

# The Economics of Long-Term Digital Storage

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## Abstract

Paper as the medium for the world's memory has one great advantage; it survives benign neglect well. Bits, on the other hand, need continual care, and thus a continual flow of money. A Blue Ribbon panel described economic sustainability as the major issue facing long-term digital preservation. This is despite Kryder's Law, the 30-year history of the cost of digital storage media dropping exponentially. If economics are the major concern even when Kryder's Law holds, what will happen if it slows or stops? We present evidence that it will, and some simulations of the impact on digital preservation costs.

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## 1 Introduction

Paper as the medium for the world's memory has one great advantage; it survives benign neglect well. Bits, on the other hand, need continual care, and thus a continual flow of money. A Blue Ribbon panel described economic sustainability as the major issue facing long-term digital preservation [10]. This is despite Kryder's Law, the 30-year history of the cost of digital storage media dropping exponentially. If economics are the major concern even when Kryder's Law holds, what will happen if it slows or stops?

We present the growing body of evidence suggesting that Kryder's Law will not be as helpful in the future as it has been in the past. The dimming prospect for Kryder's Law is a major motivation for research under way with participants from UC Santa Cruz's Storage Systems Research Center, Stony Brook University's Filesystems and Storage Lab, the LOCKSS<sup>1</sup> Program at the Stanford Libraries and NetApp. The goal is to develop a comprehensive economic model of long-term digital storage capable of being used for scenario planning by a wide range of digital archives, and which can be used as a component of broader models of digital preservation costs. Results from prototypes of this model illuminate issues important for preservation such as the impact of the recent storage price spike, and the cost-effectiveness of cloud storage.

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## 2 Economics of Digital Preservation

There is a substantial body of work on the cost of digital preservation. Some does not, or not yet, cover storage costs:

- CMDP [23] is an effort under way, funded by the Danish Ministry of Culture, to build a cost model for each of the activities identified in the OAIS reference model [12]. Initial work focuses on the early activities, preservation planning and ingest; CMDP has yet to deal with long-term storage costs.
- The Blue Ribbon Task Force on Sustainable Digital Preservation and Access was funded by the NSF, the Andrew W. Mellon Foundation, the Library of Congress, the U.K. Joint Information Systems Committee (JISC), the National Archives and Records Administration, and the Council on Library and Information Resources. Their final report does not treat storage costs [10].

Others include storage costs:

- LIFE [36] is funded by the UK's JISC to build a life-cycle model of e-literature in a series of phases. Storage costs were first treated retrospectively in Phase 2 [7] and at a more detailed prospective level in Phase 3 [37].
- KRDS [9] is also funded by JISC. It is primarily focused on identifying the value of digital collections, but in its initial phase [8] it developed a cost model including storage costs.
- The PrestoPrime project funded by the EU developed an interactive simulation of preservation costs including storage costs [3].
- ENSURE [38] is an EU-funded project in its early stages of building a preservation cost model "Based on cost data collection" that "aims to tackle the challenges that face cost modelling for long-term digital preservation".
- Stephen Chapman [13] compared historic storage costs for analog items in the Harvard Depository with those for digital objects at OCLC.
- The California Digital Library has developed a Total Cost of Preservation model that includes storage costs [1].

Storage costs are only one element of the total cost of digital preservation. These studies confirm that a significant part of

the total, half in some studies, has to be paid up-front as content is ingested. But storage is important in each of these models as it is a large part of the continuing cost. The models these studies use to project future storage costs are based on collecting historical cost data and using it to project future costs. They implicitly assume that Kryder's Law continues in the future as it has in the past. If this assumption were not to hold it would have two significant effects:

- The proportion of overall of digital preservation costs represented by storage costs would greatly increase, since the cost of storing any individual object would no longer rapidly become insignificant.
- The projected total future cost of digital preservation would rise significantly.

If Kryder's law will not continue the current cost forecasting techniques will produce misleadingly optimistic projections, leading to increased risk of economic failure. We need a new approach to modeling the storage cost component of the overall cost of digital preservation.

Strictly, Kryder's Law is not about cost. It states that the areal density of bits on disk platters roughly doubles every two years [35]. The cost implication of this was popularized by Clayton Christensen's 1997 book *The Innovator's Dilemma* [14] but it has actually held for about three decades. Until very recently, the disk drive business was highly competitive, with no manufacturer having a dominant market share, so increases in areal density resulted in corresponding decreases in cost per bit. In practice, consumers got double the capacity at approximately the same price every two years.

### 3 Storage Technology Futures

Unfortunately, there is a growing body of evidence suggesting that future improvements in storage cost per bit will be much slower than in the past. This applies to disk, tape and the various forms of solid state storage. IDC's projections [17] for the storage industry as a whole show slowing in both the rate of decrease in cost per bit and in the rate of investment in digital storage through 2015.

#### 3.1 Disk

In 2011 disk represented 70% of all the bytes of storage shipped [29]. The disk industry's roadmap used to predict a consistent 40%/yr improvement in bit density on disk platters, which translated to a 40%/yr reduction in cost per bit stored [35]. In recent years the industry has failed to achieve this roadmap target [28]. The current roadmap predicts no more than a 20%/yr improvement in bit density for the next five years [21]. There are reasons to believe that even this may be optimistic, and also that even if it were to be achieved it might not translate directly into a 20%/yr drop in cost per bit.

- Over the last many years the disk drive industry was a commodity business marked by intense competition and low margins. Eventually, the weaker players became vulnerable and in 2012 a spate of mergers transformed the industry [11]. Western Digital and Seagate now have more than 85% of the market [21], so there is much less competition. The market is expected to support considerably

higher margins in the future. An increase in margins represents an effective reduction in the future rate of cost drop.

- The recording technology used by the most recent five generations of disk drives is Perpendicular Magnetic Recording (PMR). According to earlier versions of the industry roadmap, it should have been replaced by Heat Assisted Magnetic Recording (HAMR) by early 2010. HAMR uses a laser to heat the magnetic material on the platter to reduce the size of the area whose magnetism is changed by a write operation. The transition from PMR to HAMR has been delayed because it has turned out to be vastly more difficult and expensive than was predicted. The cost of this transition was a factor driving the consolidation of the industry.
- Unable to deploy HAMR, the industry has resorted to what can only be described as desperate measures to stretch PMR into a sixth generation using a technique called *shingled writes*. This involves writing tracks on the disk so close together that they overlap, and using sophisticated signal processing techniques to disentangle them on a read. This causes system-level problems because disks are no longer randomly writable, they become in effect append-only devices [5]. Mitigating these problems by adding capabilities to the disk hardware increases cost and reduces capacity; addressing them by changing operating systems is expensive and disruptive. Shingled write technology may not be a way for disks to stay on the Kryder's Law curve for another technology generation.
- In the past the disk industry has responded to difficulty in increasing bit density and thus in offering higher capacity in the same form factor by adding platters [28]. Since adding platters adds cost, and very few more platters can be added without disruptive and expensive changes in the drive form factor, this is less effective than increasing bit density in decreasing cost per bit.
- The favored successor technology to HAMR is Bit-Patterned Media (BPM), which uses lithographic techniques to create an extremely small location for each bit on the platter. The transition from HAMR to BPM is now expected to be even more difficult and expensive than the PMR to HAMR transition. It is therefore likely to encounter similar delays, which act to reduce the rate of cost drop.
- As magnetic particles on the platter get smaller, the temperature below which they can retain information for a given time decreases [27].

The miniaturization of magnetic recording devices, which store information in nano-sized magnetic grains or "bits," is constrained by the so-called superparamagnetic limit: when grains are too small, thermal fluctuations can easily flip the direction of magnetization in each bit, causing permanent loss of information.

For the temperatures and times involved in disk storage, this is expected to limit bit densities to well under 100Tb

per square inch [33]. At the current roadmap's 20%/yr density increase, this limit could be encountered as soon as 2030; at the 40% used by e.g. [24] it would be encountered sometime after 2022. It is to be expected that the rate of increase in bit density will slow as the limit is approached; the current slowing may be early evidence of this.

- Most disks used for storing long-term data are consumer 3.5" SATA drives, providing large capacity per drive with reasonable performance and good reliability [31, 32]. Because they were an essential component of consumer desktop PCs, they have had very large manufacturing volumes and thus very low costs. The consumer PC market has moved to laptops, which use 2.5" drives, and is moving to tablets and ultrabooks, which use flash memory<sup>2</sup>. 2.5" disks use the same recording technology as 3.5" disks, and their cost per bit has been decreasing at a similar rate, but they are typically 3-4 years later than 3.5" disks at reaching a particular \$/GB value [18] and thus, at the historic 40%/yr price drop, 3-5 times as expensive. 3.5" drives consequent loss of manufacturing volume will probably slow the cost drop for long-term data. If long-term data migrates to 2.5" drives it will suffer a significant cost increase. Because both form factors are on parallel Kryder's Law curves, 2.5" drives will never catch up with where 3.5" drives would be if they still existed. By the time this migration occurs, the consumer laptop market for 2.5" drives will probably be in eclipse, reducing their manufacturing volumes too.
- Disk industry insiders [6] regard HAMR as much more suitable for 2.5" than for 3.5" drives. If it is initially deployed only on 2.5" drives, this will drive long-term data from 3.5" to 2.5" drives more quickly, making the price increase sharper.
- The 2011 floods in Thailand destroyed about 40% of the world's disk drive manufacturing capacity. Disk drive prices doubled almost overnight, and have yet to return to pre-flood levels [25], let alone to the levels to which they would have dropped absent the floods. Part of the reason is the enormous cost to the industry of replacing the lost capacity [26], but an additional reason is that the disk manufacturing duopoly has seized the opportunity to increase their margins, which were about 6% for Western Digital and 3% for Seagate pre-flood and are now about 16% and 37%, respectively [20].

## 3.2 Tape

Tape is an important medium for long-term storage of large amounts of data. At scale, i.e. in large tape robots, its low media costs, low power consumption and relatively high reliability outweigh its long access times. The recording technology used by tape lags about 8 years behind disk, but it is on approximately the same cost per bit curve as disk.

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<sup>2</sup>A total of 415M PCs sold in 2011, of which 66M were tablets (growing at 274%/yr) and about 210M were laptops (growing at 7%) including netbooks and ultrabooks. That leaves 139M desktops (growing at 2%) and servers, which are candidates for 3.5" drives [22, 15]

However, tape's share of the total storage market is shrinking, which means it will get less of the total storage R&D investment pool than it used to. Thus we can expect tape's cost per bit to continue dropping, albeit somewhat more slowly than previously, for perhaps another 8 years. This will significantly increase tape's cost advantage over disk while it happens, although the technological issues of Section 3.1 will eventually affect tape too.

## 3.3 Solid State Memories

Flash memory is currently much more expensive per byte than hard disk but because of its other attributes, low power, small form factor, robustness, it has captured a significant part of the storage market. It may be that these attributes, which are also important for long-term storage [2], will drive flash into that market too. However, there are a large number of alternative solid state technologies on the horizon, some of which are even more promising for long-term storage than flash. Kryder and Kim [24] surveyed the prospects in 2020 for both flash and the alternative solid state technologies, comparing them with their projection for hard disk technology at that date based on a 40% annual increase in bit density. At this rate in 2020 hard disk would still have a factor of 3-10 in bit density to go before reaching the superparamagnetic limit. They conclude:

“...to compete with hard drives on a cost per terabyte basis will be challenging for any solid state technology, because the ITRS lithography roadmap limits the density that most alternative technologies can achieve.”

Adjusting their projections for a 20% annual increase in hard drive bit density reduces the 2020 target from  $10Tb/in^2$  to  $1.8Tb/in^2$ , or from a 40TB to a 7TB 2.5" drive. This would probably lead to solid state technology capturing more of the storage market, and thus more of the R&D investment, than Kryder and Kim assume, reducing still further hard disk's competitiveness. It would not, however, change their basic conclusion that competing with hard disk on a cost per bit basis would be a challenge. By 2020 all the solid state technologies they surveyed would be approaching technological limits, whereas the lower bit density growth rate implies that then hard disks would still be a factor of 15-50, or 1-2 decades from the superparamagnetic limit.

Thus, although we may expect solid state technology to become more cost-competitive with hard disk in the short term, by the end of this decade this competitiveness will probably decline.

## 4 Storage Business Models

There are three fundamentally different business models for long-term storage:

- It can be *rented*. For example, Amazon's Simple Storage Service (S3) charges \$0.125 per GB per month with discounts for large volumes [4]. This rent can be decreased or even increased over time, so from the service's point of view the model is not dependent on the Kryder's Law decrease. From the customer's point of view, this model is risky. Unexpected rent increases or even temporary fluctuations in the customer's money supply can lead to per-

manent loss of data due to inability to pay the monthly rent. Each access to data in S3 costs on the order of a month's storage; customers could be in the awkward position of being able to pay for their data to be stored but being unable to afford to access it.

- The stored content can be *monetized*. For example, Gmail offers a gradually increasing amount of e-mail storage free to users. Google makes money by selling ads when the user accesses their mail. As each message gets older, it is accessed less and less frequently, as is common in archived data. Thus Google makes less and less money from older and older mail, meaning that the Kryder's Law decrease in the cost per bit of storing old mail is important to this business model. But it is not essential. Google can adjust the rate at which it supplies storage to users, reduce their storage allocation, or even start charging users who never click on ads for their e-mail storage, to match their cost of storage and the income from advertisements over time. The customer has no leverage over the service, making it risky for them. The survival of the data is at the whim of the service; if it no longer makes money from the data it will no longer be motivated to preserve it.
- The stored content can be *endowed*, deposited in the storage service together with a sum of money thought to be sufficient to pay for its storage through its entire life. Determining an appropriate sum involves projecting both the Kryder's Law decrease in cost and future interest rate which will apply to the unexpended part of the endowment. If these projections turn out to be too low the data is at risk, since the service will not be able to afford to keep it.

None of these business models has the properties a customer would like.

## 5 Discounted Cash Flow

For the purpose of building models the endowment approach has a great advantage. It provides an apples-to-apples way to compare the flows of money through time. In effect, it uses the economists' standard technique for doing so, Discounted Cash Flow (DCF). DCF computes the *net present value* of a future expenditure by assuming a constant interest rate, the *discount rate*, and computing the amount less than the future expenditure which, with the addition of the interest accumulated by then, would amount to the future expenditure when it occurs.

Recent research has thrown serious doubt upon both the practical usefulness and theoretical basis of DCF. Its practical usefulness is suspect because it involves choosing a discount rate that will apply for the duration. In practice, people applying DCF choose unrealistically high interest rates, making investment in long-term projects much more difficult to justify than it should be [19]. Its theoretical basis is suspect because the single constant interest rate averages out the effect of periods of very high or (as now) very low interest rates. This would be correct if the outcome was linearly related to the interest rate, but it isn't [16]. This non-linear behavior implies that Monte Carlo models are required to compute the net present value of expenditures.

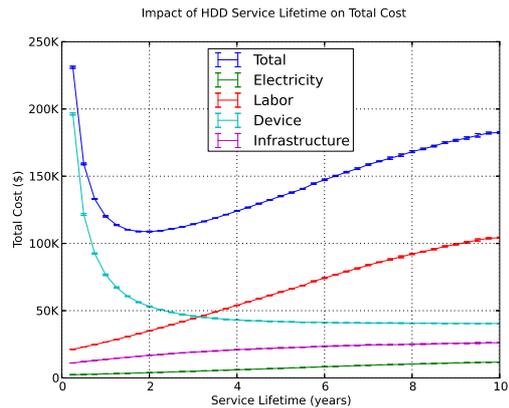


Figure 1: The effect of hard drive service lifetime on 10-year cost of ownership of an archive growing 57%/yr.

## 6 Economic Models of Storage

The difference between the net present value computed by DCF and that computed by models including variable interest rates increases through time, making DCF less and less useful for analyzing storage costs the longer the duration of storage.

The inadequacy of DCF and the prospect of no longer being able to count on the rapid decrease in cost per bit to make long-term storage costs insignificant motivated our work to develop a Monte Carlo model. The goal is to understand the impact of changes in Kryder's Law and other factors such as interest rates on the cost of storing data.

This work is at an early stage. To explore the problem space, and to communicate with potential users, we have developed some prototype models. The prototypes are producing plausible results, but they have not been validated against real-world data, so their results should not be relied upon. With experience from the prototypes and the feedback we have received from potential users we are developing an integrated, comprehensive model. In the meantime we present results from two of the prototypes.

### 6.1 Short-Term Model

Our first model follows a unit of hardware, as it might be a shelf of a filer in a data center, facing an exponentially growing demand to store data. Disks are added as needed; their capacities grow over time according to Kryder's Law. They consume power and labor, and are replaced as they fail or end their service life.

Figure 1 shows an example analysis. Parameters are set to plausible values, such as 57% annual growth in demand for data storage [17] and 5% probability of failure in service (estimated from Pinheiro *et al* [31]). The graph shows how total cost of ownership and its components vary with the service life of the disks. It demonstrates the well-known observation that disks (and tapes) are replaced when their density becomes too low to justify the space and power they use, not when their life expires. With our chosen parameters, the model predicts optimum replacement in under 3 years.

Note the counter-intuitive increase of the labor component

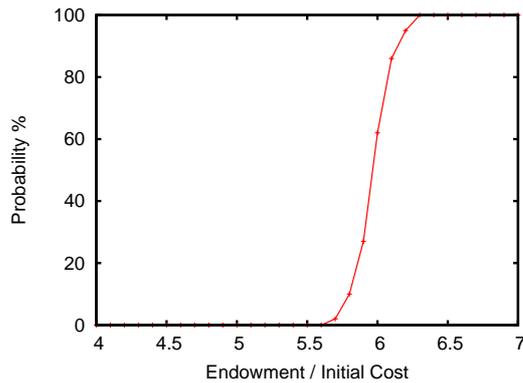


Figure 2: Survival Probability vs. Endowment as a multiple of initial cost.

with increasing service life of the disks. Each disk is assumed to consume a fixed amount of labor to install and replace. As service life increases the total number of drives in use increases; the demand for storage remains the same but the average drive becomes smaller and older.

## 6.2 Long-Term Model

The long-term prototype follows a unit of data through time as it migrates from one storage medium to another, taking up a smaller and smaller proportion of each successive medium. It computes the *endowment* needed to preserve the data using a model of interest rates based on the 20-year history of inflation-protected US Treasury bonds [34].

This model includes storage media, with purchase and running costs. They are replaced with successor media when their service life expires, or when new media become available whose costs are enough lower to justify the cost of migrating out of the old medium into the newer one. The endowment earns interest, and pays for the purchase, running and migration costs.

Different models of interest rate variation through time can greatly affect the endowment computation [16], so the absolute value of the endowment computed by the long-term prototype should be treated skeptically. Nevertheless, with similar parameters this model produces similar endowment values to those of other approaches, e.g. [1, 3]. When comparing the effect of other parameters through time, for example different storage technologies or media replacement policies, we use the same interest rate model for each, so their relative cost is unaffected.

### 6.2.1 Varying Kryder's Law Rates

Figure 2 shows a simple output of this model, plotting the probability that the data will last 100 years without running out of money (Y axis) against the endowment as a multiple of the initial storage cost for a fixed Kryder's Law rate, in this case 25%/yr. Interest rates are modeled on the past 20 years, and the service life of the media is 4 years. As one would expect, it is an S-curve. If the endowment is too small, running out of money is certain. If it is large enough, survival is certain. The insight from this graph is that the transition from 0% to 100% survival takes place over only about 10% of the critical endow-

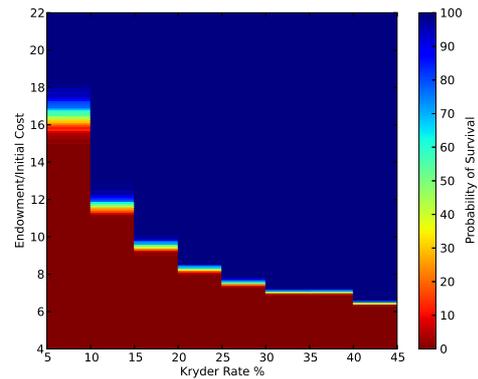


Figure 3: Survival Probability vs. Endowment vs. Kryder rate.

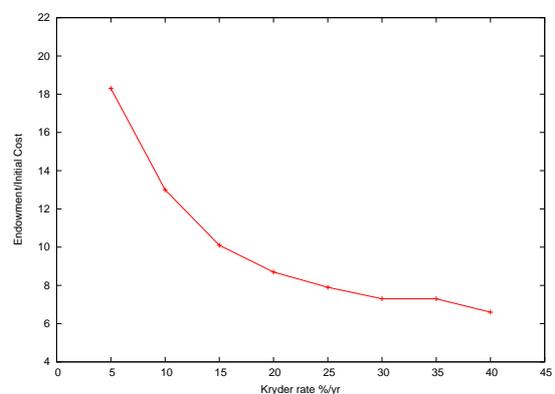


Figure 4: Endowment vs. Kryder rate.

ment value. A 25%/yr Kryder's Law rate dominates the effect of the much lower interest rates.

Repeating the simulation for a range of Kryder's Law rates gives the surface shown as a heat map in Figure 3. Note that the transition is less abrupt the lower the Kryder rate.

Taking the 98% survival probability contour of this surface gives the graph of Figure 4. One insight from this graph is that historic Kryder's Law rates have been on the flatter, right hand side of the graph, where their effect on the endowment needed is small. The values we expect in the future are on the steep, left hand side of the graph, where the endowment needed is much larger and depends sensitively on the Kryder's Law value. Thus we will be moving from an era when storage was affordable and predicting future storage costs was less important to an era when storage is expensive and predicting future costs is very important.

### 6.2.2 Price Spikes

Figure 5 shows an example analysis of the impact of a spike in disk costs such as that caused by the recent floods in Thailand. Interest rates are modeled on the past 20 years, media costs drop exponentially at various rates, and the service life of the media is 4 years. After a variable delay, media costs double for

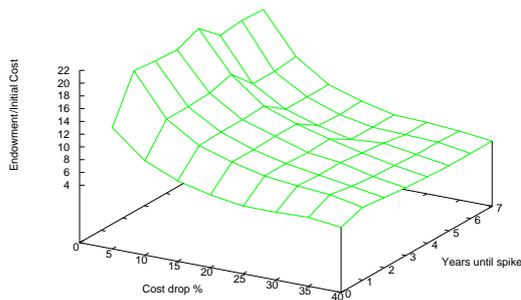


Figure 5: The impact of spikes in media cost on the endowment required for 95% survival at various rates of media cost decrease. Zero delay has no spike for comparison. Note the impact of a spike at the 4-yr media life.

a year then resume their exponential decrease. The graph shows the endowment that provides 95% probability of surviving 100 years without exhausting it, as a multiple of the initial cost. Plausibly, if storage costs drop rapidly spikes have little effect but if they drop slowly the effect is large. Also, if costs drop slowly enough that media are replaced at their service life, and the spike happens at that time, the effect is amplified.

### 6.2.3 Solid State Storage

As we see from the short-term model (Section 6.1), the raw media cost is only a part of the total cost of storage, even with a relatively short 10-year time horizon. The cost differential between flash and hard disk has been decreasing as flash gains market share. For long-term storage flash has advantages including low power consumption, small form factor, physical robustness and long device lifetime. Suitably exploited [2], these factors can outweigh the higher purchase price and deliver lower total cost of ownership over a period.

In principle, at times of low interest rates (such as now) it makes sense to invest in storage technologies with higher capital cost but lower running costs and long lifetimes. At times of high interest rates, it makes sense to invest in technologies with lower capital costs and higher running costs and short lifetimes.

Unfortunately, for an organization to justify investing in solid state storage on this basis requires that it have both a long enough *planning horizon* and an accounting policy that distinguishes between capital and operating costs. Many organizations lack both; for example most University libraries run on annual budget cycles, are not allowed to carry reserves from year to year, and cannot borrow to finance equipment purchases. Thus, even if solid state storage could offer lower total cost of ownership over say 5 years, they would be unable to invest to capture these savings. This is an example of the problem of short-termism identified by Haldane and Davies [19].

Our long-term model includes a planning horizon parameter, but we have not yet been able to conduct a detailed study of its effect on investing in solid state storage.

Service	Launch	Launch	2012	Decrease
	mo/yr	\$/GB/Mo	\$/GB/Mo	%/yr
Amazon S3	03/06	0.15	0.125	3
Rackspace	05/08	0.15	0.15	0
Azure	11/09	0.15	0.14	3
Google	10/11	0.13	0.13	0

Table 1: Price history of storage services.

### 6.2.4 Cloud Storage

Table 1 shows the history of the prices charged by several major storage services. It shows that they drop at most 3%/yr. This is in stark contrast with the 30-year history of raw disk prices, which have dropped at least 30%/yr.

This comparison is somewhat unfair to S3. Amazon has used the decrease in storage costs to implement a tiered pricing model; over time larger and larger tiers with lower prices have been introduced. The price of the largest tier, now 5PB, has dropped about 10% per year; prices of each tier once introduced have been stable or dropped slowly.

Nevertheless, it is clear that the benefits of the decrease in raw storage prices are not going to cloud storage customers. Backblaze provides unlimited backup for personal computers for a fixed price, currently \$5/mo. Before the floods in Thailand, they documented the build cost of their custom storage hardware at under \$8K for 135TB [30]. They claimed their 3-year cost of ownership of a Petabyte was under \$100K; even S3's lower-cost Reduced Redundancy Storage (RRS) would have charged \$2.3M over the same period. Adjusting for the current 60% increase in disk prices since the floods [25] would make the build cost \$11.2K. Given S3's dominance of the cloud storage market, and thus purchasing volumes, it is very unlikely that their costs are much higher than Backblaze's. Despite this, 135TB in S3-RRS costs more than \$10K/mo. In the first month, an S3-RRS customer would pay almost as much as it would currently cost to buy the necessary hardware.

Why is cloud storage so expensive? Actually, in many cases, it isn't. Many customers have data whose life is much less than the life of the hardware, so they cannot amortize a hardware purchase over its life. Many customers, for example startup companies, have a very high cost of capital. Amazon and its competitors price against the value they deliver to these customers; not against their costs.

But Amazon and its competitors should be riding the Kryder's Law curve like everyone else. Why aren't they reducing their prices? Because they don't have to. Suppose you have 135TB in S3-RRS and you decide you are paying too much. You need to move your data somewhere cheaper. You are going to take a month to do it. It will cost you \$10,750, more than a month's storage, in bandwidth charges to get your data out [4], let alone the staff and other costs of doing the transfer, and checking that it worked. A competitor is going to have to be a great deal cheaper than S3 to motivate you to pay these transition costs. Since S3 has the vast majority of the market, their costs are probably lower than any competitor's. If a competitor cut prices enough to take significant market share from S3, Amazon would undercut them.

## 7 Conclusions

From the foregoing, we can draw the following conclusions:

- Optimistically, for the rest of this decade the rapid decrease in cost per bit of storage that has been a constant of the last three decades will be much slower; it might even stop.
- This will make the expenditure commitment implied by a decision to preserve some digital content (a) much bigger and (b) much harder to predict than would be expected on the basis of history.
- In a period of economic stringency, this increases the importance of developing accurate, predictive models of storage and other preservation costs.
- For much of this decade tape is likely to maintain or improve its existing cost advantage over disk.
- If organizations can change their accounting methods to properly recognize the long-term cost of ownership of preserved data, current low interest rates provide an opportunity to invest in solid state technologies which, despite their higher capital cost, are for this decade likely to provide lower total cost than disk, while retaining its rapid access.
- The pricing models of current commercial cloud storage services are not suitable for long-term storage.

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## Litteratur

- [1] Stephen Abrams, Patricia Cruse, John Kunze, and Michael Mundrane. Total Cost of Preservation (TCP): Cost Modeling for Sustainable Services. <https://wiki.ucop.edu/download/attachments/163610649/TCP-total-cost-of-preservation.pdf>, April 2012.
- [2] Ian Adams, Ethan L. Miller, and David S. H. Rosenthal. Using Storage Class Memory for Archives with DAWN, a Durable Array of Wimpy Nodes. Technical Report UCSC-SSRC-11-07, University of California, Santa Cruz, October 2011.
- [3] Matthew Addis and Mariusz Jacyno. Tools for modelling and simulating migration-based preservation. [https://prestoprimews.ina.fr/public/deliverables/PP\\_WP2\\_D2.1.2\\_PreservationModellingTools\\_R0\\_v1.00.pdf](https://prestoprimews.ina.fr/public/deliverables/PP_WP2_D2.1.2_PreservationModellingTools_R0_v1.00.pdf), December 2010.
- [4] Amazon. Simple Storage Service. <http://aws.amazon.com/s3/#pricing>, 2012.
- [5] Ahmed Amer, JoAnne Holliday, Darrell D. E. Long, Ethan L. Miller, Jehan-François Pâris, and Thomas Schwarz. Data management and layout for shingled magnetic recording. *IEEE Transactions on Magnetics*, 47(10), October 2011.
- [6] Dave Anderson. Hard Drive Directions. [http://www.digitalpreservation.gov/news/events/other\\_meetings/storage09/docs/2-4\\_Anderson-seagate-v3\\_HDtrends.pdf](http://www.digitalpreservation.gov/news/events/other_meetings/storage09/docs/2-4_Anderson-seagate-v3_HDtrends.pdf), September 2009.
- [7] P. Ayris, R. Davies, R. McLeod, R. Miao, H. Shenton, and P. Wheatley. The LIFE2 Final Project Report. <http://eprints.ucl.ac.uk/11758/>, 2008.
- [8] Neil Beagrie. Keeping Research Data Safe (Phase 1). <http://www.jisc.ac.uk/publications/reports/2008/keepingresearchdatasafe.aspx>, May 2008.
- [9] Neil Beagrie. KRDS/I2S2 Digital Preservation Benefit Analysis Tools Project. <http://beagrie.com/krds-i2s2.php>, 2012.
- [10] Blue Ribbon Task Force on Sustainable Digital Preservation and Access. Sustainable Economics for a Digital Planet. [http://brtf.sdsc.edu/biblio/BRTF\\_Final\\_Report.pdf](http://brtf.sdsc.edu/biblio/BRTF_Final_Report.pdf), April 2010.
- [11] Russell Brandom. How Three Hard Drive Companies Gobbled Up The Industry. <http://www.buzzfeed.com/tommywilhelm/how-three-hard-drive-companies-gobbled-up-the-indu>, June 2012.
- [12] CCDS. Reference model for an open archival information system. <http://public.ccsds.org/publications/archive/650x0b1.pdf>, 2003.
- [13] Stephen Chapman. Counting the costs of digital preservation: Is repository storage affordable? *J. Digital Information*, 4(2), 2006.
- [14] Clayton M. Christensen. *The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail*. Harvard Business School Press, June 1997.
- [15] delboy. 66 Million Tablets Sold In 2011 Worldwide Led By iPad. <http://www.worldtvpc.com/blog/67-million-tablets-sold-2011-world/>, 2012.
- [16] J. Dooyne Farmer and John Geanakoplos. Hyperbolic Discounting is Rational: Valuing the Far Future With Uncertain Discount Rates. Technical Report 1719, Cowles Foundation, Yale University, Aug 2009.
- [17] John F. Gantz, Alex Manfrediz, Stephen Minton, David Reinsel, Wolfgang Schlichting, and Anna Toncheva. The diverse and exploding digital universe. <http://www.emc.com/collateral/about/news/idc-emc-digital-universe-2011-infographic.pdf>, March 2011.

- [18] Edward Grochowski and Jr. Robert E. Fontana. An Analysis of Flash and HDD Technology Trends. [http://www.flashmemorysummit.com/English/Collaterals/Proceedings/2011/20110809\\_F2C\\_GrochowskiFontana.pdf](http://www.flashmemorysummit.com/English/Collaterals/Proceedings/2011/20110809_F2C_GrochowskiFontana.pdf), August 2011.
- [19] Andrew G Haldane and Richard Davies. The Short Long. In *29th Societe Universitaire Europeene de Recherches Financieres Colloquium: New Paradigms in Money and Finance?*, May 2011.
- [20] Joel Hruska. HDD Pricewatch: Higher prices are the new normal. <http://www.extremetech.com/computing/129874-hdd-pricewatch-higher-prices-are-the-new-normal>, May 2012.
- [21] IHS iSuppli. HDD Areal Density Doubling in Five Years. <http://www.storagenewsletter.com/news/marketreport/ihs-isuppli-storage-space>, May 2012.
- [22] Joe McKendrick. Milestone: more smartphones than PCs sold in 2011. <http://www.smartplanet.com/blog/business-brains/milestone-more-smartphones-than-pcs-sold-in-2011/21828>, February 2012.
- [23] Ulla Bøgvad Kejser, Anders Bo Nielsen, and Alex Thirifays. Cost Model for Digital Preservation: Cost of Digital Migration. *Intl. J. Digital Curation*, 6(1), 2011.
- [24] Mark H. Kryder and Chang Soo Kim. After Hard Drives - What Comes Next? *IEEE Trans. on Magnetics*, 45(10), October 2009.
- [25] Paul Kunert. Hard disk drive prices quick to rise, slow to fall. *The Register*, May 2012.
- [26] Paul Kunert. WD: HDD prices won't fall to pre-flood levels until 2013. *The Register*, July 2012.
- [27] Ashot Melikyan. Synopsis: Pushing the superparamagnetic limit. <http://physics.aps.org/synopsis-for/10.1103/PhysRevB.78.214424>, 2008.
- [28] Chris Mellor. Drive suppliers hit capacity increase difficulties. *The Register*, July 2010.
- [29] Chris Mellor. WD bigshots spin superfast disk roadmap. *The Register*, May 2012.
- [30] Tim Nufire. Petabytes on a Budget v2.0: Revealing More Secrets. <http://blog.backblaze.com/2011/07/20/petabytes-on-a-budget-v2-0revealing-more-secrets/>, July 2011.
- [31] Eduardo Pinheiro, Wolf-Dietrich Weber, and Luiz Andre Barroso. Failure Trends in a Large Disk Drive Population. In *Proceedings of 5th USENIX Conf. on File and Storage Technologies*, San Jose, CA, February 2007.
- [32] Bianca Schroeder and Garth Gibson. Disk failures in the real world: What Does an MTTF of 1,000,000 Hours Mean to You? In *Proceedings of 5th USENIX Conf. on File and Storage Technologies*, San Jose, CA, February 2007.
- [33] Y. Shiroishi, K. Fukuda, I. Tagawa, H. Iwasaki, S. Takenoiri, H. Tanaka, H. Mutoh, and N. Yoshikawa. Future options for hdd storage. *IEEE Transactions on Magnetics*, 45(10), October 2009.
- [34] US Dept. of Treasury. Daily Treasury Yield Curve Rates. <http://www.treasury.gov/resource-center/data-chart-center/interest-rates/Pages/default.aspx>, 2012.
- [35] Chip Walter. Kryder's Law. *Scientific American*, 293, August 2005.
- [36] Paul Wheatley, Paul Ayris, Richard Davies, Rory McLeod, and Helen Shenton. LIFE: costing the digital preservation lifecycle. In *iPRES2007*, September 2007.
- [37] Paul Wheatley and Brian Hole. LIFE3: Predicting Long Term Digital Preservation Costs. In *iPRES2009*, September 2009.
- [38] Pengfei Xue, Essam Shehab, Paul Baguley, and Mohamed Badawy. Cost modelling for long-term digital preservation: Challenges and issues. In *Proc. 9th Intl. Conf. on Manufacturing Research ICMR2011*, pages 187–192, September 2011.