ECE566
Enterprise Storage Architecture

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Storage Efficiency

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Two views of file system usage

- User data view:
  - "How large are my files?" (bytes-used metric)
    or
    "How much capacity am I given?" (bytes-available metric)
  - **Bytes-used**: Total size = sum of all file sizes
  - **Bytes-available**: Total size = volume size or "quota"
  - Ignore file system overhead, metadata, etc.
  - In pay-per-byte storage (e.g. cloud), you charge based bytes-used
  - In pay-for-container storage (e.g. a classic webhost), you charge based on bytes-available

- Stored data view:
  - How much actual disk space is used to hold the data?
  - Total usage is a separate measurement from file size or available space!
    - "ls –l" vs. "du"
  - Includes file system overhead and metadata
  - Can be reduced with *trickery*
  - If you're the service provider, you buy enough disks for this value

Storage efficiency

- $\text{StorageEfficiency} = \frac{UserData}{StoredData}$
- Without storage efficiency features, this value is < 1.0. Why?
  - File system metadata (inodes, superblocks, indirect blocks, etc.)
  - Internal fragmentation (on a file system with 4kB blocks, a 8193 byte file uses three data blocks; the last block is almost entirely unused)
  - RAID overhead (e.g. a 4-disk RAID5 has 25% overhead)
- Can we add features to storage system to go above 1.0?
  - Yes!
    (otherwise I wouldn't have a topic called "storage efficiency")

Why improve storage efficiency?

- Why do we want to improve storage efficiency?
  - Buy fewer disks! Reduce costs!
  - If we're a service provider, you charge based on *user data*, but your costs are based on *stored data*.
    Result: More efficiency = more profit
    (and the customer never has to know)
- Note: all these techniques **depend on workload**

Techniques to improve storage efficiency

More efficient RAID

Snapshot/clone

Zero-block elimination

Thin provisioning

Deduplication

Compression

"Compaction" (partial zero block elimination)

RAID efficiency

- What's the overhead of a 4-disk RAID5?
  - 1/4 = 25%
- How to improve?
  - More disks in the RAID
- What's the overhead of a 20-disk RAID5?
  - 1/20 = 5%
- Problem with this?
  - Double disk failure very likely for such a large RAID
- How to fix?
  - More redundancy, e.g. RAID-6
    (Odds of triple disk failure are << odds of double disk failure, because we're ANDing unlikely events over a small timespan)
- What's the overhead of a 20-disk RAID6?
  - 2/20 = 10%
- **Result: Large arrays can achieve higher efficiency than small arrays**

Techniques to improve storage efficiency

- More efficient RAID
- **Snapshot/clone**
- Zero-block elimination
- Thin provisioning
- Deduplication
- Compression
- "Compaction" (partial zero block elimination)

Snapshots and clones

- This one is simple.

- If you want a copy of some data, and you don't need to write to the copy: **snapshot**.
  - Example: in-place backups to restore after accidental deletion, corruption, etc.

- If you want a copy of some data, and you do need to write to the copy: **clone**.
  - Example: copy of source code tree to do a test build against

We covered snapshots and clones in the last lecture – review if you missed it!

Techniques to improve storage efficiency

- More efficient RAID
- Snapshot/clone
- **Zero-block elimination**
- Thin provisioning
- Deduplication
- Compression
- “Compaction” (partial zero block elimination)

Zero block elimination

- This one is also simple.
- If the user writes a block of all zeroes, just note this in metadata; don't allocate any data blocks
- Why would the user do that?
  - Initializing storage for random writes (e.g. databases, BitTorrent)
  - Sparse on-disk data structures (e.g. large matrices, big data)
  - A "secure erase": overwrite data blocks to prevent recovery*

* Note that this form of secure erase only works if you're actually overwriting blocks in-place. We've learned that this isn't the case in log-structured and data-journaled file systems as well as inside SSDs. Secure data destruction is something we'll discuss when we get to security...

Techniques to improve storage efficiency

- More efficient RAID
- Snapshot/clone
- Zero-block elimination
- **Thin provisioning**
- Deduplication
- Compression
- "Compaction" (partial zero block elimination)

Thin provisioning

- Technique to improve efficiency for the bytes-available metric
- Based on insight in how people size storage requirements

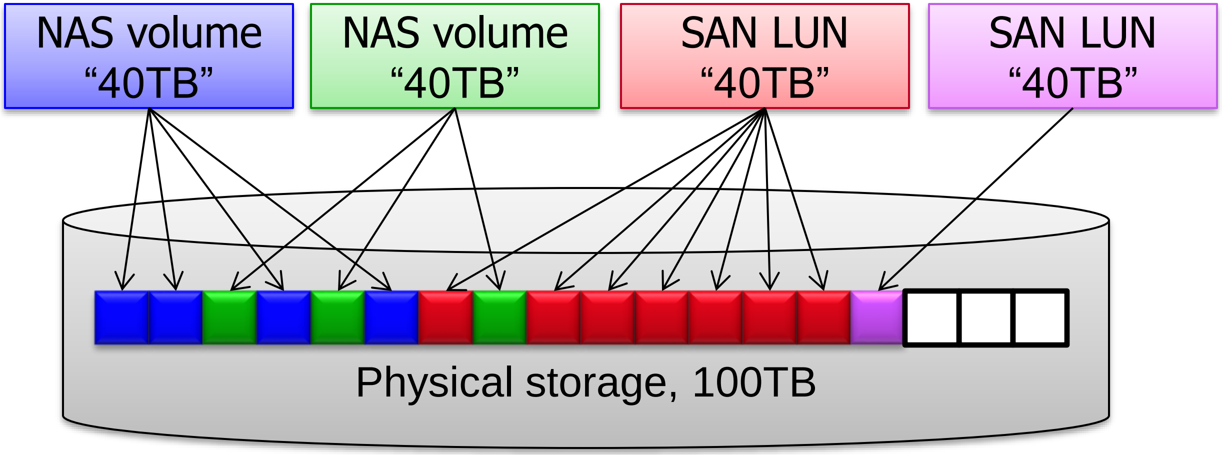
- System administrator:
  - "I need storage for this app. I don't know exactly how much it needs."
  - "If I guess too low, it runs out of storage and fails, and I get yelled at."
  - "If I guess too high, it works and has room for the future."
  - Conclusion: Always guess high.

Thin provisioning

- Storage provider:
  - "Four sysadmins need storage, each says they need 40 TB."
  - "I know they're all over-estimating their needs."
  - "Therefore, the odds that *all* of them need *all* their storage is very low."
  - "I can't tell them I think they're lying and give them less, or they'll yell at me."
  - "Therefore, each admin must *think* they have 40TB to use"
  - "I don't want to pay for 4*40=160TB of storage because I know most of it will remain unused."
  - **"I will <u>pool</u> a lesser amount of storage together, and everyone can pull from the same pool (<u>thin provisioning</u>)"**

Thin provisioning

- Result:
  - Buy 100TB of raw storage
  - For each sysadmin, make a 40TB file system (NAS) or LUN (SAN)
  - When used, all four containers use blocks from the 100TB pool

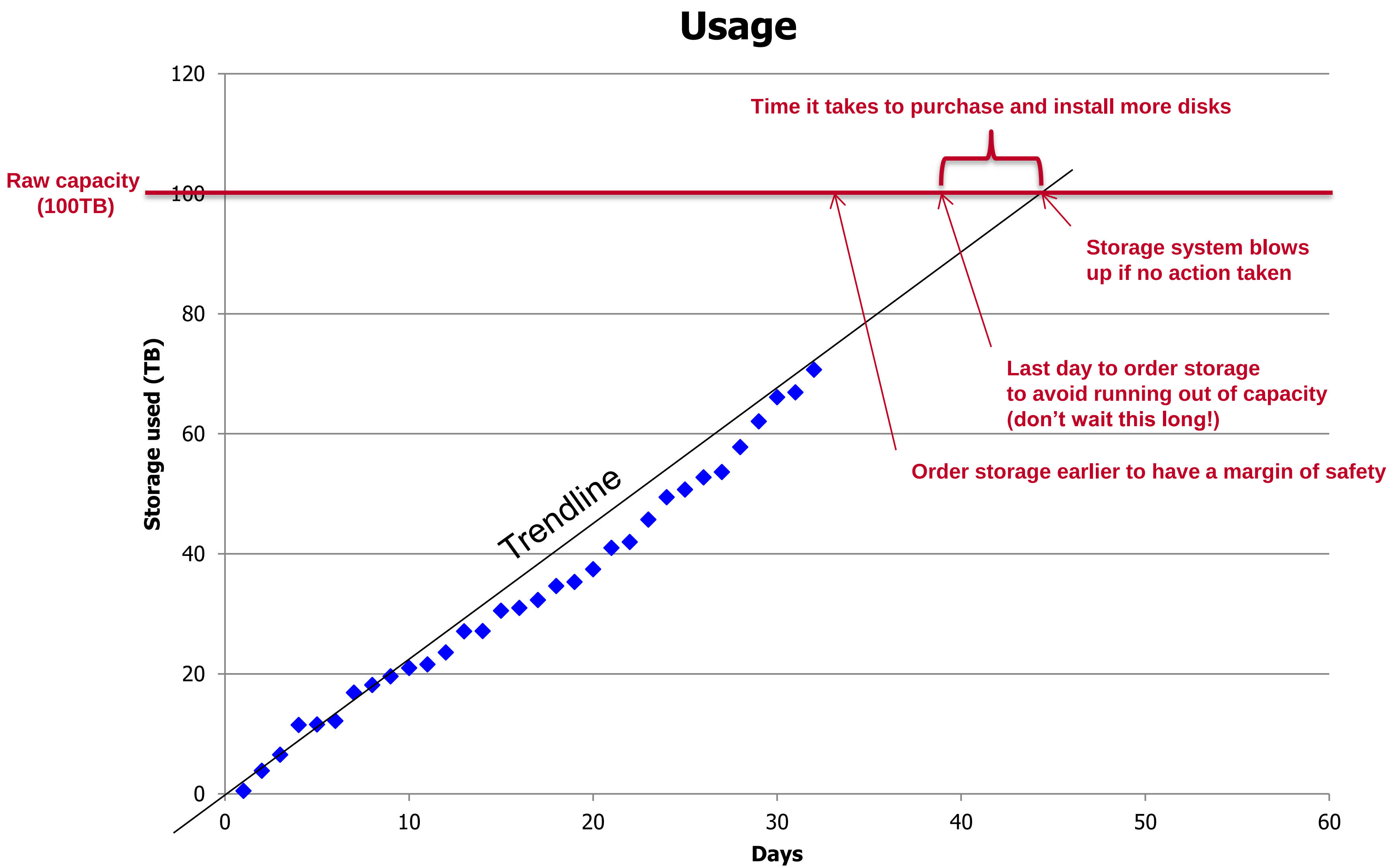


Managing thin provisioning

- Storage is "**over-subscribed**" (more allocated than available)
  - Need to monitor usage and add capacity ahead of running out

- Administrator can set their *risk level*:
  - More over-subscribed = cheaper, but more risk of running out if a sudden burst in usage happens
  - Less over-subscribed = more expensive, less risk

Managing thin provisioning



Reservations

- Per-user guarantees: “reservations”
  - Can set controller to guarantee a certain capacity per user
  - Reservations must add up to less than total capacity
- Example: Every user guaranteed 100/4=25TB
  - Limits damage if capacity runs out
- Example: Priority app guaranteed 40TB, rest have no reservation
  - Priority app will ALWAYS get its full capacity, even if system otherwise fills up

Techniques to improve storage efficiency

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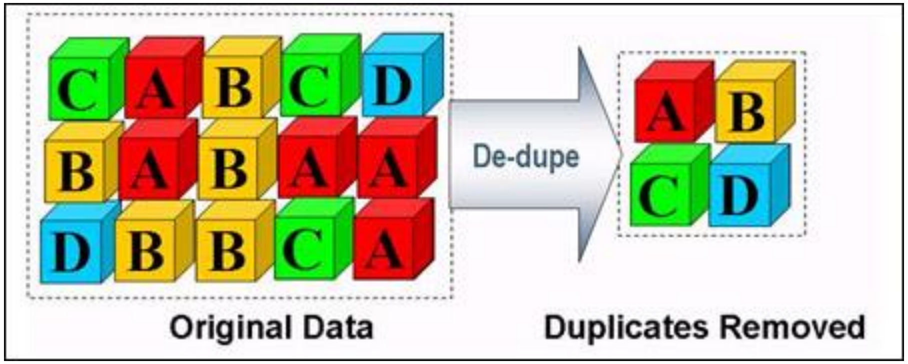
Deduplication simplified

- Basic concept:



- Split the file in to chunks
- Hash each chunk with a big hash
- If hashes match, data matches:
  - Replace this with a reference to the matching data
- Else:
  - It’s new data, store it.

Figure from http://www.eweek.com/c/a/Data-Storage/How-to-Leverage-Data-Deduplication-to-Green-Your-Data-Center/

Common deduplication data structures

- A simplistic model of deduplication:
  - Metadata:
    - Directory structure, permissions, size, date, etc.
    - Each file's contents are stored as a **list of hashes**
  - Data pool:
    - A flat table of hashes and the data they belong to
    - Must keep a reference count to know when to free an entry

^ A perfectly fine way to make a simple dedupe system in FUSE

- But now we know about filesystems and can be more clever:
  - Rather than files being a list of hashes, a deduplicating *file system* can use the inode's usual block pointers!
    - Difference: multiple block pointers can point to the same block
    - Blocks have reference counts
    - A table mapping *Block hash* to *block number* stored on disk (and cached in memory as hash table)

Inline vs. post-process

- Big design question: **inline** vs **post-process**
- Inline:
  - When a write occurs, determine the resulting block hash and deduplicate at that time.

  \+ File system is always fully deduplicated

  \+ Simple implementation

  – Writes are slowed by additional computation
- Post-process
  - Write committed normally; background daemon periodically hashes unhashed blocks to deduplicate them.

  \+ Low overhead to the write itself

  – More overall writes to disk (write + read + possible change)

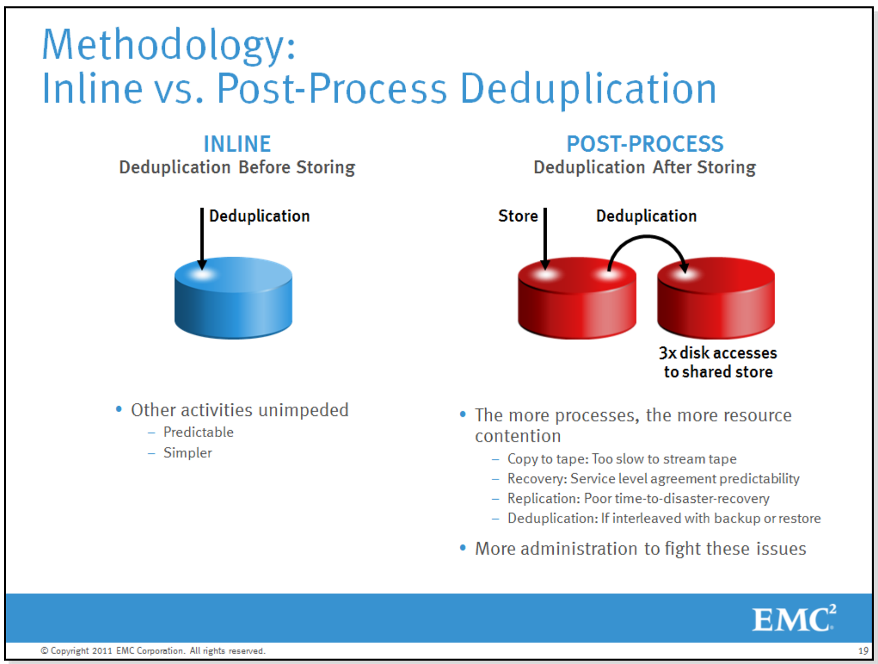
  – Disk not fully deduplicated until later (increased average space usage)

  – Need to synchronize user I/Os versus background daemon I/Os for consistency

LOL industry

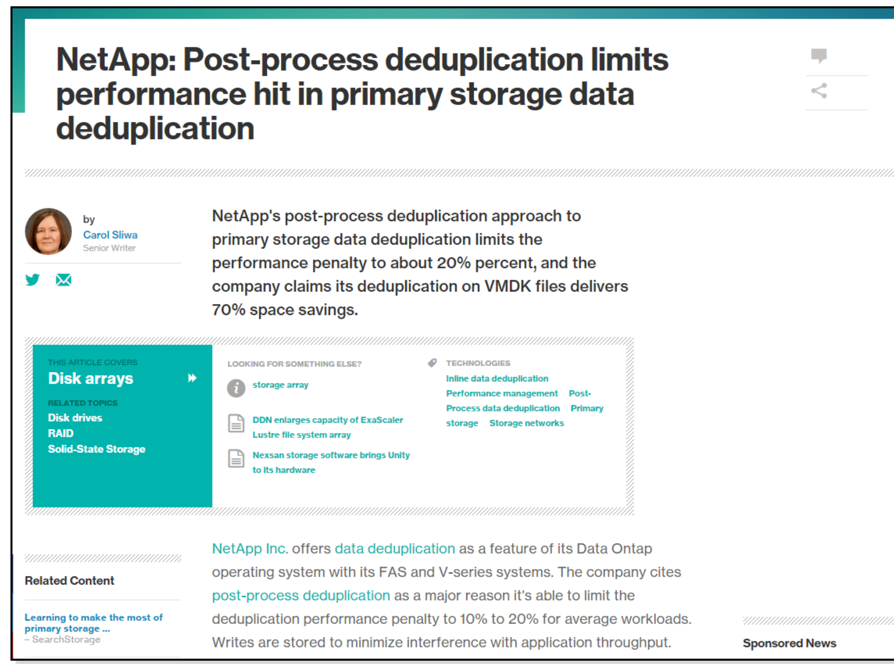
- Choice between inline and post-process is tradeoff, no one right answer.
- That doesn't stop industry vendors from using it to spread FUD (Fear, Uncertainty, and Doubt).

EMC product slide



“Post-process dedupe does more accesses, so it must be slow!”

NetApp-friendly article



“Post-process dedupe makes writes faster, anything that lacks it must be slow!”

Fixed vs. variable-sized blocks

- Insertion/deletion: A common modification.

MY TEXT FILE
This is my text file.
It contains bytes.
I like my text file.
It is a very good text file.
01234567890123456789...

Copy+modify →

MY TEXT FILE
By Tyler Bletsch
This is my text file.
~~It contains bytes.~~
I like my text file.
It is a very good text file.
01234567890123456789...

(Side note: you can't literally "insert" or "delete" stuff to a file and have it shift like this – your text editor reads the whole file, you change it in RAM, then you save the whole file. The actual file system only supports in-place changes; no shifts.)

Fixed vs. variable-sized blocks

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- With 8-byte fixed-sized blocks:

MY TEXT	FILE|Thi	s is my	text fil	e.|It co	ntains b	ytes.|I	like my	text fil	e.|It is	a very	good tex	t file.|	01234567	89012345	6789...

MY TEXT	FILE|By	Tyler Bl	etsch|Th	is is my	text fi	le.|I li	ke my te	xt file.	|It is a	very go	od text	file.|01	23456789	01234567	89...

- All blocks past the change differ!
- Bad, because this is a common case

Variable-sized blocks

- What if, instead of fixed-sized blocks, we made blocks divided based on the *content* of the file?
  - Resulting blocks may be of variable size
- Naive rule: divide a block whenever there's a space

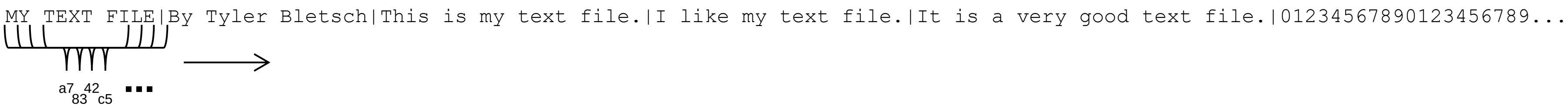
```
MY TEXT FILE|This is my text file.|It contains bytes.|I like my text file.|It is a very good text file.|01234567890123456789...
MY TEXT FILE|By Tyler Bletsch|This is my text file.|I like my text file.|It is a very good text file.|01234567890123456789...
```

- Way more blocks match! Mismatches only near the insertion/deletion, which is what we want!

- Could there be any issue with the "divide on space" rule?
  - Yes, obviously. Blocks too small (text file), or blocks too large (binary file).
  - Need a content-based dividing rule that won't go crazy on specific data

Rabin-Karp Fingerprinting

- Hash every offset with a "sliding window":



- Declare a block boundary every time the hash value equals a "special constant" (e.g. zero)
- Boundaries will depend on data, but in a "deterministically random" way (i.e. the byte sequences that cause division won't be "special" in any way)
- Parameters:
  - **Hash size:** On average, block size will be 2^{hash_bits}; can select hash size to give desired average block size
  - **Window size:** How much data to consider to make boundaries. The number of byte sequences that result in a boundary is, on average, $2^{window\_bits - hash\_bits}$

Rabin-Karp Fingerprinting

- Efficiency: all those hashes must be expensive, right?
  - Given windows size ***m*** and file size ***n***, don't you need ***n*m*** hash updates?
  - Not if we use *trickery*: **rolling hash**

```
for i from 1 to n-m+1
  h = hash(s[i+1 .. i+m])
```

→

```
h = hash(s[1 to m])
for i from 2 to n-m+1
  h = h – s[i-1]
  h = h + s[i+m]
```

"–" means "computationally remove from the hash"
"+" means "computationally add to the hash"

- Now just ***n-m*** "hash updates"

Techniques to improve storage efficiency

- More efficient RAID
- Snapshot/clone
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- **Compression**
- "Compaction" (partial zero block elimination)

Compression

- Represent the data with fewer bits.
- Fundamental concept: Identify patterns which can be abbreviated
  - Many, many, many algorithms out there – beyond scope of course
    - Lempel-Ziv and descendants (deflate, PKZIP, GZIP, etc.)
    - Probabilistic models
    - Grammar-based codes

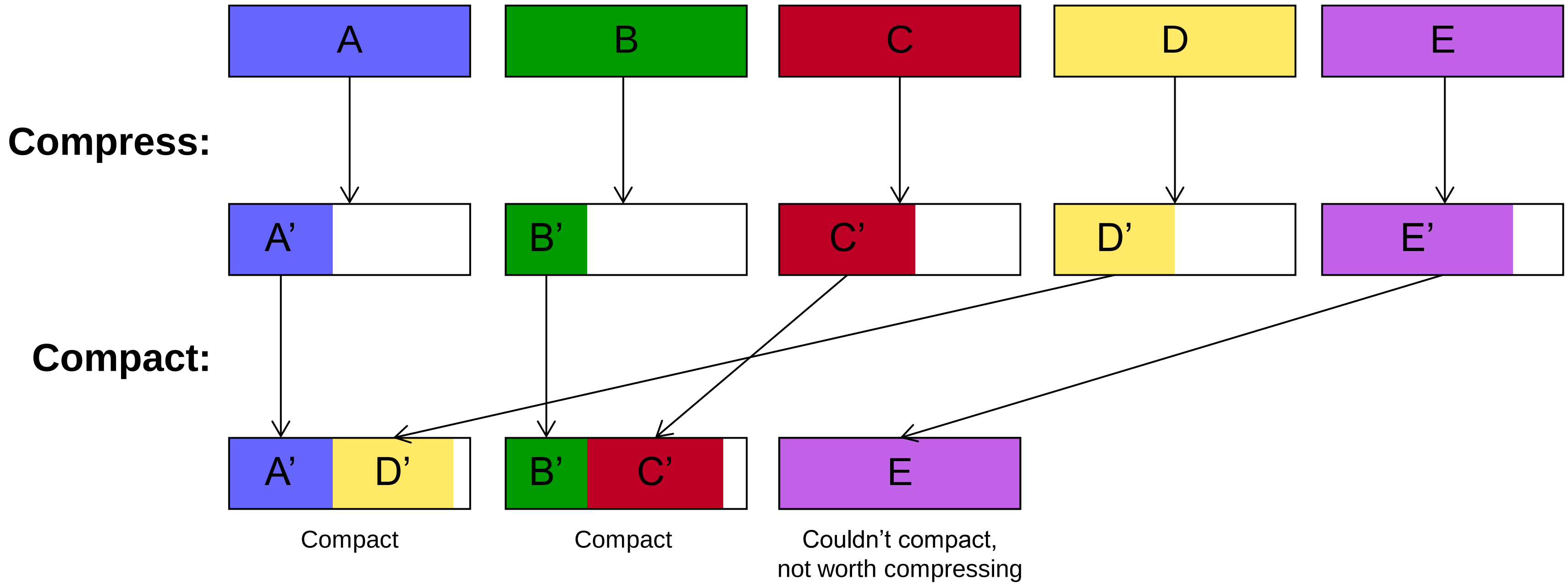
- A truth we've seen a hundred times: this is a tradeoff
  - Time vs. storage

Challenge when applied to disk storage

- Still need to **seek**: if we compress a file end-to-end, we don't know where to go to find a given offset
  - Solutions:
    - Compress blocks rather than files ← Upcoming example
    - Store some kind of index to allow seeking in compressed data (e.g., an uncompressed offset -> compressed offset table)
    - Probably other ideas...
- **Block storage:** If we compress a data block, but we still store it in a disk block, we didn't save anything...
  - Solutions:
    - Pack multiple compressed blocks into one real block ← Upcoming example
    - Consider larger "chunks" and compress them down to fewer blocks
    - Probably other ideas...

Compression with compaction

- Compression with simple compaction



- Data block pointers are now {block_num, offset, length}

Techniques to improve storage efficiency

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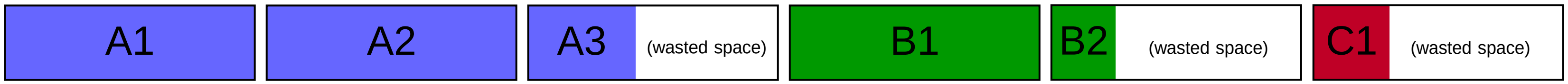
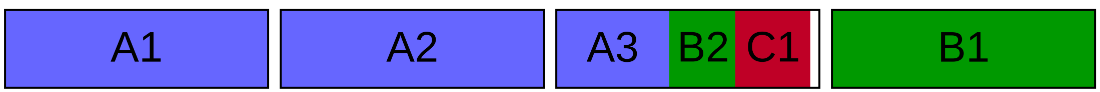
- **"Compaction" (partial zero block elimination)**

Tail Compaction

- Remember **internal fragmentation**: the end of every file that’s not a multiple of the block size will waste some space:



- **Tail packing:** What if we take all these ends-of-files and have them share a block?



Tradeoff:

\+ Reduces space lost to internal fragmentation

– Extra filesystem metadata overhead

– More/worse seeks

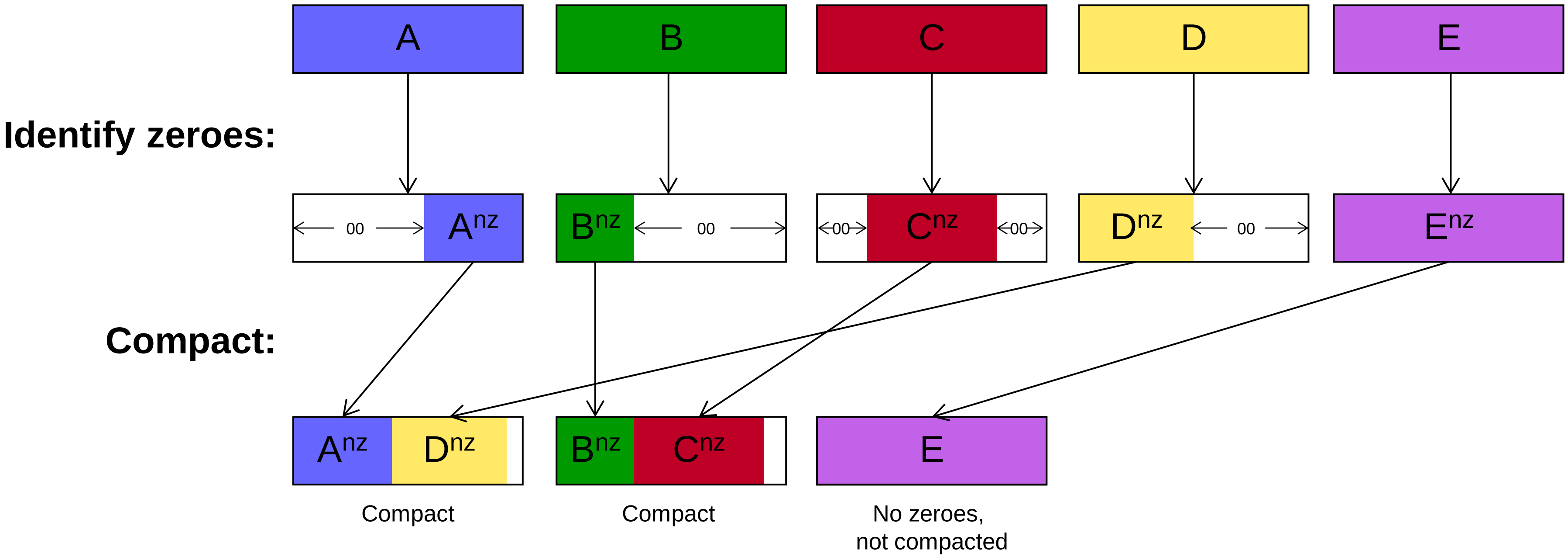
General compaction

- Can go further…
- Remember how we were able to ignore zero-blocks?
- What if a block is partially zeroed...can we take advantage of that?

- Basically same as the compaction step we saw in compression, except just for zero data
  - Simple idea, only worth doing if the workload has sparse files
  - Sparse files: files that are mostly “empty” (zeroes), e.g. scientific sparse matrix data

Compression with compaction

- Compression with simple compaction



- Data block pointers are now {block_num, offset, length} (again)

Conclusion

- There are many ways to reduce physical storage needs
- By doing many at once, can often cut storage needs dramatically (50%+)
- **Depends strongly on workload:**

More efficient RAID	• Need large array
Snapshot/clone	• Only if you need copies
Zero-block elimination	• Only for sparse data
Thin provisioning	• Only if average utilization << peak utilization
Deduplication	• Only if data has duplication
Compression	• Only if data is compressible
"Compaction" (partial zero block elimination)	• Only for sparse data

- Example: For a long time, NetApp ran a promotion called the "NetApp 50% Virtualization Guarantee": if you're storing VMs on NetApp, they guaranteed you'd need 50% less disk capacity vs. competitors. They pay you otherwise.
  - Note: NetApp arrays are large, VMs are often cloned, virtual disks are sparse, have low average utilization, lots of duplication, and are often compressible.
  - Result: They very rarely had to pay out.