF media with $10\mu^2$ (micron) data locations (8μ worfels with 2μ spacing) = 1,000,000 worfels/cm^2. Applying the *35,960-state permutation table* (*i.e.*, superimposing 4 wavelengths per worfel) and drawing from a palette (N) of *32 different wavelengths*—yields 35,960,000,000 bits (≈ 35.9 gigabits)/cm^2; or 35.9 x (6.42 cm^2 per square inch) ≈ 230.4 gigabits/in^2.

And for a 4"x5" media (20 in^2, 10cm x 12cm), 20 x 230.4 ≈ *4.6 terabits per 4x5 inch WORF media*.

But this configuration still does not demonstrate the full bandwidth possible with superimposed, multi-wavelength *worflets*, for there are multiple variables to consider in assessing practical WORF data density. For instance, a *25% increase* in the *palette* (N)—from 32 to 40 wavelengths—increases the number of combinations by ((40*39*38*37)/(32*31*30*29)), or 254%.

Data density can be further dramatically increased by combining worflet permutations into matrices, drawing from even larger wavelength palettes. For example, the square matrix in Fig. 4 is a permutation worflet set ($\overline{W}$) containing 16 worfels, wherein worflet **a** contains one unique set of up to 5 distinct, superimposed *M*-ary wavelengths (**ω**), i, j, k, l, m; and worflet **b** contains up to 5 distinct, *different*, superimposed wavelengths, n, o, p, q, r. The total amount of data computed would have no **a ω**'s duplicated in **b**, expressed in set theory:

$$\overline{\boldsymbol{W}} = \begin{pmatrix} \mathbf{a} & \mathbf{b} & \mathbf{a} & \mathbf{b} \\ \mathbf{b} & \mathbf{a} & \mathbf{b} & \mathbf{a} \\ \mathbf{a} & \mathbf{b} & \mathbf{a} & \mathbf{b} \\ \mathbf{b} & \mathbf{a} & \mathbf{b} & \mathbf{a} \end{pmatrix}$$

Figure 4. Worfels (data locations) ***a*** *and* ***b*** *have different worflet sets of superimposed wavelengths, dramatically increasing data density for the* $\overline{W}$ *permutation set.*

$\mathbf{a} = \sum \omega i, \omega j, \omega k, \omega l, \omega m$

$\mathbf{b} = \sum \omega n, \omega o, \omega p, \omega q, \omega r$

$\exists\ \omega \in \mathbf{a} \Rightarrow \omega \notin \mathbf{b}$

This is similar to the permutations stored in the Inca quipu dye-based colored string system discussed in Sect. 3 [30, 33], but with a greater ability to increase data density since WORF can chose from a larger palette of narrowband, stable wavelengths.

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