REVIEW ARTICLE

Capacity Reclamation and Thin-Provisioning Efficiency in Large-Scale Enterprise Storage Systems

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Abstract

Background: Thin provisioning improves storage utilization by decoupling logical capacity presented to applications from physical capacity consumed in a shared pool. Its practical efficiency, however, depends on whether blocks released by hosts can be identified, safely unmapped, and returned to the array without excessive metadata cost, fragmentation, or performance interference.

Objective: To synthesize storage-systems evidence into an engineering framework for capacity reclamation and thin-provisioning efficiency in large-scale enterprise environments.

Methods: A structured narrative review was performed using storage-systems research, standards-oriented technical literature, and enterprise implementation studies. Evidence was organized around allocation efficiency, host-to-array reclamation, deduplication and snapshot interactions, capacity attribution, fragmentation, and operational safeguards against pool exhaustion.

Results: The literature shows that thin provisioning alone removes reservation waste but does not guarantee high physical utilization. Deleted host blocks can remain allocated unless discard/UNMAP semantics propagate across the full storage stack. Deduplication, snapshots, clones, and shared chunk ownership further decouple logical deletion from physically reclaimable capacity. Large-scale systems therefore require explicit metrics for live physical occupancy, reclaimable dead space, reclamation lag, reserve headroom, and data-reduction-adjusted growth. Reclamation should be scheduled as a controlled background workload and coordinated with snapshot retention, deduplication metadata, and pool-growth thresholds.

Conclusion: Efficient thin provisioning is best managed as a closed-loop capacity-control problem. High utilization is achieved not by aggressive oversubscription alone, but by accurate capacity accounting, end-to-end release semantics, bounded reclamation lag, and sufficient operational reserve to absorb bursts and reclamation failures.

Keywords: capacity reclamation; enterprise storage; space reclamation; storage virtualization; thin provisioning; UNMAP; deduplication; storage efficiency

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1. Introduction

Large-scale enterprise storage systems commonly expose logical volumes whose aggregate advertised capacity exceeds the physical capacity immediately committed behind them. This abstraction, generally described as thin provisioning, replaces static reservation with allocation on write. The model can substantially reduce stranded capacity because storage is drawn from a common pool only as applications consume it. The central operational problem is that allocation is naturally visible to the storage array, whereas deallocation may not be. A file deleted by an application can disappear from the host namespace while the corresponding physical blocks remain allocated at the storage layer, creating dead space that is logically free but physically unavailable [1-3].

The distinction becomes important as shared storage reaches hundreds of terabytes or petabytes. A few percentage points of unreclaimed capacity can represent many terabytes of unnecessary physical occupancy, while a thin pool operated too close to exhaustion can fail abruptly when burst growth exceeds available headroom. Capacity efficiency therefore cannot be represented adequately by a single utilization percentage. It depends on the relationship among logical provisioned capacity, live logical data, physically allocated blocks, reclaimable dead blocks, snapshot- or clone-retained blocks, deduplication sharing, metadata, and reserve capacity.

Earlier storage research also established that data reduction and capacity management are tightly coupled. Inline deduplication can lower physical demand by eliminating repeated content, but it introduces reference-sharing and metadata structures that complicate deletion and capacity attribution [4-8]. In globally deduplicated systems, deleting a logical object does not necessarily free its referenced chunks because other objects may still own them. Conversely, estimating the physical effect of deleting a volume can be difficult without expensive per-chunk accounting; sketch-based approaches were later proposed specifically to estimate reclaimable and attributable capacity at scale [9].

File-system behavior adds another layer. Copy-on-write layouts, snapshots, block sharing, and fragmentation can delay or prevent physical release even after user-visible data are removed. Work on WAFL, for example, demonstrates that free-space and intra-block fragmentation can reduce effective capacity and performance and that a virtualization layer can be used to relocate blocks while limiting metadata updates [10]. Thus, capacity reclamation is not merely a host command or array feature; it is an end-to-end property of the allocation stack.

This review examines capacity reclamation and thin-provisioning efficiency as a systems optimization problem. The objectives are to: (1) define practical metrics that distinguish logical allocation from physical occupancy; (2) synthesize evidence on host-to-array reclamation, deduplication, deletion, and fragmentation; (3) identify failure modes that cause persistent dead space or thin-pool exhaustion; and (4) propose an implementation framework suitable for large-scale enterprise storage.

2. Methods

A structured narrative review and engineering synthesis was undertaken. Literature searches were directed to IEEE, ACM, USENIX, storage-systems proceedings, and standards-oriented technical sources. Search concepts included thin provisioning, space reclamation, capacity reclamation, discard, UNMAP, virtual storage, storage utilization, deduplication, deletion, snapshot space, capacity attribution, free-space fragmentation, and enterprise storage. Citation chaining was used to identify foundational systems work relevant to large shared storage pools.

Sources were prioritized when they addressed at least one of five technical questions: how physical allocation is deferred; how

unused host blocks are communicated to underlying storage; how deduplication or block sharing alters physical reclaimability; how deletion or garbage collection scales in distributed storage; or how capacity state can be measured and controlled without unacceptable I/O overhead. Studies dealing exclusively with server CPU provisioning or unrelated cloud-resource scheduling were excluded from the evidence table.

Because the selected studies span primary storage, secondary storage, virtualized environments, deduplicating arrays, and file systems, direct statistical pooling was not appropriate. Findings were synthesized by mechanism and by operational outcome. Reported quantitative results were retained only when they were clearly attributable to the original study; equations introduced below are engineering definitions used to standardize reasoning across heterogeneous systems rather than pooled effect estimates.

Let L_p denote total logical provisioned capacity, P_{pool} the usable physical pool, P_{alloc} the physical capacity currently allocated, D_{live} the live logical data represented by that allocation, and P_{dead} the allocated capacity no longer required by the host but not yet returned to the free pool. A simple oversubscription ratio is $O=L_p/P_{pool}$. Physical utilization can be expressed as $U_p=P_{alloc}/P_{pool}$, while dead-space fraction is $F_{dead}=P_{dead}/P_{alloc}$. When R is the amount of eligible dead space actually returned to the pool during a reclamation interval, reclamation efficiency is $\eta_r=R/P_{dead,eligible}$. Reclamation lag is the elapsed time between host-level release and physical availability in the storage pool.

For operational control, reserve headroom $H=P_{pool}-P_{alloc}$ must be interpreted relative to net growth. If G is the current physical growth rate after data reduction and C_r is the sustained reclamation rate, an approximate time-to-exhaustion under stable conditions is $T_{exhaust}\approx H/(G-C_r)$ when $G>C_r$. This approximation is intentionally conservative: burst growth, snapshot creation, rebuild traffic, metadata expansion, and temporary failure of reclamation can shorten the available response window.

3. Results

The evidence converged on four themes: thin allocation reduces reservation waste but does not reclaim deleted blocks by itself; reclamation requires a complete release path across host and array layers; advanced data-reduction features complicate the relationship between logical deletion and physical release; and high utilization is safe only when capacity accounting and reserve policies are coupled to workload growth. The principal included studies are summarized in Table 1.

Thin provisioning changes when capacity is allocated, not the semantics of deletion. Vendor-independent storage guidance and enterprise implementations describe the same basic failure mode: after a host deletes data, the host file system may mark extents free while the array continues to regard the corresponding logical block addresses as allocated [1-3]. Space-reclamation commands such as SCSI UNMAP provide a mechanism for the host stack to report that selected ranges no longer contain useful data, allowing the storage system to deallocate or recycle their physical backing.

The performance literature suggests that thin allocation need not impose a substantial steady-state penalty when implemented carefully. Evaluations of virtualized thin disks reported performance comparable with thick-provisioned virtual disks across tested workloads, supporting the premise that allocation-on-demand can be practical when zeroing, metadata updates, and extent growth are controlled [11]. However, reclamation itself is additional work. Large deallocation bursts can trigger metadata updates, internal garbage collection, data movement, or flash erase activity; therefore, reclamation should be treated as a schedulable background workload rather than assumed to be free.

3.1 End-to-end reclamation and dead-space formation

Figure 1 illustrates the end-to-end reclamation path. Allocation flows naturally from application writes through the file system and virtual volume to the shared pool. Reclamation travels in the opposite direction and is therefore easier to break: a file-system delete must be converted into freed extents, those extents must be exposed through the block layer, and the storage target must support and act on the release notification. Any layer that suppresses, batches indefinitely, or does not understand the signal can leave physical capacity allocated.

This explains why host free space and array free space can diverge sharply. From the application's perspective, deleted capacity is immediately reusable within the file system. From the array's perspective, it remains allocated until a reclaim operation is issued and processed. The resulting dead-space fraction is especially important in virtual-machine farms, databases with repeated create/drop cycles, temporary analytics workspaces, and backup staging areas, where logical churn can be high even when net live data grows slowly.

Reclamation granularity also matters. If the array allocates capacity in extents or slabs larger than the blocks freed by the host, scattered deletes may not create a fully releasable allocation unit. Coalescing adjacent frees, batching release requests, and periodic hole punching can improve physical yield. The trade-off is delay: more batching can reduce command overhead but increases reclamation lag and therefore the amount of dead space temporarily carried by the pool.

3.2 Deduplication, snapshots, and attributable capacity

Deduplication can increase effective capacity by orders of magnitude for highly redundant workloads, but the physical space associated with a logical volume becomes non-additive. Sparse indexing and flash-assisted chunk indexing were developed to preserve deduplication throughput at large scale without keeping a complete chunk index in memory [5,6]. Cluster-level routing research further showed that deduplication effectiveness and node-balance depend on how content is partitioned across nodes [7]. These findings are directly relevant to thin provisioning because data-reduction ratios alter physical growth and therefore the safe amount of logical oversubscription.

Deletion is more complex when chunks are shared. Strzelczak and colleagues showed that globally deduplicated distributed storage requires failure-tolerant reference management so that unnecessary blocks can be identified and reclaimed while reads and writes continue [8]. The system-level implication is that 'bytes deleted' and 'bytes reclaimable' are different quantities. A 1-TB logical deletion may free substantially less than 1 TB physically if most referenced chunks remain owned by other objects, snapshots, or clones.

Harnik and colleagues addressed this capacity-accounting problem explicitly by estimating how much physical space would be reclaimed if a volume or group of volumes were removed and by estimating attributed capacity in deduplicated storage [9]. Their work demonstrates that capacity management at scale may require approximate analytical structures rather than exhaustive ownership enumeration. For enterprise operations, this supports maintaining two separate views: logical consumption for tenant or application governance and physical attributable/reclaimable capacity for pool planning.

Snapshots and copy-on-write clones create a similar divergence. Deleting or overwriting active data may leave old blocks retained by a snapshot. Those blocks are no longer part of the live namespace but are not reclaimable until the final snapshot reference disappears. Figure 2 therefore separates live data, shared data, snapshot-retained blocks, dead-but-unreclaimed blocks, metadata/reserve, and the free pool. This state model is more informative than a single 'used capacity' counter.

3.3 Fragmentation and the cost of reclamation

Capacity reclamation can expose or amplify fragmentation. A thin pool may contain adequate free capacity in aggregate while the layout of free extents is unfavorable for large sequential allocations or for internal data-reduction structures. Storage Gardening demonstrated that free-space, file-layout, and intra-block fragmentation can persist in an enterprise copy-on-write file system

and that virtualization can facilitate relocation of blocks, including blocks referenced by read-only snapshots [10]. Reclamation policy should therefore consider not only the number of free bytes but their allocatability and the data movement required to consolidate them.

Aggressive background reclamation also competes with foreground I/O. Deduplication indexing work illustrates the broader principle that metadata access can dominate performance unless it is carefully organized [5,6]. Similarly, deletion work in distributed deduplicated storage allows operators to constrain the resources consumed by deletion, making its user-I/O impact configurable [8]. In a thin-provisioned pool, the optimal policy is consequently not 'reclaim immediately at any cost' but 'bound reclamation lag while preserving foreground service levels.'

3.4 Closed-loop efficiency model for large storage pools

The synthesis supports a closed-loop capacity-control model (Figure 3). The first step is measurement: logical provisioned capacity, live logical data, physical allocation, snapshot-retained data, deduplication ratio, dead-but-allocated space, free-pool headroom, and recent growth should be observed separately. The second step is classification: determine which space is immediately reclaimable, reference-retained, administratively protected, or unavailable because of allocation granularity. The third step is controlled reclamation, using host discard/UNMAP, file-system trim operations, snapshot retirement, garbage collection, or data relocation as appropriate.

Verification follows execution. The system should confirm that physical allocation has fallen as expected and that reclamation has not produced unacceptable latency, queue depth, or internal write amplification. Finally, thresholds and schedules should be retuned. A workload with stable deletion and low foreground demand may tolerate frequent reclamation, whereas a latency-sensitive database may benefit from batched reclamation during lower-demand periods.

Table 2 formalizes the principal metrics. Table 3 maps common causes of stranded capacity to observable symptoms and corrective controls. Table 4 converts the evidence into a deployment framework for heterogeneous enterprise storage classes. Across all classes, the key safety rule is that oversubscription must be coupled to a response interval: the free pool should contain enough headroom to accommodate expected physical growth during the time required to detect a threshold breach, initiate reclamation or expansion, and complete the corrective action.

4. Discussion

Thin provisioning is frequently described as a capacity-saving feature, but the evidence indicates that it is better understood as a capacity-allocation mechanism whose efficiency depends on complementary controls. It removes the need to reserve the full advertised size of every volume, yet it cannot by itself identify which previously written blocks have become disposable. Without reclamation, a long-lived thin pool can progressively approach thick-provisioned behavior as deleted blocks accumulate physically.

The most consequential management error is to equate host-reported free space with physical headroom. In large virtualized estates, a guest operating system can report substantial free capacity while the datastore or array remains heavily allocated. Nested virtualization can create multiple layers of this mismatch. Effective monitoring must therefore reconcile capacity at the application or guest layer, the host file-system layer, the virtual-volume layer, and the physical storage pool. The expected relationship is not equality, but unexplained divergence should be investigated.

A second error is to maximize oversubscription without modeling physical growth. An oversubscription ratio of 2:1 or 5:1 has no intrinsic meaning because the risk depends on workload behavior, data reduction, snapshot retention, and the speed with which new capacity can be added. A pool supporting stable virtual desktops with high deduplication may safely present far more logical capacity than a pool supporting incompressible scientific data or encrypted databases. The relevant control variable is the distribution of net physical growth during the intervention window, not the logical ratio alone.

A third error is to schedule reclamation independently of performance. Reclamation consumes storage-controller cycles, metadata bandwidth, backend writes, flash erase work, or network traffic depending on the architecture. Systems literature on deduplication and distributed deletion repeatedly emphasizes the need to control metadata and background-work overhead [5-8]. Enterprise practice should apply the same principle to thin-pool reclamation: rate-limit or schedule it when necessary, but monitor lag so that batching does not silently convert into chronic dead-space accumulation.

Deduplication and snapshots make capacity reporting more difficult but also more important. Logical ownership is not equivalent to physical ownership when data are shared. Capacity planning should therefore separate at least three concepts: logical referenced capacity, physical attributable capacity, and physically reclaimable capacity. This distinction prevents misleading chargeback and poor placement decisions. It also explains why deleting a large volume may produce an unexpectedly small increase in physical free space when shared or snapshot-retained blocks dominate.

At very large scale, approximate capacity estimation may be preferable to exact accounting for every block. Harnik et al. demonstrated that sketch-based estimators can answer reclaimable-capacity questions in deduplicated storage with analytical guarantees and practical performance [9]. The broader lesson is that capacity telemetry itself must scale; an accounting mechanism that requires exhaustive scanning whenever an operator asks 'what will this deletion free?' is operationally unsuitable for multi-petabyte estates.

Fragmentation introduces another limit to simplistic capacity metrics. Reclaimed bytes are useful only if the system can allocate them efficiently without disproportionate metadata or relocation cost. Copy-on-write systems, snapshots, and sub-block packing can create layouts in which physical free space is fragmented or partially occupied. Defragmentation or storage-gardening mechanisms may therefore be part of capacity optimization rather than merely performance maintenance [10].

The proposed framework has several implications for implementation. First, storage pools should expose high-watermark alerts based on physical allocation, with lower warning thresholds when growth is bursty or capacity procurement is slow. Second, a reserved emergency margin should not be consumed by ordinary oversubscription. Third, reclamation success should be verified by comparing expected eligible bytes with actual physical reduction. Fourth, snapshot and clone retention should be visible in the same capacity dashboard because retained references are a common explanation for apparently ineffective reclamation. Fifth, service-level policies should define both a maximum acceptable reclamation lag and a maximum foreground-performance impact.

This review has limitations. The available literature is heterogeneous and includes primary storage, backup systems, hypervisor storage, vendor implementations, and deduplicated arrays. Few studies report standardized thin-provisioning efficiency metrics across petabyte-scale production systems, precluding formal meta-analysis. Some implementation details are architecture-specific, particularly allocation granularity and discard behavior. Accordingly, the numerical formulas in this paper should be treated as operational definitions and planning approximations rather than universal performance laws. Nevertheless, the mechanisms are consistent across storage layers and provide a defensible basis for capacity-control design.

5. Conclusion

Capacity reclamation is the mechanism that converts thin provisioning from deferred allocation into sustained physical efficiency. Thin provisioning can remove reservation waste, but

deleted capacity remains stranded unless release semantics propagate from the host to the underlying storage and unless shared references, snapshots, and allocation granularity permit physical deallocation. At enterprise scale, the appropriate optimization target is therefore not maximum logical oversubscription; it is maximum safe physical utilization with bounded reclamation lag.

A robust design measures logical and physical capacity separately, estimates reclaimable space, monitors net physical growth, protects reserve headroom, and schedules reclamation as a controlled background service. Deduplication, snapshots, clones, and fragmentation should be incorporated into the same accounting model because each changes the relationship between logical deletion and physical release. The resulting closed-loop approach provides a more reliable basis for thin-pool efficiency, capacity planning, and avoidance of sudden pool exhaustion in large-scale enterprise storage systems.

Ethical considerations

Ethical approval was not required because this study synthesized previously published technical literature and did not involve human participants, identifiable personal data, or experimental intervention.

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Tables

Table 1. Included studies and their contribution to thin-provisioning and capacity-reclamation efficiency.

Study	Venue/year	Storage context	Method or mechanism	Relevance to synthesis
Lillibridge et al. [5]	FAST, 2009	Large-scale inline deduplication	Sparse indexing with sampling/locality	Reduced index-memory demand while preserving scalable deduplication; informs data-reduction-adjusted capacity planning.
Soundararajan et al. [12]	FAST, 2009	Virtual storage for database workloads	Online multi-resource allocation	Demonstrated that shared virtual storage requires dynamic resource control; supports treating reclamation as managed background work.
Gulati et al. [18]	FAST, 2009	Distributed access to shared arrays	Proportional resource allocation	Showed need for workload isolation in shared storage, relevant when reclamation competes with foreground I/O.
Debnath et al. [6]	USENIX ATC, 2010	Inline deduplication metadata	Flash-assisted chunk index	Reported 7-60× throughput improvement over disk-index baselines in tested enterprise backup datasets.
Meyer & Bolosky [4]	FAST, 2011	Practical deduplication	857 desktop systems; live and backup data	Quantified realistic deduplication savings and the incremental benefit of block-level approaches.
Dong et al. [7]	FAST, 2011	Deduplication clusters	Content-aware routing	Examined deduplication effectiveness and storage-utilization balance across multi-node clusters.
Wallace et al. [13]	FAST, 2012	Production backup storage	>10,000 systems; detailed traces	Demonstrated high churn and redundancy characteristics that materially affect physical-capacity behavior.
Strzelczak et al. [8]	FAST, 2013	Global deduplicated storage	Concurrent deletion algorithm	Showed that physical reclamation requires reference-safe deletion and resource-bounded background processing.
Wang et al. [16]	Computer Engineering, 2014	Thin-provisioning implementation	Integrated file-system/block/iSCSI design	Reported >97% reclamation percentage in the evaluated system, with performance effects dependent on implementation.
Harnik et al. [9]	FAST, 2019	Deduplicated all-flash storage	Sketch-based capacity estimation	Provided scalable estimates of reclaimable and attributable capacity, enabling deletion and placement decisions.
Kesavan et al. [10]	FAST, 2019	Enterprise copy-on-write file system	Virtualization-assisted defragmentation	Showed that free-space and intra-block fragmentation can waste capacity and that block relocation can improve efficiency.

Table 2. Core capacity metrics for thin-provisioned enterprise storage.

Metric	Expression	Interpretation	Operational use
Oversubscription ratio	$O = L_p / P_{pool}$	Logical capacity advertised relative to usable physical pool.	Capacity governance; not a safety metric by itself.
Physical utilization	$U_p = P_{alloc} / P_{pool}$	Fraction of physical pool currently allocated.	Primary high-watermark measure.
Dead-space fraction	$F_{dead} = P_{dead} / P_{alloc}$	Allocated capacity no longer required by host but not yet physically free.	Detects ineffective reclamation.
Reclamation efficiency	$\eta_r = R / P_{dead,eligible}$	Fraction of eligible dead space returned during a reclamation interval.	Compares expected vs. realized reclamation.
Reclamation lag	$t_{reclaim} - t_{free}$	Delay from host release to physical availability.	Controls temporary stranded capacity.
Data-reduction ratio	DR = logical referenced bytes / physical unique bytes	Effect of deduplication/compression on physical growth.	Required for safe thin-pool forecasting.
Reserve headroom	$H = P_{pool} - P_{alloc}$	Immediately available physical capacity.	Buffer against bursts and reclamation failure.
Approx. time to exhaustion	$T_{exhaust} \approx H / (G - C_r)$, if $G > C_r$	Planning horizon under net physical growth.	Sets alert threshold and intervention urgency.

Table 3. Common causes of stranded capacity and corresponding controls.

Observed condition	Typical symptom	Likely mechanism	Control
Host deletes not propagated	Host free space increases; array allocation unchanged	Discard/UNMAP disabled or unsupported in one layer	Validate end-to-end release path; run controlled reclaim.
Snapshots or clones retain blocks	Deletion yields little physical free space	Historical references remain active	Expose snapshot-retained bytes; align retention with capacity policy.
Global deduplication sharing	Large logical deletion produces modest physical release	Chunks remain referenced by other objects	Use attributable/reclaimable capacity estimates rather than logical size.
Fine-grained scattered frees	Persistent dead space despite trim	Array allocation unit larger than freed ranges	Coalesce/batch releases; periodic reclaim; consider relocation.
Reclamation competes with production I/O	Latency or queue depth rises during trim/GC	Background metadata and data movement consume resources	Rate-limit, schedule, and monitor reclamation.
Thin pool approaches exhaustion rapidly	Short alert-to-full interval	Burst growth or reduced data-reduction ratio	Maintain emergency reserve and growth-aware thresholds.
Fragmented free space	Adequate free bytes but inefficient allocation/performance	Copy-on-write, snapshots, sub-block holes	Defragment/storage-garden where supported; monitor allocatable extents.
Telemetry disagreement across	Guest, datastore and array report	Different allocation semantics	Reconcile layer-specific counters; alert

Observed condition	Typical symptom	Likely mechanism	Control
layers	materially different free capacity	and delayed propagation	on unexplained divergence.

Table 4. Deployment framework by enterprise storage workload class.

Workload class	Thin-provisioning value	Data reduction	Dominant risk	Recommended capacity-control pattern
Latency-sensitive databases	Moderate	Low to moderate	Short snapshots; predictable churn	Batch reclamation off-peak; conservative headroom; validate latency impact.
Virtual-machine / VDI pools	High	Often high	Frequent create/delete; many thin virtual disks	Enable end-to-end UNMAP; monitor guest-to-array divergence; exploit dedup safely.
Analytics / temporary workspaces	High	Workload dependent	Large transient datasets	Automate lifecycle deletion; reclaim after job windows; preserve burst reserve.
Backup / secondary storage	Moderate to high	High for repeated backups	High churn, dedup ownership complexity	Use reference-safe deletion; capacity-attribution estimates; rate-limited GC.
Snapshot-heavy primary storage	Moderate	Moderate	Blocks retained beyond active namespace	Track snapshot-retained capacity separately; expire snapshots before expecting release.
All-flash shared arrays	High	Compression/dedup common	Fast media but metadata/GC still finite	Use thin provisioning with telemetry-driven reclamation and flash-aware background limits.

Figures

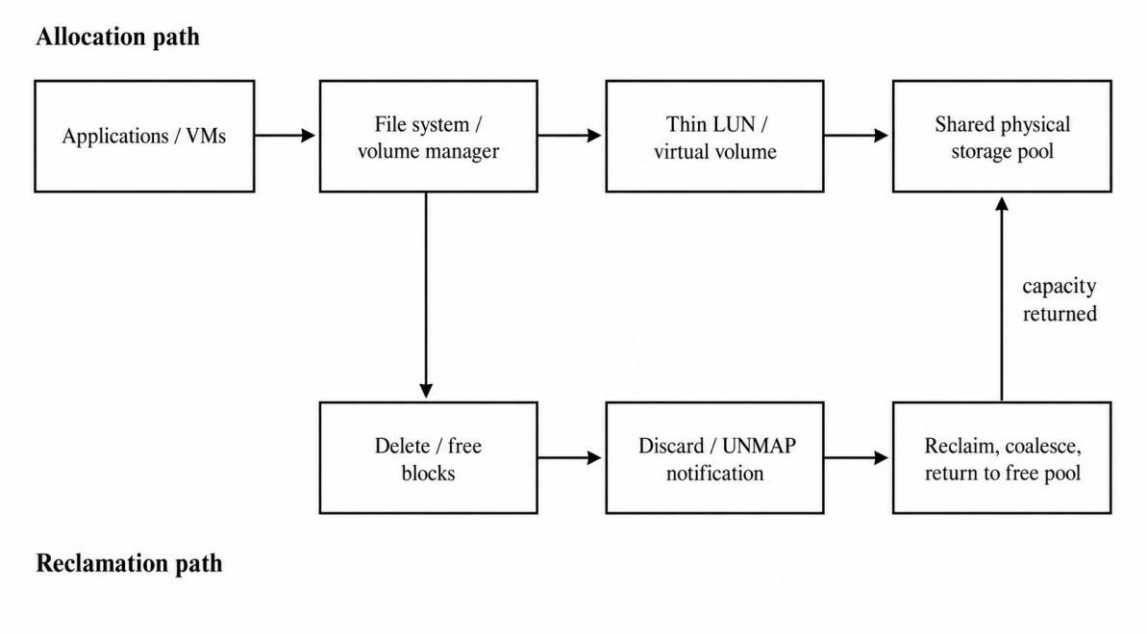

Figure 1. End-to-end allocation and reclamation path in a thin-provisioned enterprise storage stack. Physical capacity is allocated on write, whereas reclamation requires a reverse notification path from host deletion through discard/UNMAP to array deallocation.

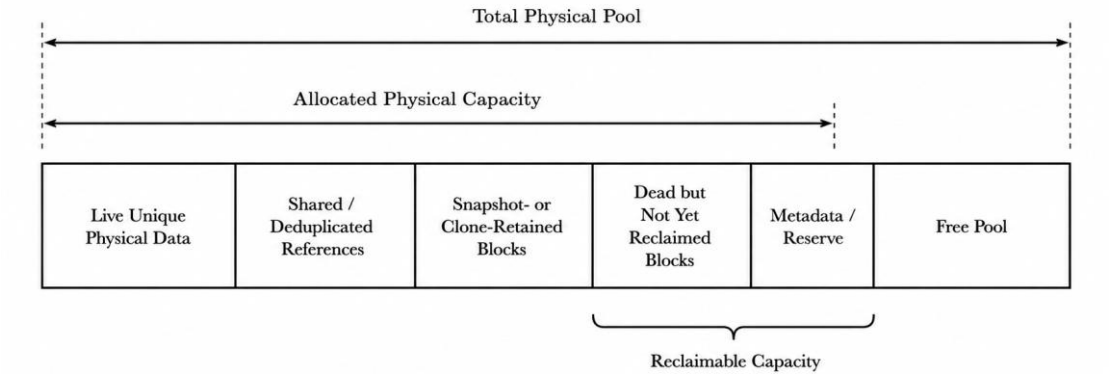

Figure 2. Capacity-state model for a shared thin-provisioned pool. Logical deletion does not necessarily produce physical free space because blocks may be shared, snapshot-retained, or dead but not yet reclaimed.

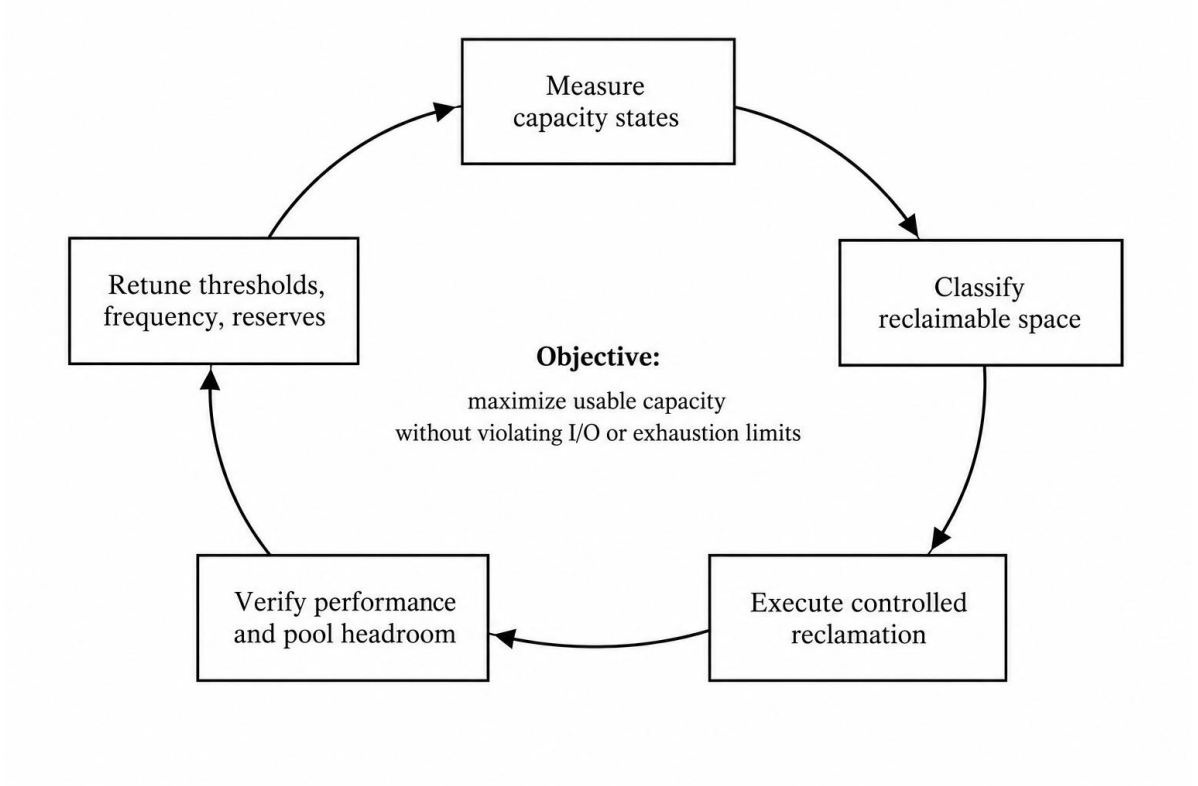

Figure 3. Closed-loop optimization model for thin-provisioning efficiency. Capacity measurements drive classification and controlled reclamation; physical response and performance impact are then verified before thresholds and schedules are retuned.