R. Fontana, G. Decad – IBM Systems
May 15, 2018

A Ten Year (2008-2017) Storage Landscape
LTO Tape Media, HDD, NAND

A Ten Year (2008-2017) Storage Landscape: LTO Tape Media, HDD, NAND

- Topics
  - Data Methodology: LTO Tape Cartridges, Hard Disk Drives, and NAND chips
  - 1 Year and 10 Year Observations
  - EB
  - Revenue
  - $/GB
  - Areal Density
  - Millions of Square Inches
  - The Future

- Some Goals
  - Provide a perspective on relative PB production for each technology
  - Trends for $/GB reductions
  - Bounds on PB production increases (manufacturing capacity)
  - Impact of Areal Density increases on reduced $/GB and increased PB production
  - Gain a perspective of “large numbers” associated with storage technologies

Storage Landscape Strategy

- The storage component landscape is monitored by tracking publically available annual market and technology trends in LTO TAPE MEDIA, HDD, and NAND
  - Areal density and Revenue
  - $/GB and Exabyte shipments

- Monitoring strategy emphasizes memory bit shipments
  - Tape: LTO Media shipments with associated cartridge capacities only since Enterprise Media shipments are not available publically. Similarly no drive shipments are included since these data are not publically available
  - HDD: Drive shipments only with associated capacities. Ideal metric would be disk surfaces shipped but these data are not available
  - NAND: Bit shipments at the factory level (not SSD shipments)

- 10 Year Observations
  - Smaller $/GB changes for all technologies
  - Sustained areal density growth in TAPE and NAND ***but*** 3X lower areal density growth in HDD
  - NAND revenue now dominates the storage landscape
  - HDD bit shipments continue to dominate the storage landscape

- A comment: LTO Tape data has no consumer based contribution in contrast with HDD and NAND landscape data

Data Sources and Methodology

- HDD Data:
  - WDC and Seagate: Quarterly Financial Reports (WDC is now reporting NAND EB with HDD EB)
  - Toshiba: Scale data from WDC/Seagate using TAM (total available market) percentages reported by Seagate/WDC
  - $/GB is a “blended” value for all drive types from Total Revenue / Total EB Shipped

- NAND Data:
  - EB Shipments: Samsung presentations
  - Revenue: Quarterly summaries from DRAM EXCHANGE
  - $/GB is a “blended” value for all chip capacities, bit/cell designs (SLC, MLC, TLC), planar and 3D processing using Total Revenue / Total EB Shipped

- LTO Media Data
  - 2008-2014: LTO cartridge sales from Santa Clara Consulting Group (SCCG)
  - **2015-2017: LTO Consortium data on units and PB shipments. Revenue determined by year end public cartridge costs (an overestimate) with resulting data discontinuity between 2014 and 2015 since SCCG no longer reports tape data**
  - $/GB is a “blended” value for all capacities from Total Revenue / Total EB Shipped

10 Year Storage Landscape

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
HDD										
Units (HDD millions)	540	557	652	620	577	551	564	470	425	406
PB Shipped (PB)	125000	200000	330000	335000	380000	470000	549000	565000	693000	780000
Areal Density (Gb/in^2)	380	530	635	750	750	900	900	1000	1100	1200
Revenue ($B)	34.0	34.0	33.0	33.5	37.5	33.4	33.4	28.3	26.8	26.1
$/GB Shipped	0.272	0.170	0.100	0.100	0.100	0.071	0.061	0.051	0.039	0.033
NAND										
Wafers (12“-millions)	7.3	8.3	9.7	11.3	12.1	13.7	14.8	15.9	17.0	18.1
PB Shipped (PB)	3000	5430	10464	18600	28000	39000	62500	83000	120000	175000
Areal Density (Gb/in^2)	200	280	330	550	550	850	1200	1500	2000	2500
Revenue ($B)	10.1	12.1	18.5	21.5	22.0	24.0	32.2	33.2	38.7	56.5
$/GB Shipped	3.33	2.23	1.77	1.16	0.78	0.615	0.515	0.401	0.320	0.320
LTO TAPE MEDIA										
Units (Cart millions)	27.1	24.3	25.0	24.3	23.4	21.6	22.2	19.4	19.4	18.0
PB Shipped (PB)	11050	11960	15340	18420	20680	24270	30100	33020	40320	44850
Areal Density (Gb/in^2)	0.9	0.9	1.2	1.2	2.1	2.1	2.1	4.1	4.1	8.0
Revenue ($B) [SCCG]	1.0	0.7	0.7	0.7	0.62	0.54	0.50			
Revenue ($B) [LTO.org]								0.59	0.65	0.66
$/GB Shipped	0.0905	0.0585	0.0456	0.0380	0.0300	0.0222	0.0166	0.0177	0.0162	0.0147

R. Fontana, G. Decad
AIP Advances
Volume 8, Issue 5,
056506 (2018)

An Example of Storage Landscape Data -- Landscape Changes: 2017 vs 2016

- 2017 Observations
  - NAND: Significant EB growth, significant revenue growth, and **NO** $/GB reduction
  - HDD: Good EB growth, continued but small revenue decrease, significant $/GB reduction
  - LTO TAPE MEDIA: Moderate EB growth, stable LTO MEDIA revenue, minimal $/GB reduction
  - Total manufactured EB increased by 17%, less than the 25% increase in 2016

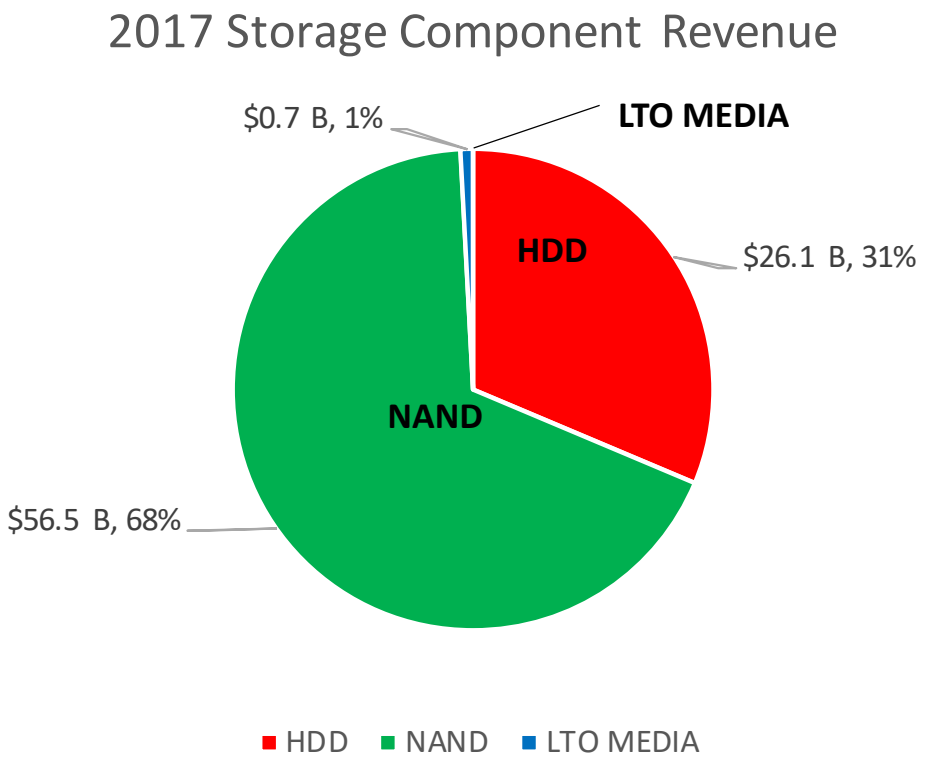
2017 LANDSCAPE	EB	REVENUE	$/GB
LTO TAPE MEDIA	45	$0.7 B	$0.0147/GB
HDD	780	$26.1 B	$0.0332/GB
NAND	175	$56.5 B	$0.3202/GB
TOTAL	1000	$83.3 B	NA

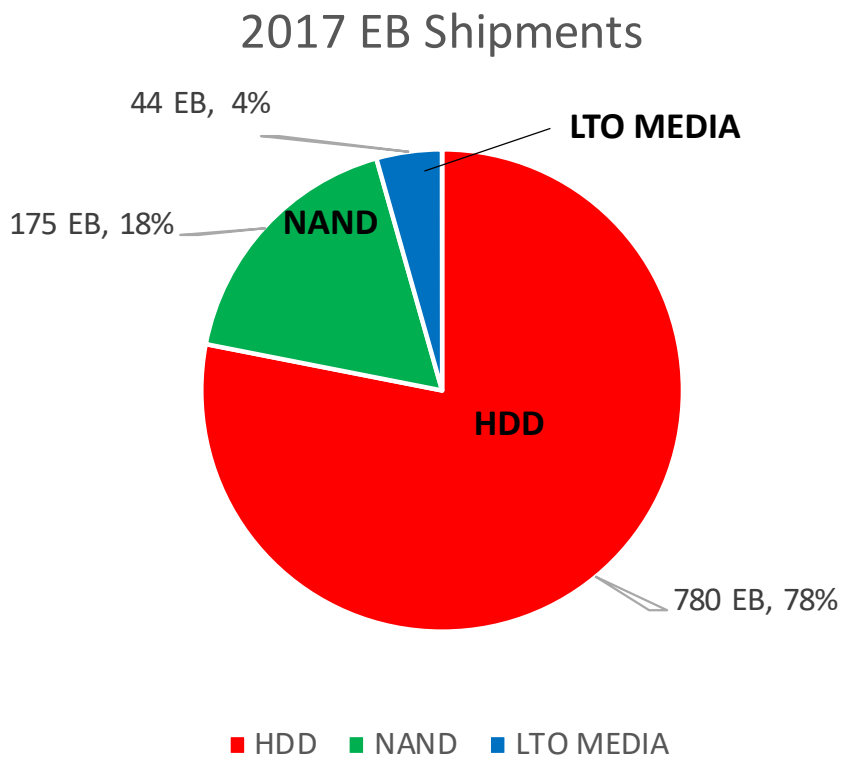
2016-2017 % CHANGE	EB	REVENUE	$/GB
LTO TAPE MEDIA	11%	1%	-9%
HDD	13%	-3%	-15%
NAND	45%	45%	0%
TOTAL	17%	26%	NA

2015-2016 % CHANGE	EB	REVENUE	$/GB
LTO TAPE MEDIA	22%	11%	-10%
HDD	23%	-5%	-23%
NAND	45%	17%	-20%
TOTAL	25%	6.5%	NA

Major Observations (2017)

- NAND vs HDD
  - NAND revenue exceeds HDD revenue by 2.2X ($56.5 B vs. $26.1 B)
  - HDD EB shipments exceeds NAND EB shipments by 4.5X (780 EB vs 175 EB

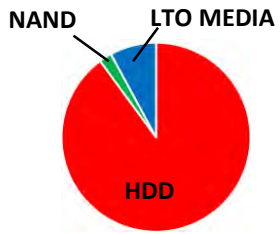




An Example of Storage Landscape Data – EB Landscape Changes: 2008 to 2017

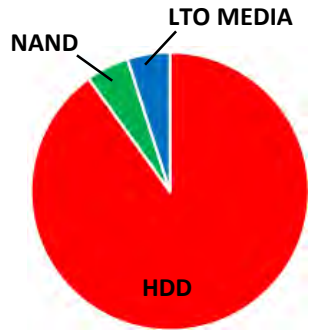
- HDD percentage of total manufactured storage drops from 90% to 78%
- NAND percentage of total manufactured storage increases from 2% to 18% (consumer market)
- LTO MEDIA percentage of total manufactured storage stable for last 8 years at 4.5%
- NAND manufactured storage exceeds LTO Media manufactured storage after 2011

2008



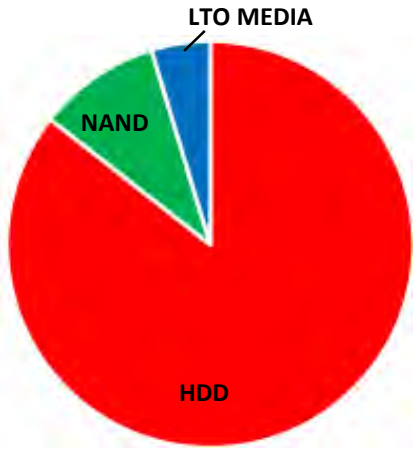
HDD	125 EB
NAND	3 EB
LTO MEDIA	11 EB

2011



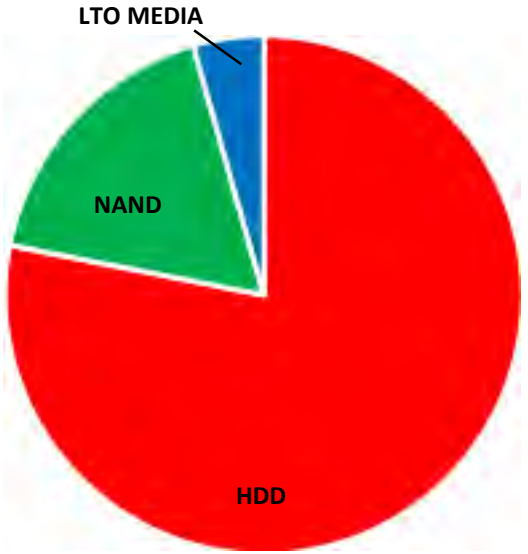
HDD	335 EB
NAND	18 EB
LTO MEDIA	18 EB

2014



HDD	549 EB
NAND	63 EB
LTO MEDIA	30 EB

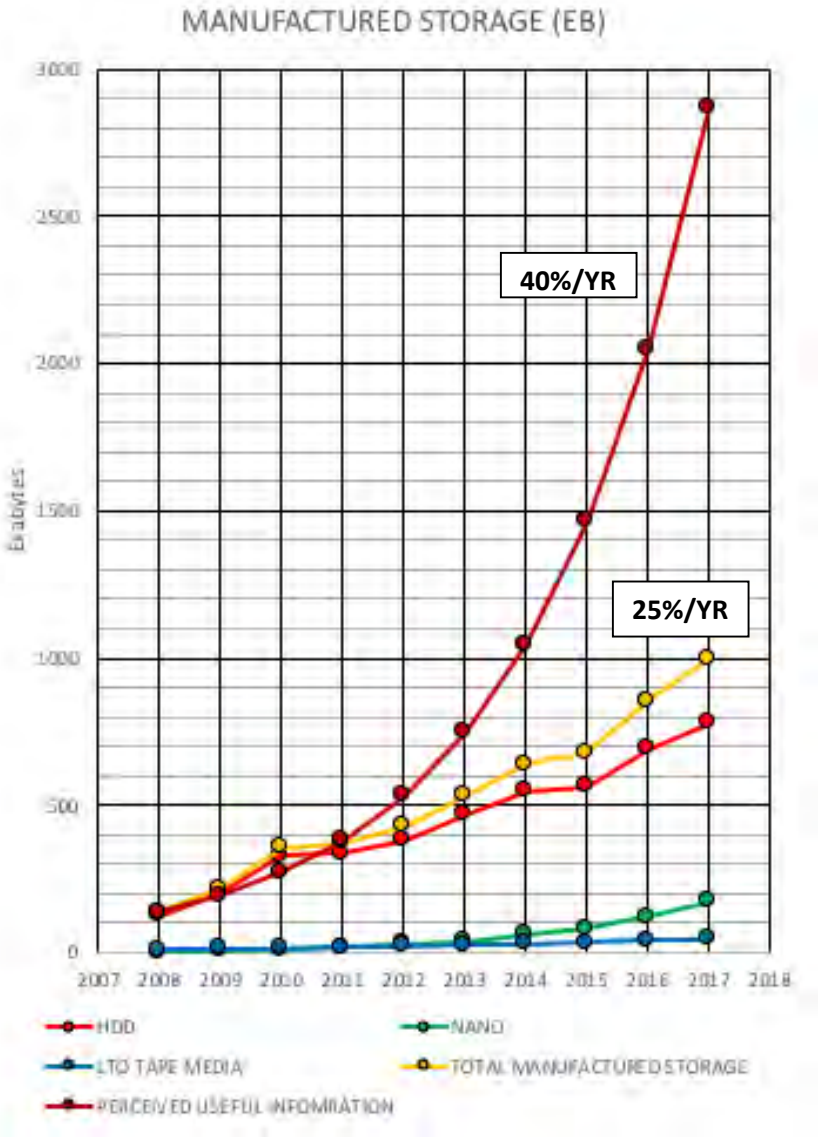
2017



HDD	780 EB
NAND	175 EB
LTO MEDIA	45 EB

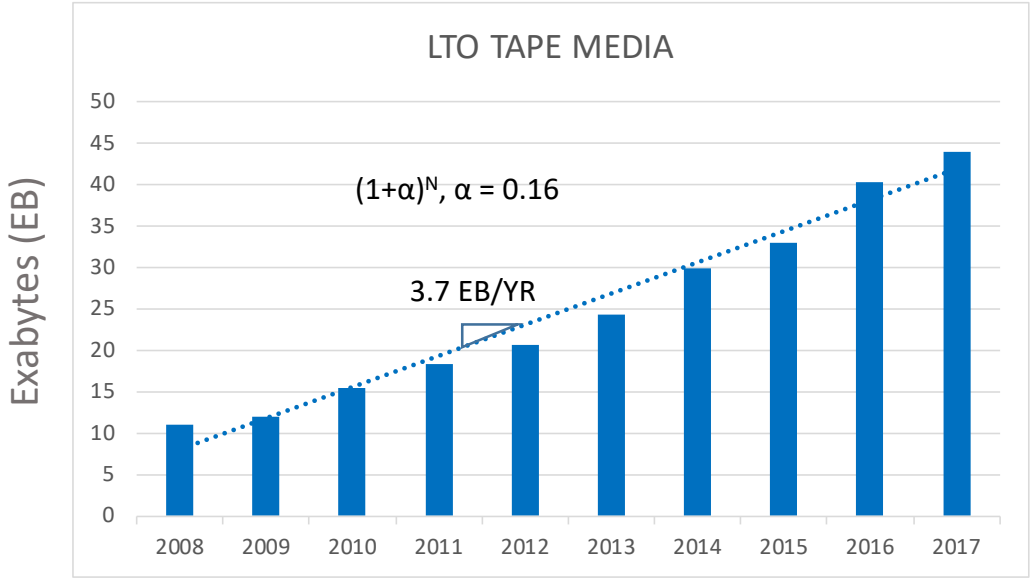
Annual Manufactured Storage and Perceived Useful Data Creation

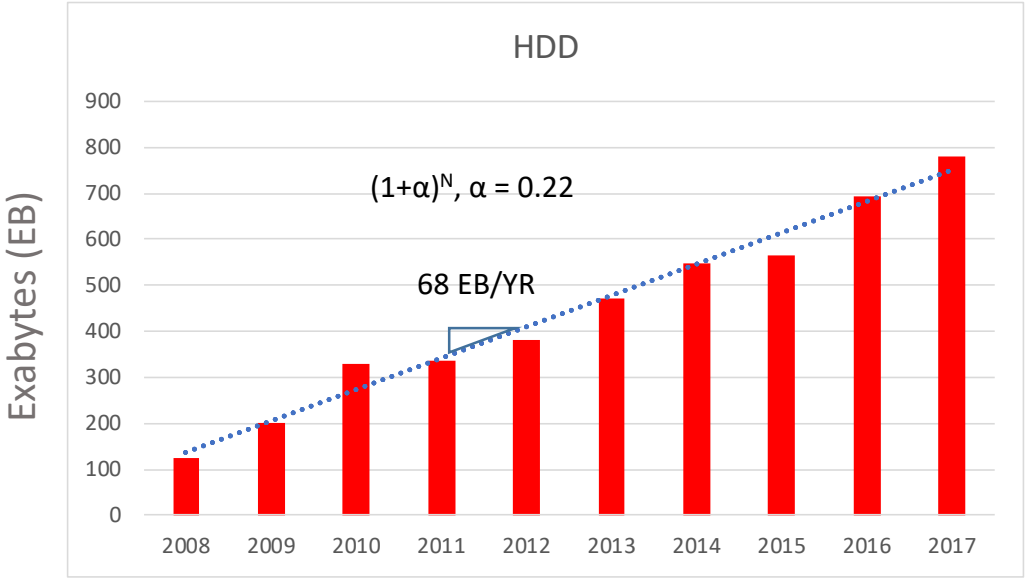
- In 2008, industry consulting firms projected that “useful” data would grow by 40% annually.
- Our 10 year data shows that manufactured storage (i.e. EB of LTO TAPE, HDD, NAND) are not keeping pace with this projection.
- Total manufactured EB grew at ~25%/yr rather than 40%/yr ***(growth is almost linear)***
- In 2017 the shortfall between “perceived” useful data and manufactured data is 2000 EB or 2 ZB!
- Useful data and manufactured storage only tracked in the 2008-2010 range when HDD benefited from advances in novel tunnel valve read sensors and exchange biased media.
- NET: Storage cost and manufacturing capacity will force decisions on which “useful” data will be retained.

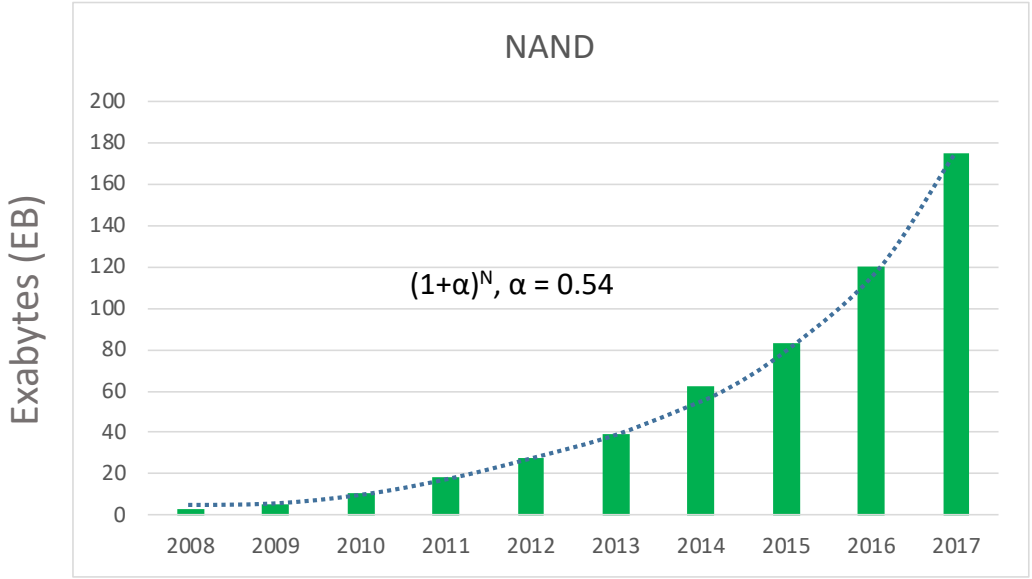


Geometric or Linear EB Growth for Memory Components

- Linear EB growth for HDD and TAPE (i.e. magnetics)
  - Only one or two competitors
  - Planar (2D) scaling becomes more difficult
  - Consumer market: erosion for HDD and not applicable for TAPE
- Geometric EB growth for NAND
  - Multiple competitors (4-5)
  - 3D scaling and bit/cell scaling
  - Consumer market (e.g. iphone)
- Growth: $(1+\alpha)^N \sim (1+ N\alpha)$ for small α

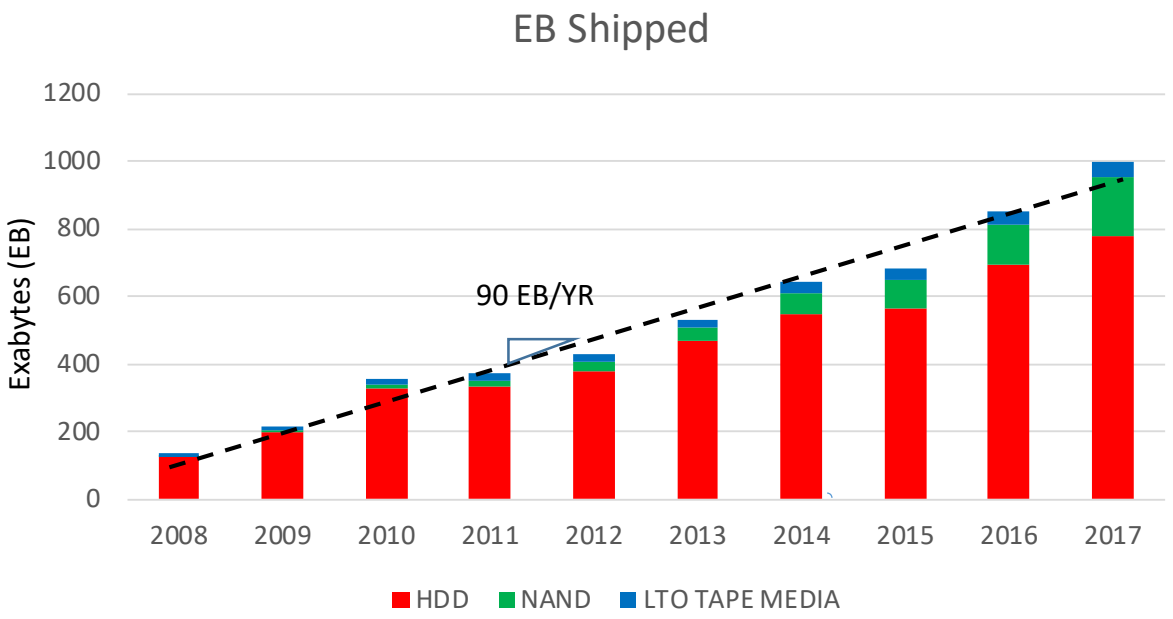


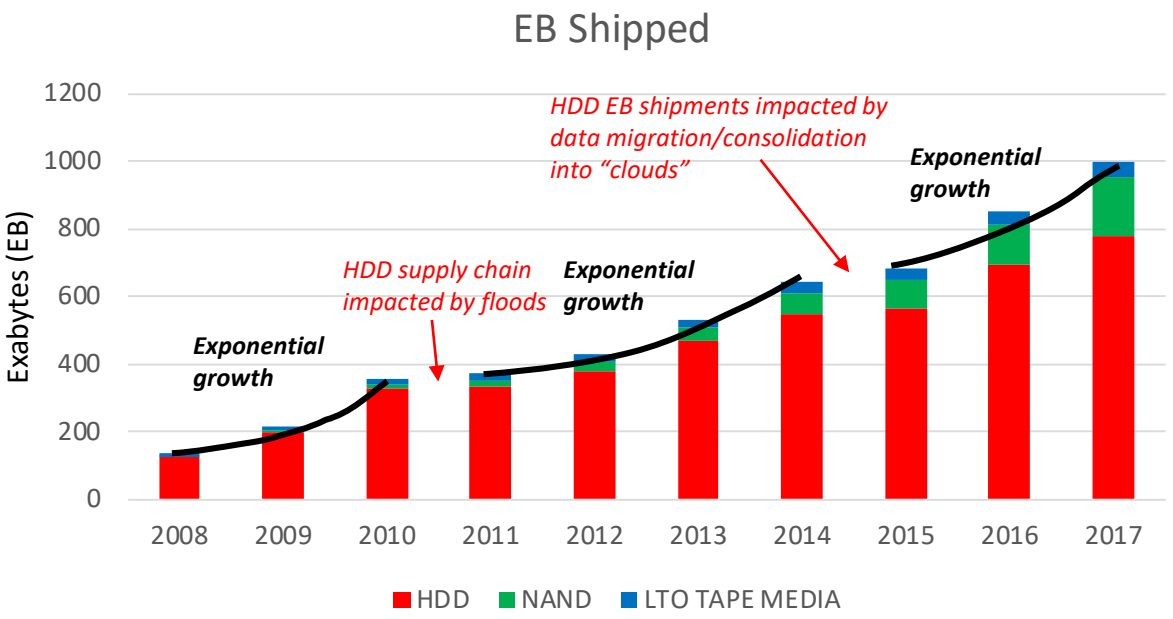




Total EB Shipped – Linear or Exponential Growth

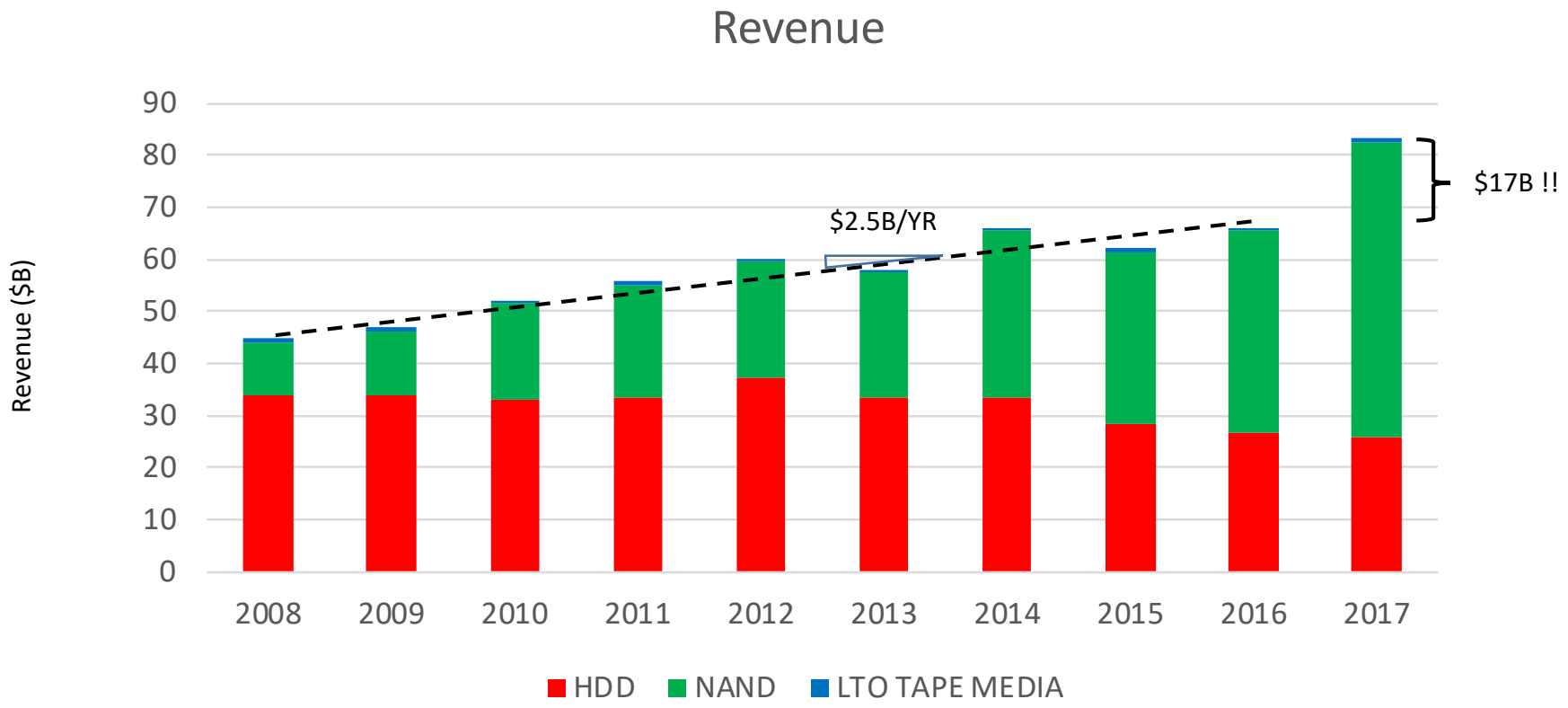
- ***Total EB growth increased at ~ 90 EB per year since 2008***
  - Deviation from linear Total EB growth are caused by fluctuations in HDD production: 2010-2011 and 2014-2015
  - 2008-2010 ➔ 60%/yr growth
  - 2011-2014 ➔ 19%/yr growth
  - 2015-2017 ➔ 22%/yr growth





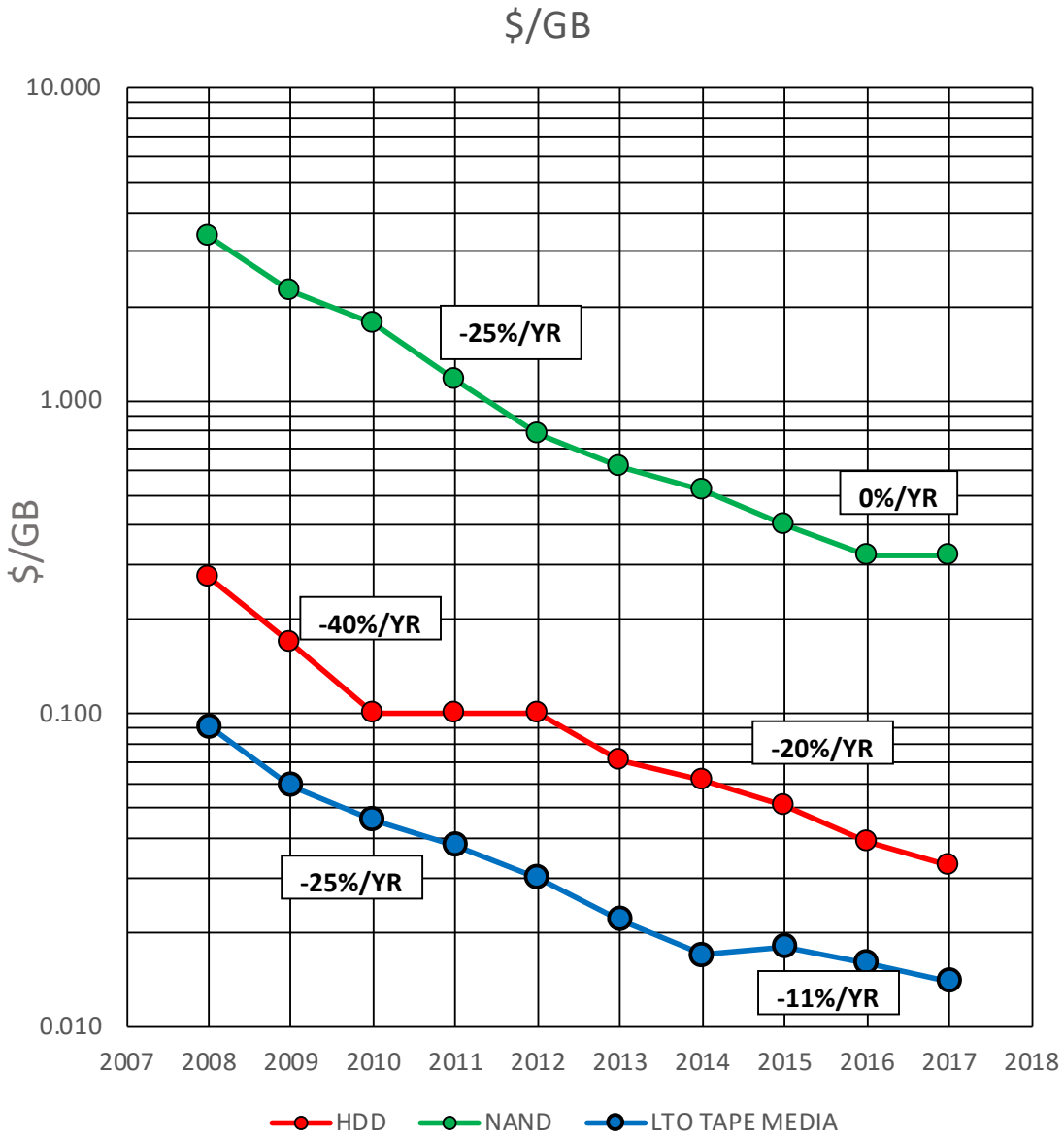
Total Revenue– Linear or Exponential Growth

- ***With the exception of 2017 (NAND supply/demand imbalance), storage revenue increased at ~ $2.5 B / YR***
  - Storage revenue growth now comes from NAND
  - 2008—2016 ~ 5%/yr
  - 2008—2017 ~ 7%/yr
  - 2016—2017 ~ 26%!!!!



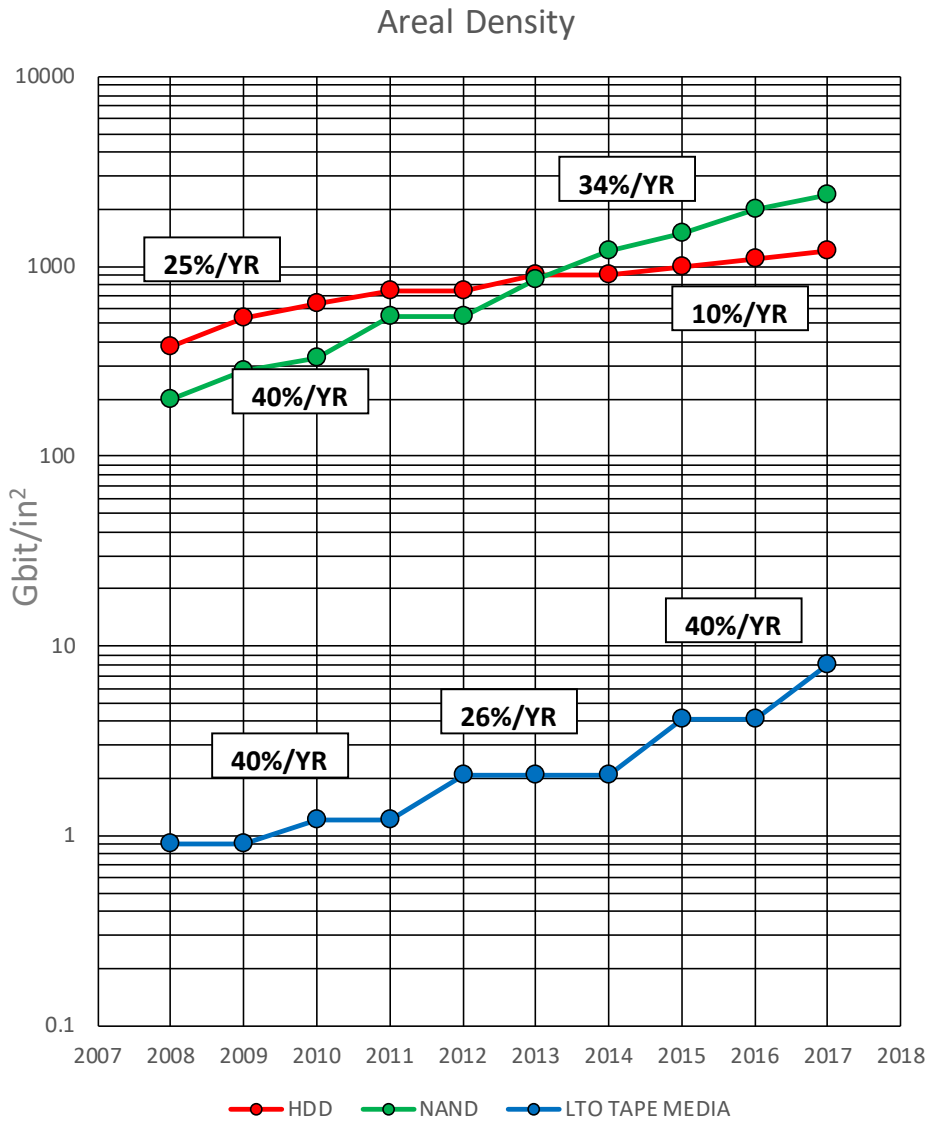
$/GB – A Geometric Environment

- $/GB show geometric trends: $C_N = C_0 \times (1 - \alpha)^N$
- NAND: First time in 10 years that $/GB deviated from 25%/YR decrease but now at "**0%/YR**" (supply-demand imbalance)
- HDD: $/GB sustains 20%/YR decrease for 5 consecutive years but 2011-2012 supply line issues ended the earlier 40%/YR decreases and annual revenue continues to decrease
- TAPE: $/GB decreases for last 3 years of 10%/YR are less than historical values of 25%/YR. Possible source supply issue for BaFe media.
- Moore's Law Comment:
  - Doubling density every two years with **no** added manufacturing cost results in halving $/bit every two years: $\alpha = 0.29$ (29%/yr decrease)
  - Storage technologies are deviating away from this "ideal" $/GB metric of -29%/YR



Areal Density – A Geometric Environment (Ideally)

- Areal Density (AD) show geometric trends: $AD_N = AD_0 \times (1 + \alpha)^N$
- NAND: AD approaches ideal Moore's Law characteristics, α = 0.41 or 41% annual areal density increase
  - Planar scaling of minimum feature by 20% annually from 2007-2010 gave 40%/YR increases in AD.
  - 3D cell design, 2 bit per cell, and 3 bit per cell sustains AD growth, somewhat lower at 34%/YR
- HDD: AD increases decrease to 10%/YR after 2012
  - Consolidation: 4 suppliers going to 2 suppliers
  - Physics: Super-paramagentic limit requires new media and new write strategy (HAMR) to maintain bit stability for small cell sizes
  - Product solution: More platters per HDD
- TAPE: LTO introduces new products on 24 month to 30 month cycles
  - AD increases sustained over a 10 year period at ~ 31%/YR (average) but in step-wise increments
  - AD growth likely sustained since bit cell size and lithographic transducer requirements preclude both physics issues (super-paramagnetic limit) and manufacturing issues



Storage Manufacturing Capability and MSI (Wafers, Cartridges, Drives)

- Storage manufactures have constraints on the maximum PB of storage that can be manufactured annually

- Storage manufactures increase PB production with a combination of two strategies
  - Capital Intensive: Increase factory space or the capability to manufacture more “square inches” of storage media, i.e. more tape, more disk surfaces, more silicon wafers, but at the same bit density.
  - Development Intensive: Increase the density of bits per square inch and build more memory bits on existing manufacturing capability

- Semiconductor manufacturers have used the MSI (millions of square inches of processed silicon wafer surfaces) term to track manufacturing capacity

- The MSI term can be applied to storage bit manufacturing
  - NAND: the number of 12” wafers fabricated annually ***(publically available)***
  - LTO MEDIA: the number of cartridges supplied annually assuming 0.5” wide tape and 1000m length ***(publically available)***
  - HDD: the number of 2.5” and 3.5” disk diameter surfaces produced annually ***(not publically available)***

- The key to increasing future EB shipments with lower $/GB is areal density growth. Without density growth, capital expenditures for factory space is required

Millions of Square Inches (MSI) – A Measure of Manufacturing Capability

- The 2017 MSI numbers

Technology	MSI Unit	PB Shipped	MSI	
LTO TAPE MEDIA	18 M Cartridges	44000	354,330	← 88.1 miles^2 (9.4 mile x 9.4 mile)
HDD	404 M HDDs [1]	780000	9,434	← 2.4 miles^2 (1.5 mile x 1.5 mile)
NAND	18 M 12” wafers	175000	2,035	← 0.5 miles^2 (0.7 mile x 0.7 mile)

1. HDD disk surface numbers are not available. HDD units shipped and average capacity per unit are publically available so estimate disk surfaces assuming all HDDs shipped at 3.5” diameter disks at the TB per surface for a high capacity, 8 platter, 12TB product, ~ 0.75 TB/surface ➔ 404 M HDDs implies 1.04 B 3.5” disk surfaces

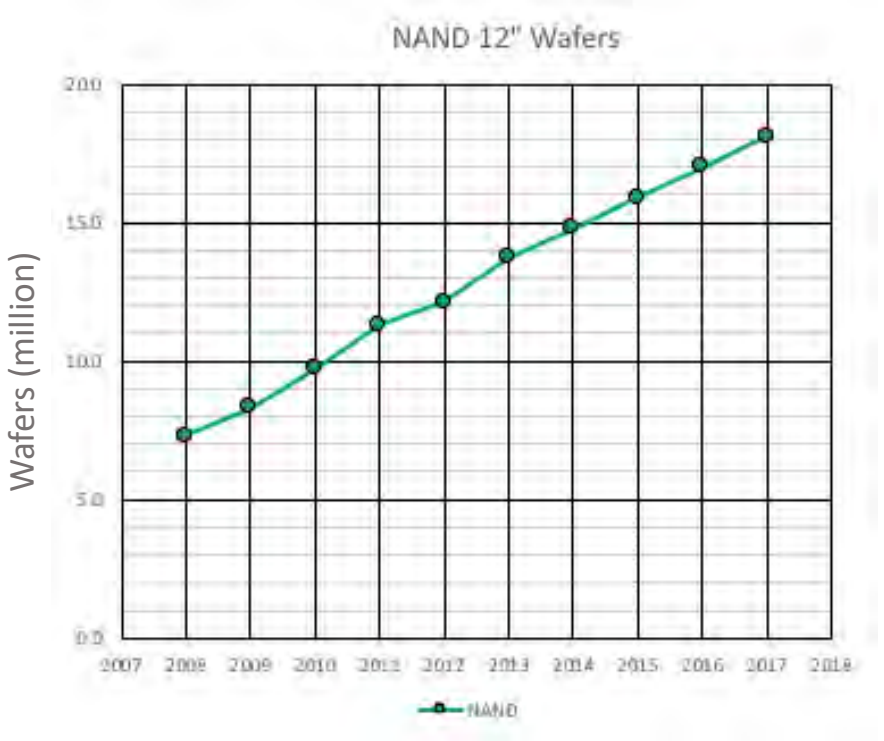
- Another option to increase annual manufactured PB – client migrates from lower density products to higher density products
  - LTO6 → LT07,
  - 2 platter 2.5” drive → 2 platter 3.5” drive,
  - 121 mm^2 16 GB NAND chip → 121 mm^2 32 GB NAND chip

HDD MSI

- From 2010 to 2017 HDD unit shipments dropped by 32% but EB shipments increased by 2.4X (13%/yr)
- Net: Average drive increased in capacity by almost 3.7X (2.4/0.68) from 0.5TB to 1.9 TB
- How did HDD increase EB shipments from 2010 to 2017
  - Areal density increased 10%/yr
  - EB shipments increased 13%/yr
  - Shortfall in areal density compensated by increase in factory investments, i.e. space, of 3%/yr.
  - An estimate: In 7 years, factory MSI increased 23%
- Net: HDD unit shipments not a measure of MSI
- Surface area issues dominate HDD manufacturing
  - Disk surfaces since average number of platters per drive is increasing
  - Wafer surfaces for head fabrication since more platters per drive requires more heads per drive
  - ***Comment: 8" head wafer has 50000 transducers. Typical factory with 100 wafer starts per day builds 1.8 B heads annually***

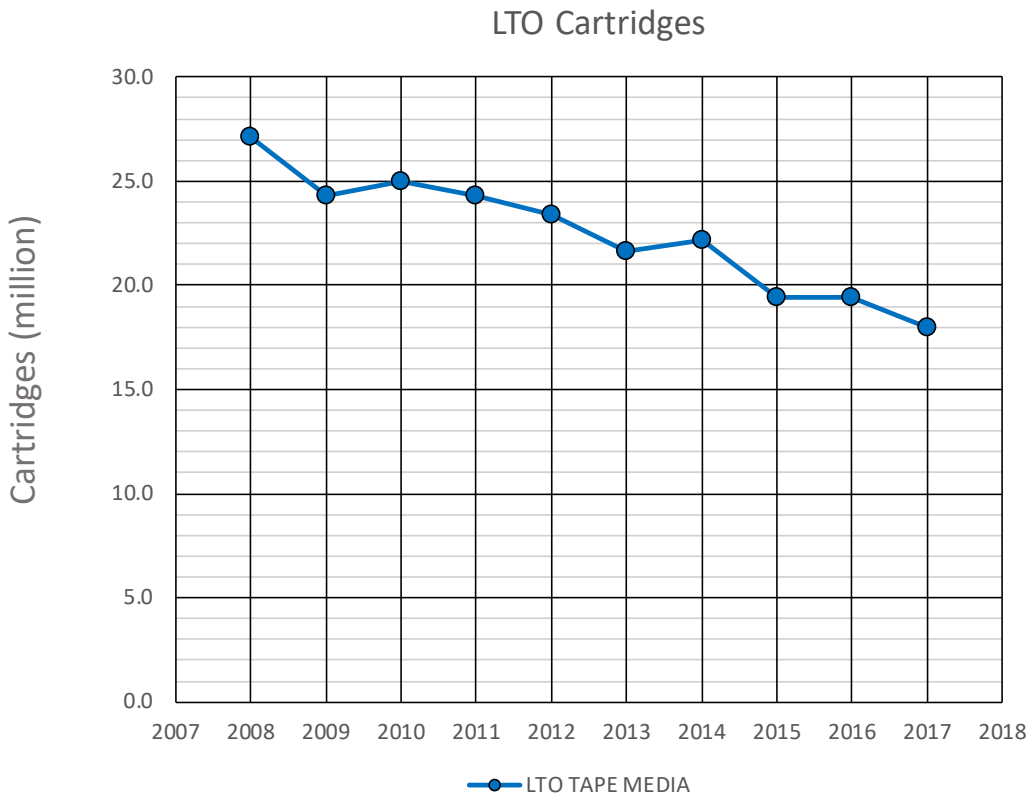
NAND MSI

- ***NAND historically increases wafer starts by ~1 M wafers each year***
- ***Some numbers***
  - 18 M wafers ➔ 175000 PB or 9.7 TB / wafer
  - 12” wafer yields ~ 400 121 mm^2chips ➔ average chip capacity ~ 24 GB or 194 Gbit
  - Best of breed chip capacity (3 bit/cell, 48-64 layers) is ~ 384 Gbit or 48 GB.
  - 7.2 B chips annually (~1.4 B smart phones built annually)
- ***MSI Implication***
  - NAND could double EB shipments by moving all production to 3D designs, i.e. 350 EB or 44% of today’s HDD EB shipments with no increase in MSI (factories)
  - Reality: NAND product mix requires a variety of chip capacity designs
- ***NAND Manufacturing Growth ~ 40%/yr with 6%/yr from MSI***
  - 1 M wafers ➔ 9700 PB (minimum) ➔ 6%
  - 34% areal density growth ➔ 60000 PB ➔ 34%
- ***HDD/NAND Manufacturing Crossover***
  - 175000 x $(1.40)^N$ = 780000 x $(1.15)^N$ ➔ N=7.5 years ***but***
  - NAND chip has 9X the areal density or 0.5 TB chip???
  - HDD has 3X areal density or a 36 TB HDD
  - Total NAND PB ➔ 2,182,000 PB or 2X present day HDD PBs
- ***Factory Issues***
  - $3B factory produces 1500 wafers daily or 500,000 annually
  - Adding 1 M wafers annually requires $6B in factory capitalization annually



LTO Media MSI

- MSI shipments dropped 7% in 2017. Over 10 years MSI has dropped by 4.5% annually while PB shipments have grown 17% annually
- ***No consumer market***
- The LTO consortium reports that 2017 compressed bit shipments were 108442 PB, a 13% increase over 2016 compressed bit shipments. An estimate for native bit shipments is 45000 PB since the bulk of cartridge shipments are LTO6 and LTO7 with 2.5X compression.
- 18,000,000 LTO cartridges produced in 2017 implies an average cartridge capacity of 2.5 TB
  - LTO6 capacity 2.5 TB
  - LTO7 capacity 6.0 TB
  - LTO8 capacity 12.0 TB
- Maximum possible PB production (all cartridges LTO7) is 108,000 PB with no MSI increase
- Maximum possible PB production (all cartridges LTO8) is 216,000 PB with no MSI increase



Summary and the Future

- EB Observations
  - NAND production increased at > 40% annual rate for 5 years – benefiting from robust consumer market (PDAs and PCs), applications in enterprise storage, transition to 3D multi-layer and multi-bit per cell designs
  - HDD PB production continues to dominate manufactured storage at 75% but revenue decline continues. HDD unit and EB shipments are shifting from consumer applications to enterprise clients
  - LTO TAPE MEDIA continues with ~ 4.5% share of manufactured storage. Note that LTO TAPE MEDIA has no consumer market
  - NAND $/GB and HDD EB volumes preclude HDD being replaced by NAND

- Manufacturing (MSI) Observations
  - NAND sustaining EB growth with ~ 6% MSI increases
  - HDD sustaining EB growth with ~ 3% MSI increases
  - LTO TAPE MEDIA sustains EB growth with 7% MSI decreases ←

- $/GB Observations
  - NAND undersupply resulted in no $/GB reduction for 2017 **(i.e. 0%/YR)** and a resultant 40% increase in revenue
  - HDD continued $/GB reductions but at 20%/YR with a resultant loss in revenue for 3 consecutive years.
  - LTO TAPE MEDIA continues $/GB reductions at 10%/YR
  - Ideal Moore's Law metric would predict 29% annual decreases in $/GB (no longer achieved)

- Revenue: NAND revenue > 2X HDD revenue!!!

Summary or Futures (i.e. Areal Density)

- NAND Areal Density
  - NAND strategy with multi layer 3D designs and multi bit per cell architecture has sustained 33%/YR density increases.
  - Transition from 3 bit to 4 bit cell designs and from 48 layer to 96 layer 3D designs will sustain areal density growth for 4 years (3X density increase)
  - Today's "Best of Breed" 48 GB chips could approach > **128 GB** capacity in 4 years
  - Annual EB shipment, now 175 EB, could become 480 EB in 3 years if 40% shipment growth rate maintained
  - Price Caveat: Today's 175 EB generated $56 B in revenue. If there is no $/GB drop, it seems unlikely that the storage clients could spend $153B on NAND alone in 2021.

- HDD Areal Density
  - HDD strategy relies on introduction of HAMR and/or MAMR; otherwise 10%/YR density increases continue as the norm
  - HDD faces difficult magnetic physics limitations (particle size, particle stability or kT thermal energy) and aggressive but expensive and straightforward lithographic processing.
  - HDD capacity strategy has used additional platters in the same form factor HDD case. 7 and 8 platter designs may migrate to 8 and 9 platter designs with a 25% boost in capacity to the **16 TB to 18 TB** range in a 3 year period.

- LTO TAPE Media Areal Density
  - LTO Tape continues on 31%/YR density increases using the introduction of tunnel sensor and BaFe media and continues on the INSIC roadmap of doubling cartridge capacity on a 2 year cycle
  - In 3 years, today's 12 TB cartridges will be in the **30 TB to 40 TB** range
  - 100 TB cartridges could be feasible in the mid 2020's (but with very critical dimensional stability and positioning realities)

Numbers for HDD, NAND Chips, LTO Media

- Total Manufactured Bytes in 2017 — 1,000 EB — (10^{21} Bytes)
- Total Revenue in 2017 — $83 B — ($8.3 x 10^{10})
- HDD Units Shipped in 2017 — 404 M — ($4.1 x 10^{8}$)
- LTO Cartridges Shipped in 2017 — 18 M — ($1.8 x 10^{7}$)
- NAND Wafers Processed in 2017 — 18 M — ($1.8 x 10^{7}$)

2017 LANDSCAPE	EB	REVENUE	$/GB
LTO TAPE MEDIA	45	$0.7 B	$0.0147/GB
HDD	780	$26.1 B	$0.0332/GB
NAND	175	$56.5 B	$0.3202/GB
TOTAL	1000	$83.3 B	NA

- Average Cartridge Capacity 2017 — 2.5 TB
- Average HDD Capacity 2017 — 1.9 TB
- Average NAND Chip 2017 — 0.024 TB
- Average NAND 12” Wafer 2017 — 10 TB

- Best of Breed LTO Cartridge 2017 — 12 TB — 3 year horizon ➔ 30 TB to 40 TB
- Best of Breed HDD 2017 — 12 TB – 14 TB — 3 year horizon ➔ 20+ TB
- Best of Breed NAND Chip 2017 — 0.05 TB — 3 year horizon ➔ 0.15 TB