System-wide Memory Management for Linux Embedded Systems

Revision 1.0

Presented by:
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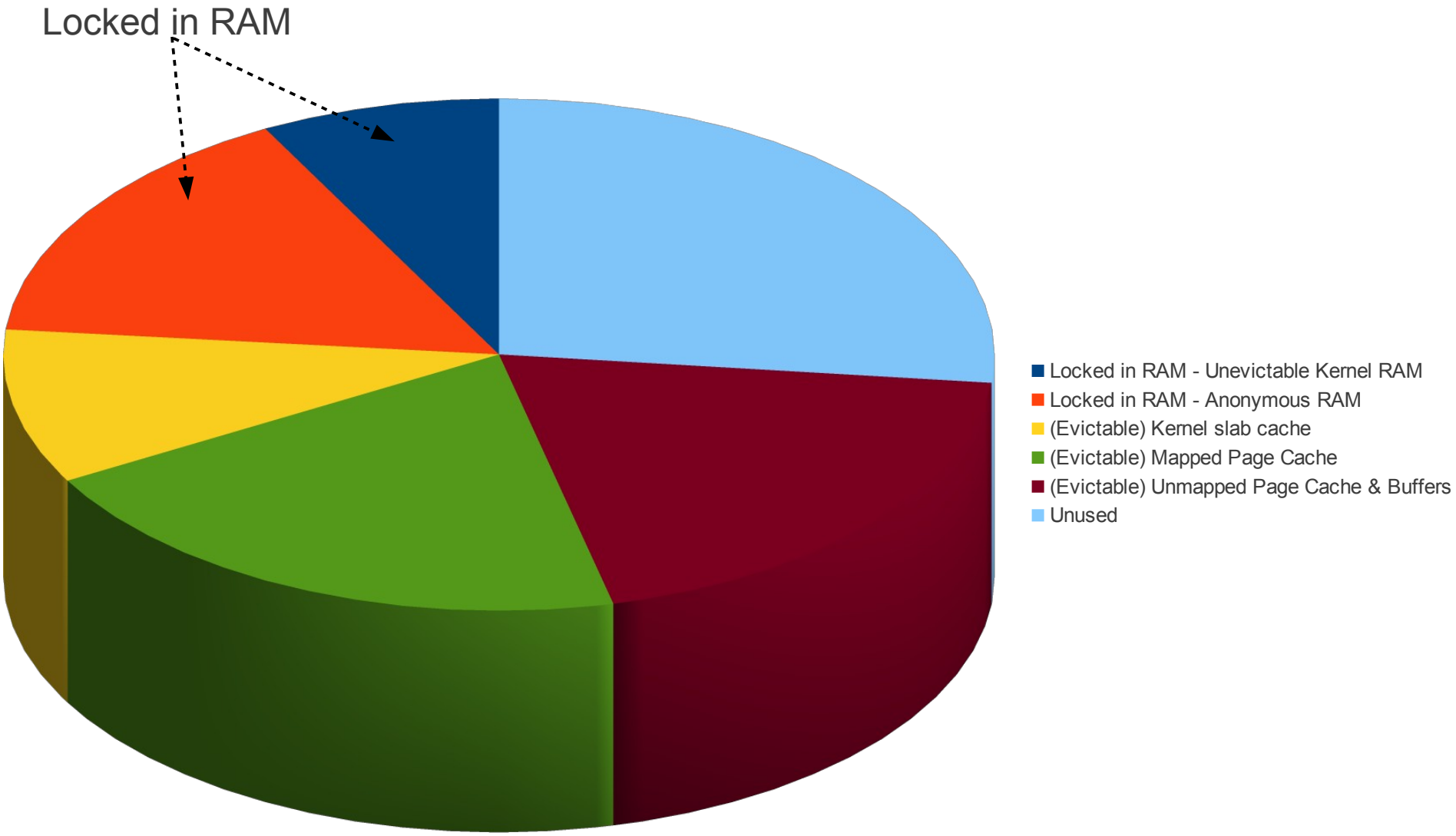
Lexmark International
at:
Embedded Linux Conference
February, 2013

Agenda

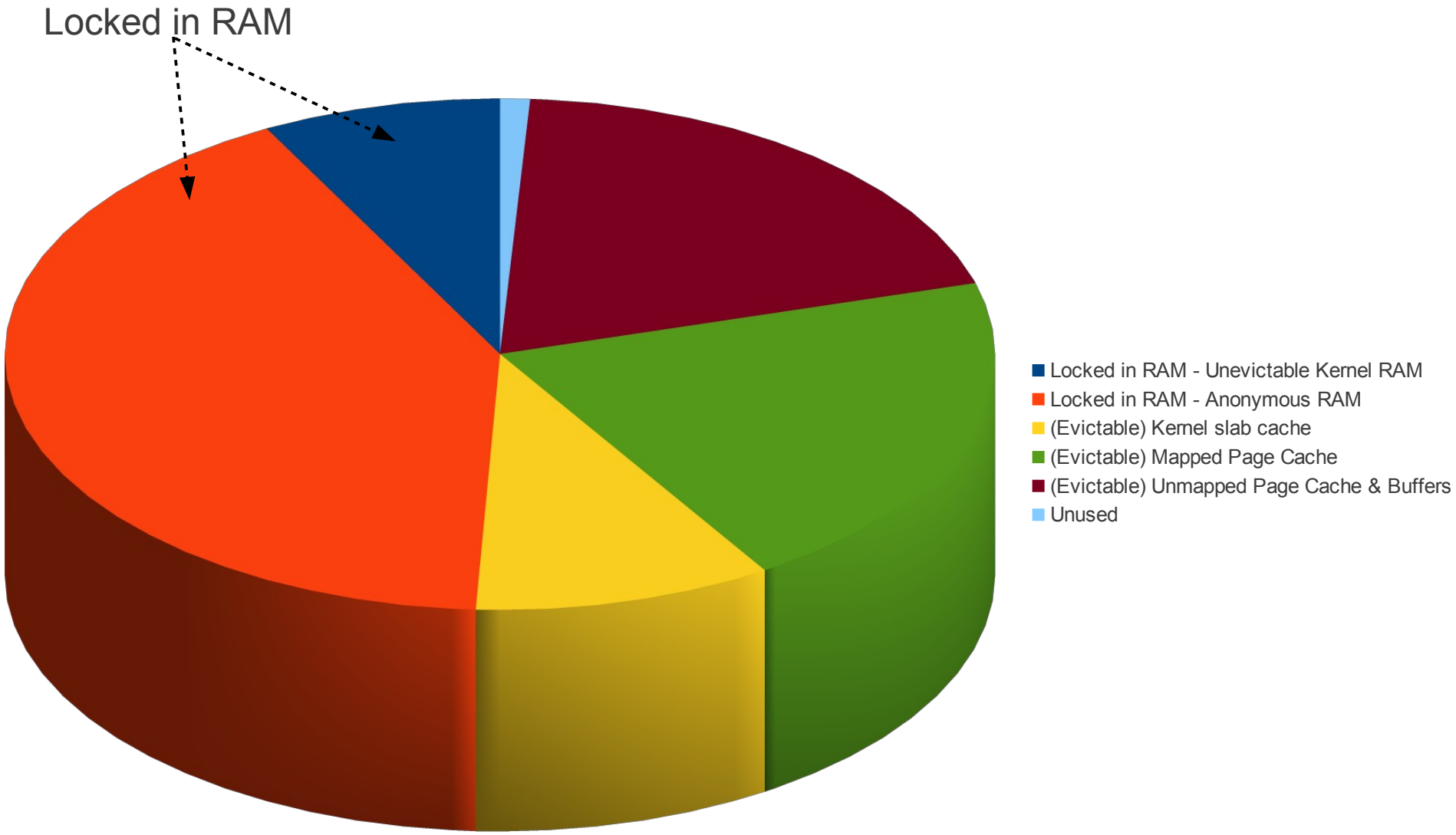
- The Problem:
  - How Linux kernel manages memory
  - Memory challenges in Lexmark devices
  - Limitations of glibc malloc for embedded
- Our Solution:
  - membroker service
  - ANR malloc & gmalloc
  - track_fs
  - Configuration
- Q&A

We're publishing these as Free (Libre) Software!

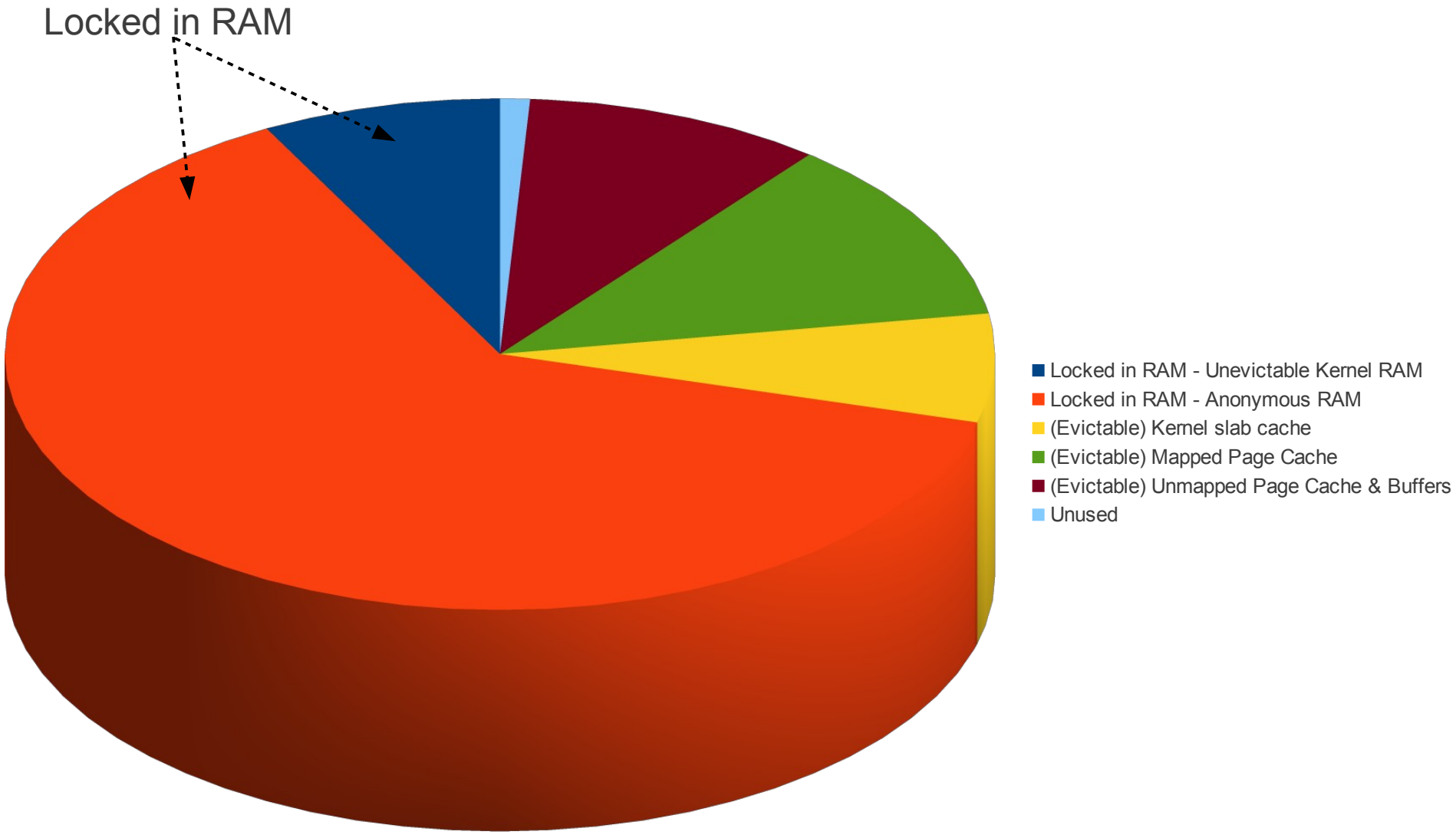
Memory Use – No memory pressure



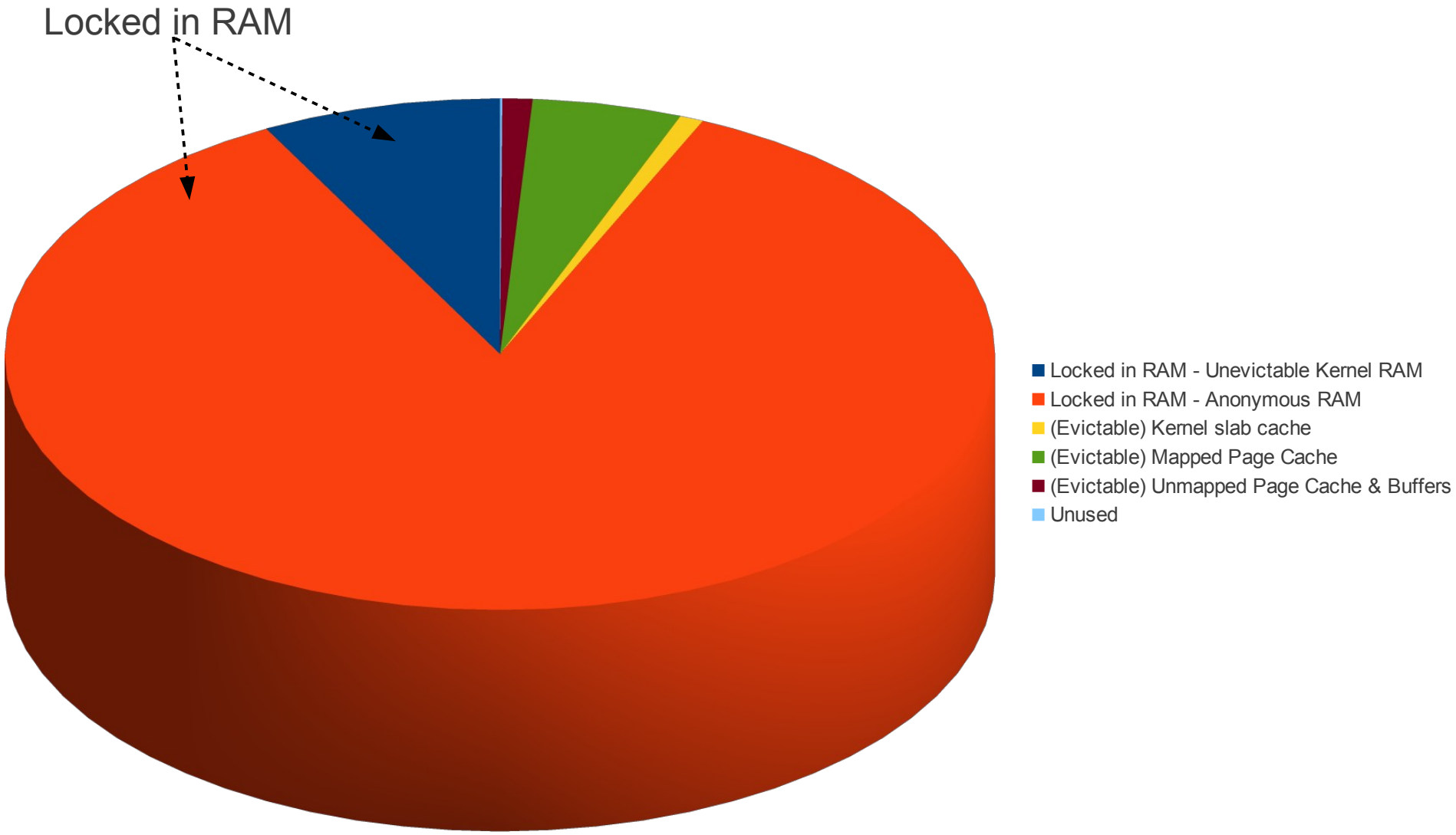
Memory Use – Light Pressure



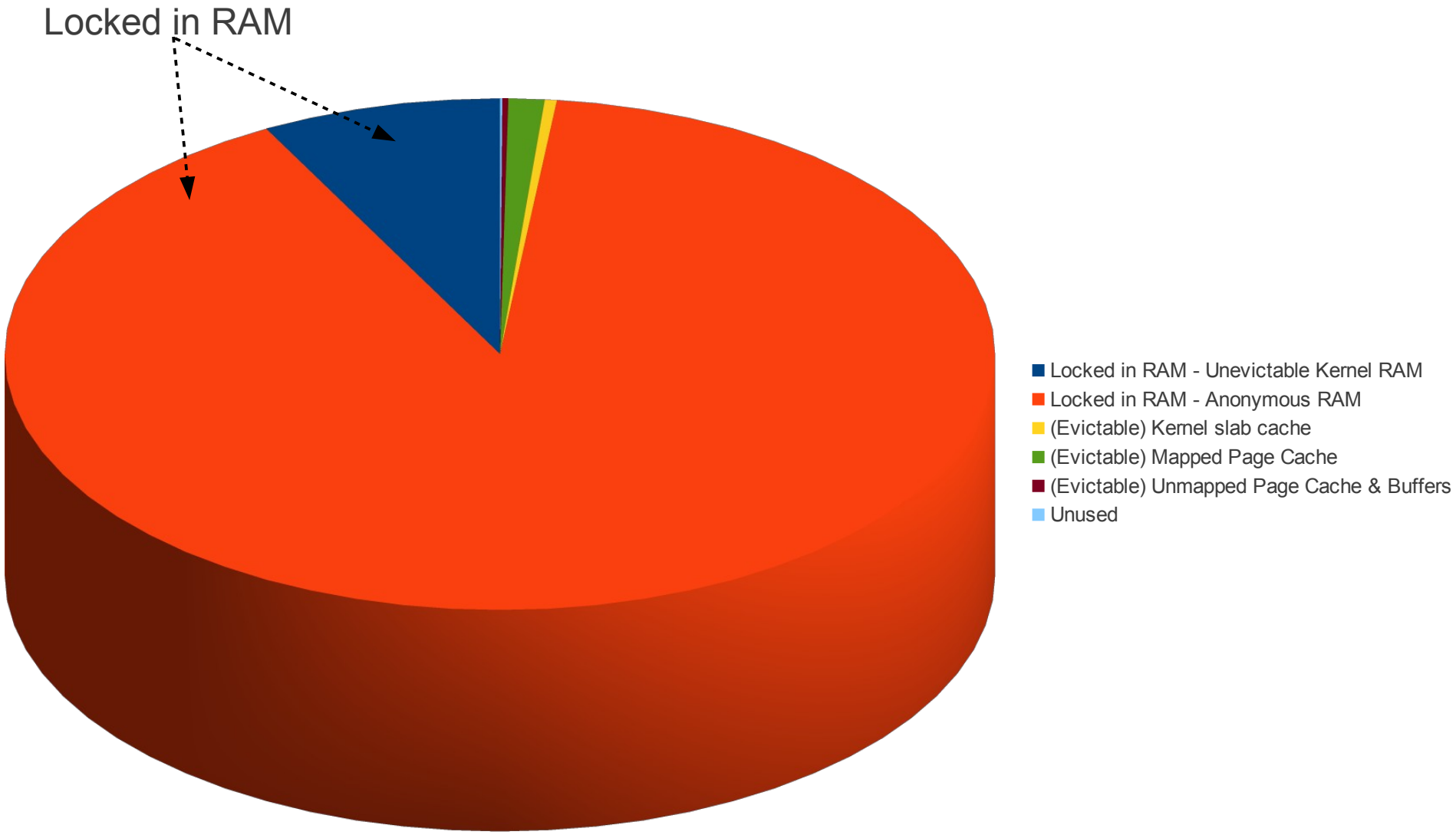
Memory Use – Anonymous Growing



Heavy Pressure – Thrashing



Extreme Pressure – Crash!



Linux without swap

- The ramp-up from "memory pressure" to "hard crash" is steep.
- out_of_memory killer - Kills an arbitrary process
  - There are /proc tunables to influence who OOM killer chooses
  - For embedded, ANY invocation of OOM killer could be fatal

Anonymous Memory

- **Locked into RAM** (unless you have swap)
- Are the majority, in my experience
  - Often 80+%
- Workstations use swap to provide virtually endless supply of anonymous pages.
- Developers get lazy - no one expects malloc() to fail

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My problem space:

My problem space

- A few “large” processes for core functionality:
  - Many threads.
  - Some threads are REALTIME ~10ms deadlines
  - Non-RT threads use lots of anonymous RAM
  - “GiveBack”: A malloc() can stall while other subsystems free caches or wait for previous processing to complete.
  - All allocations can fail.
- Many smaller processes in system
  - Typically off-the-shelf, built on glibc malloc
  - Some are long-running services
  - Occasional spikes in memory usage.
  - Code usually cannot tolerate malloc returning NULL.

Themes

- Return pages to kernel when possible
- Coordinate anonymous memory between processes
- Avoid Real-time failures related to mmap_sem

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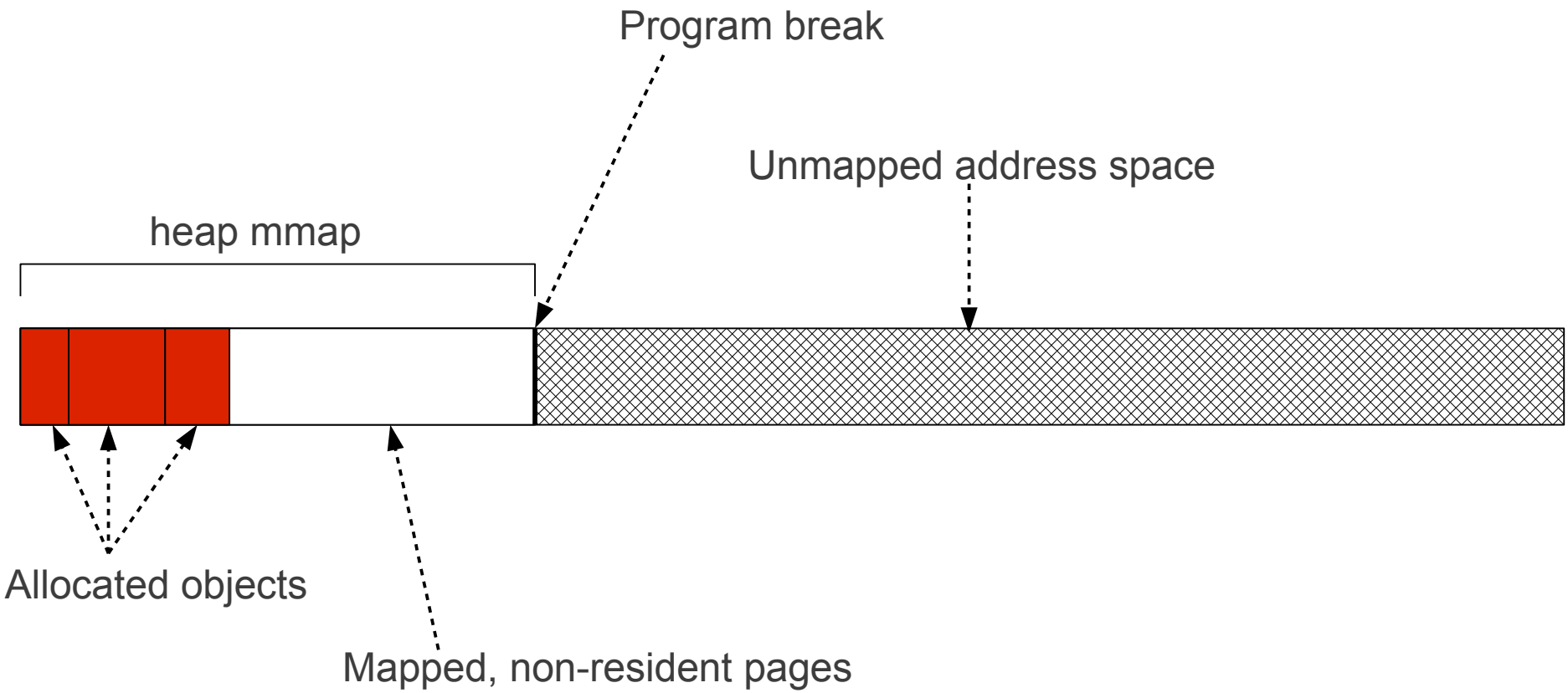
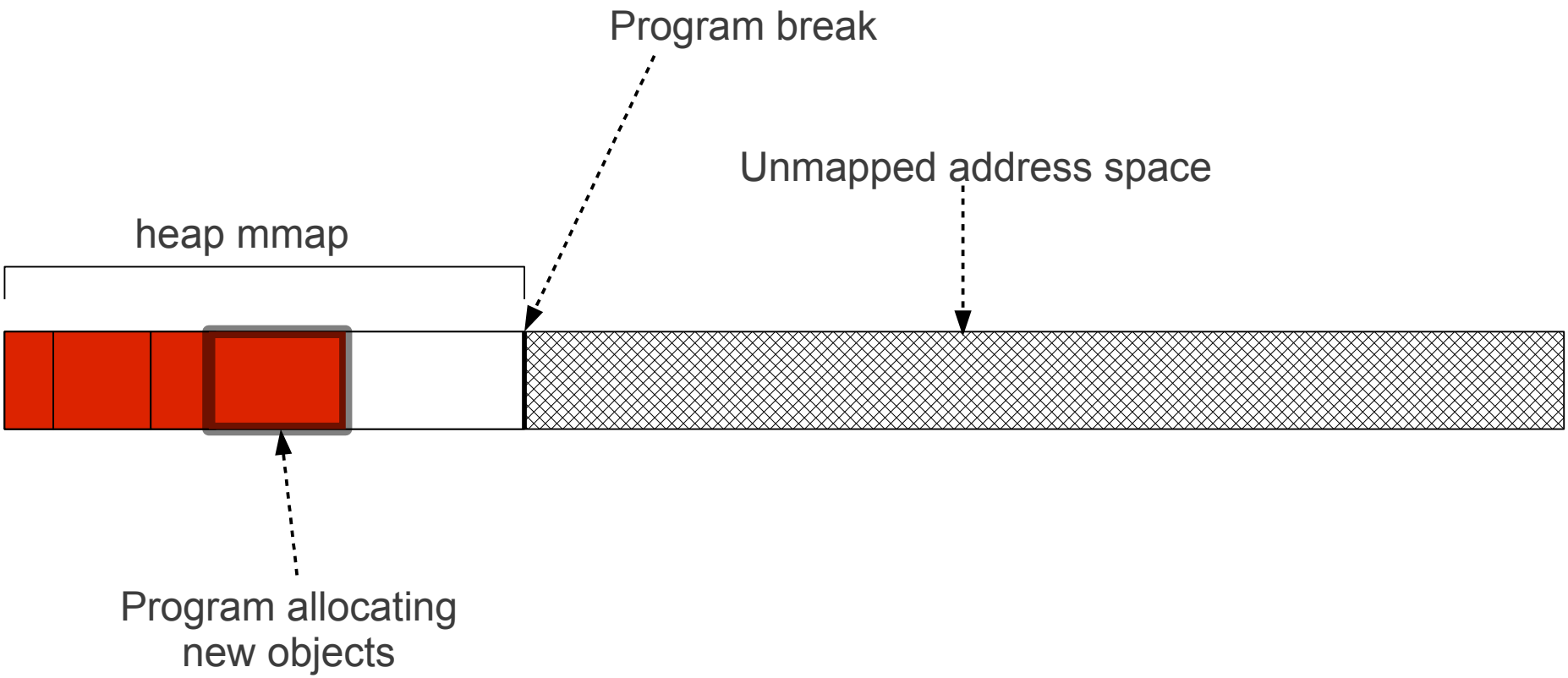
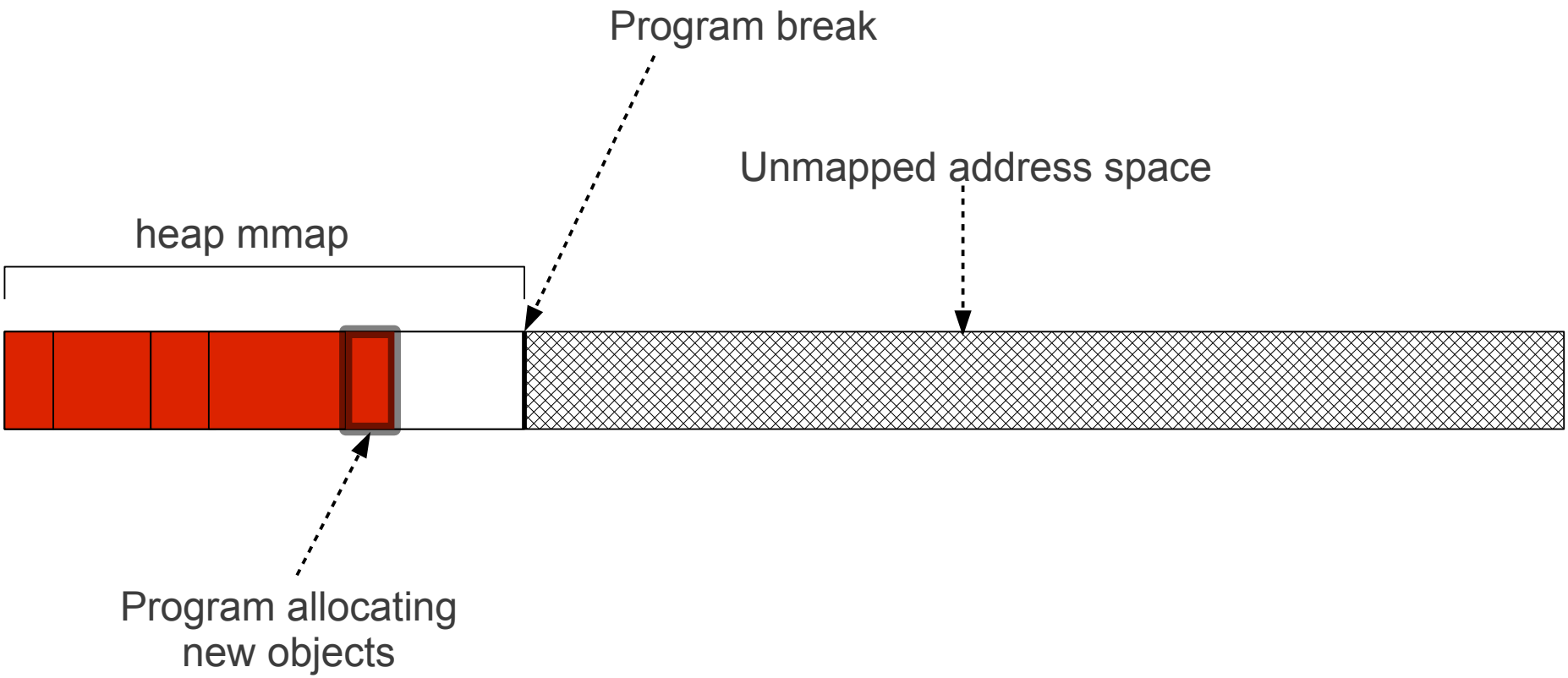
glibc heap


Program break
Unmapped address space
heap mmap
Allocated objects
Mapped, non-resident pages

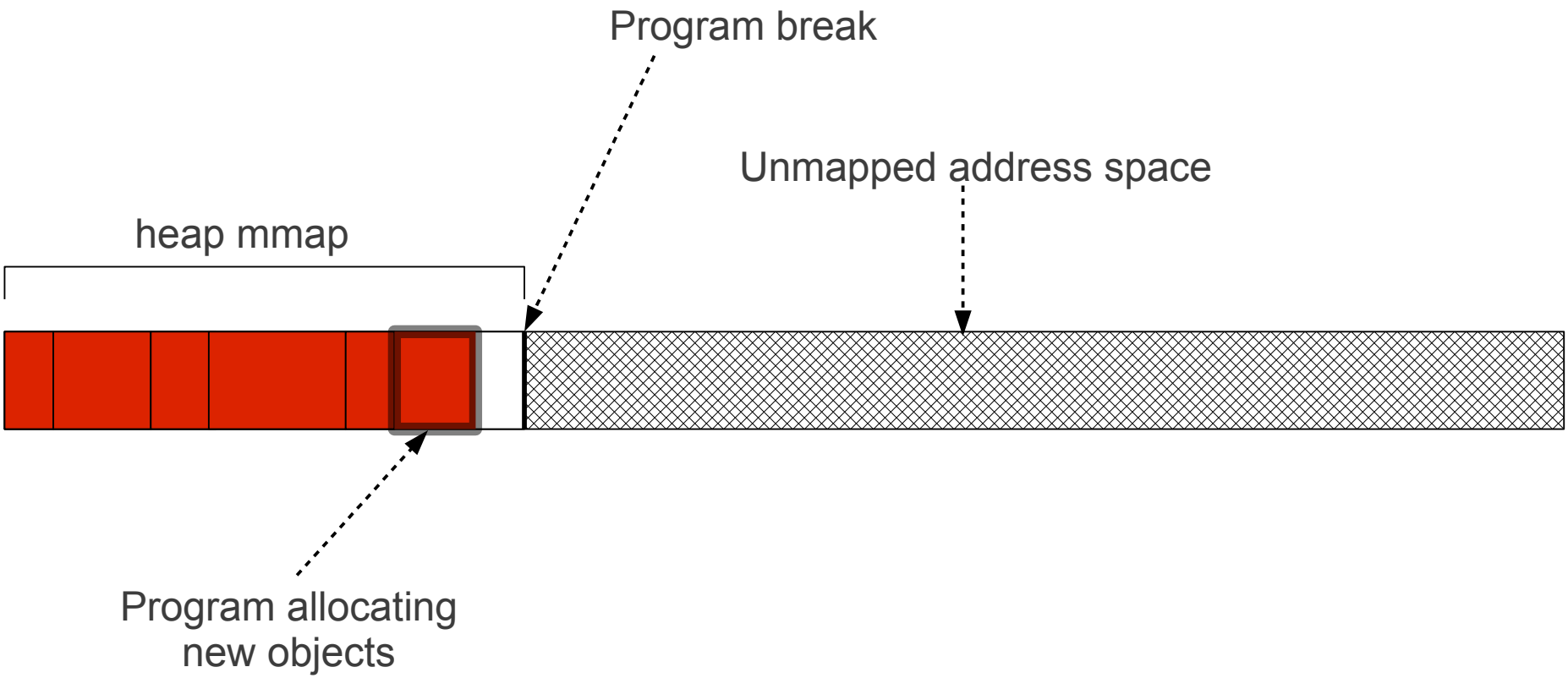
glibc heap - allocating



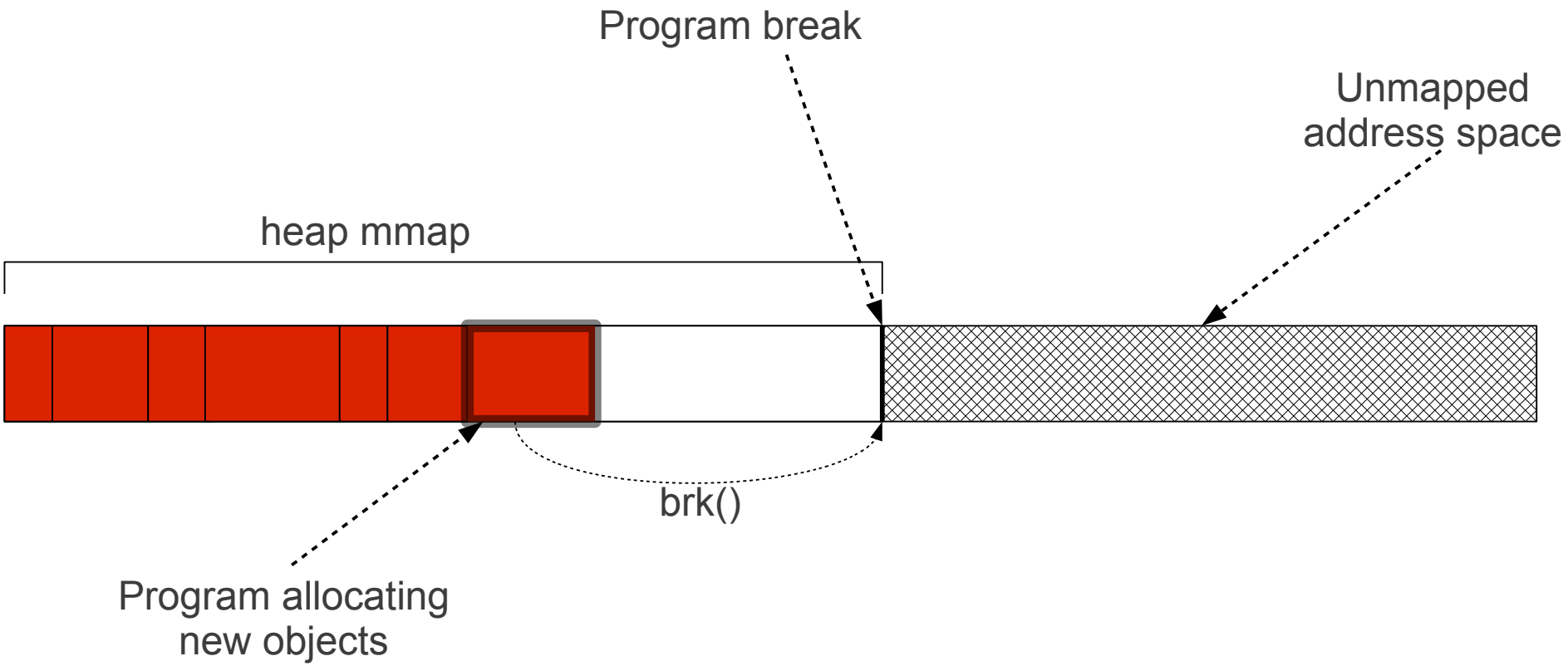
glibc heap – allocating



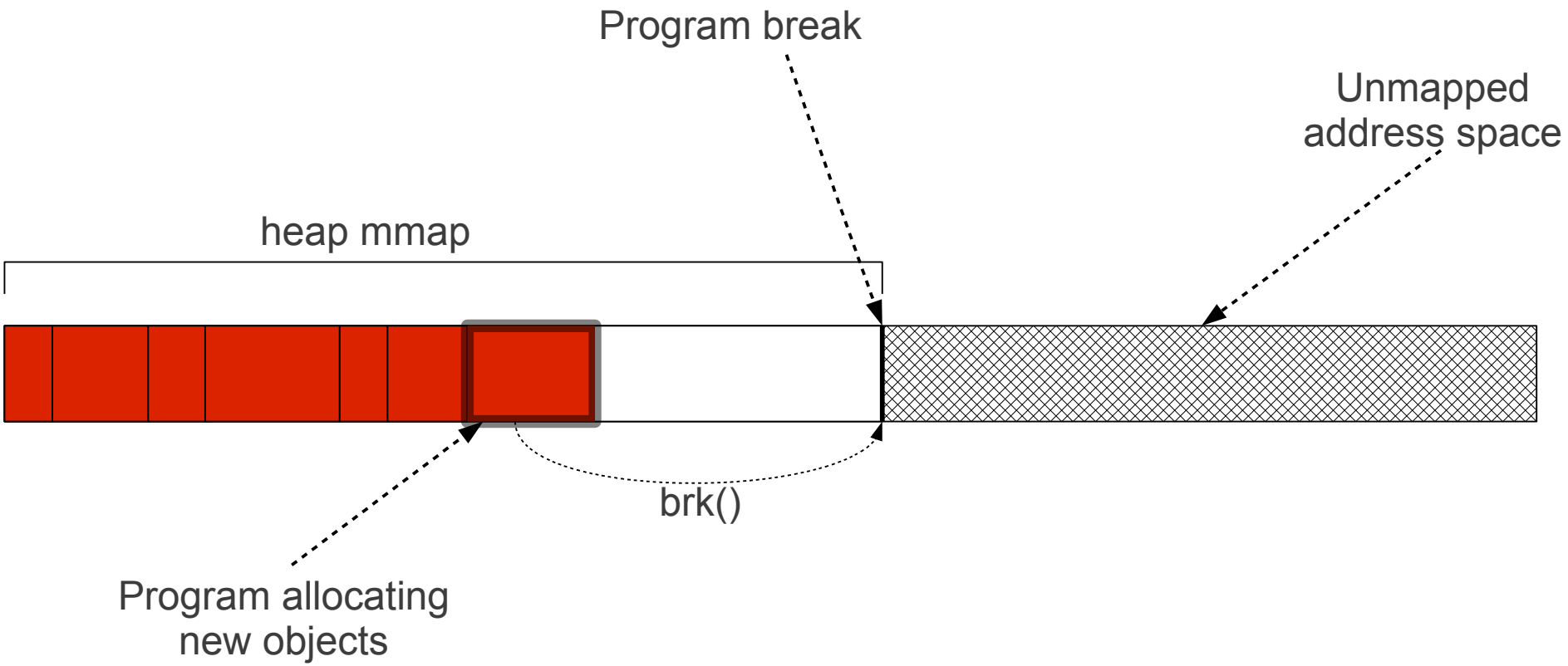
glibc heap – allocating



glibc heap – grows heap via brk()



brk() is bad for other realtime threads



brk() modifies a kernel vma.
down_write(current->mm->mmap_sem)
In-process Realtime threads fail deadlines!

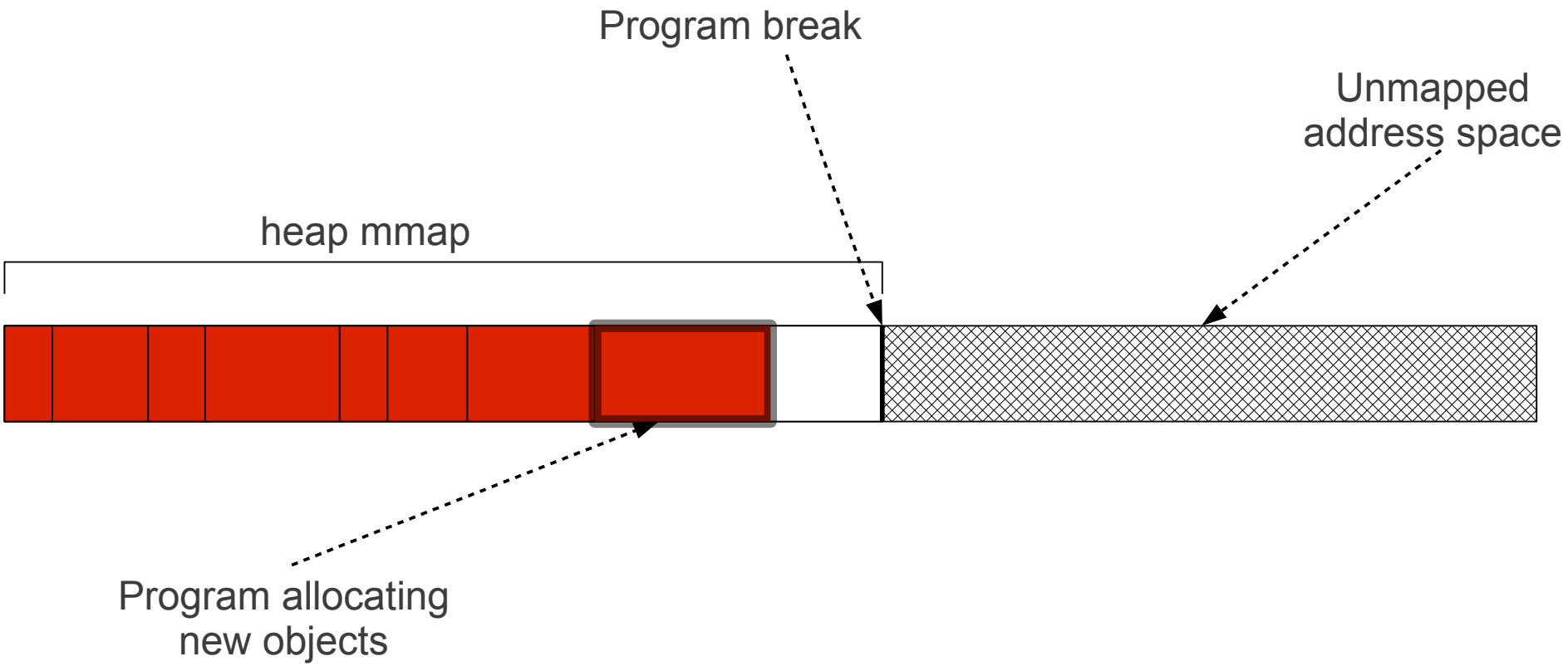
mmap_sem

- Is a read/write semaphore in the kernel
  - Can have many concurrent readers
  - Can have only one writer.
  - When writer has a lock, must be no readers
  - If a writer is waiting to acquire lock, new attempts to get read lock will block, even if reader is realtime.
- It is per thread group (i.e. per-mm)
- **No priority inheritance –** causes priority inversion
- Need write-lock to modify process's mmap

mmap_sem (continued)

- Realtime threads often need read-lock
  - Minor page faults
  - do_cache_op()
  - get_user_pages()
  - copy_to_user – some implementations
  - signal delivery

glibc heap – allocating



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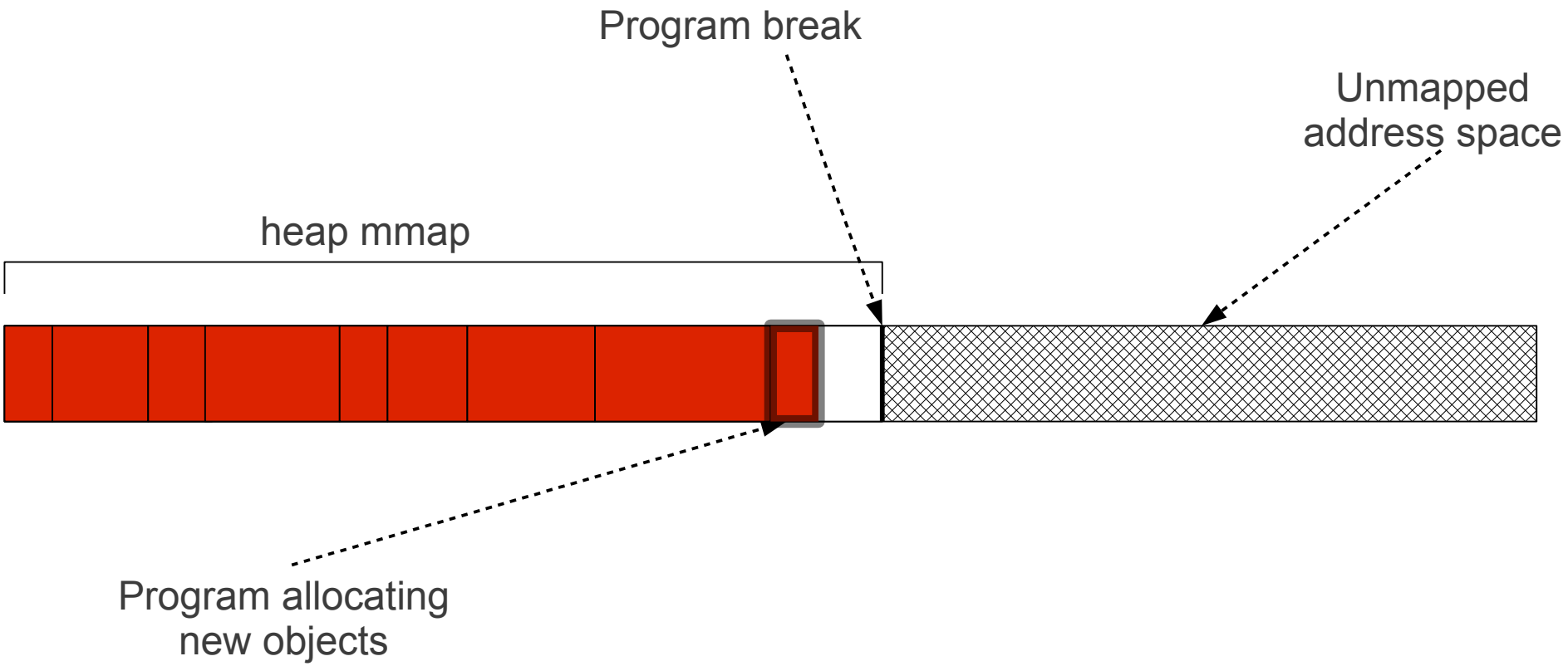
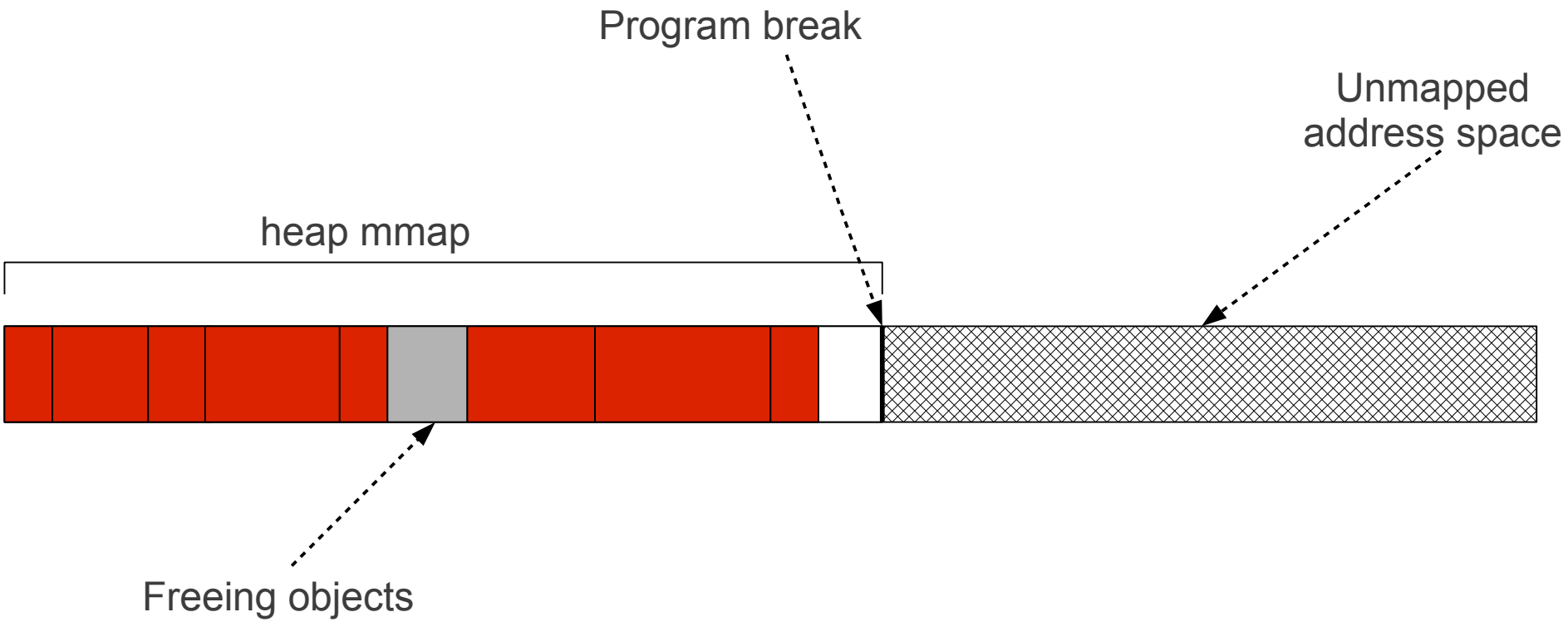


glibc heap – freeing



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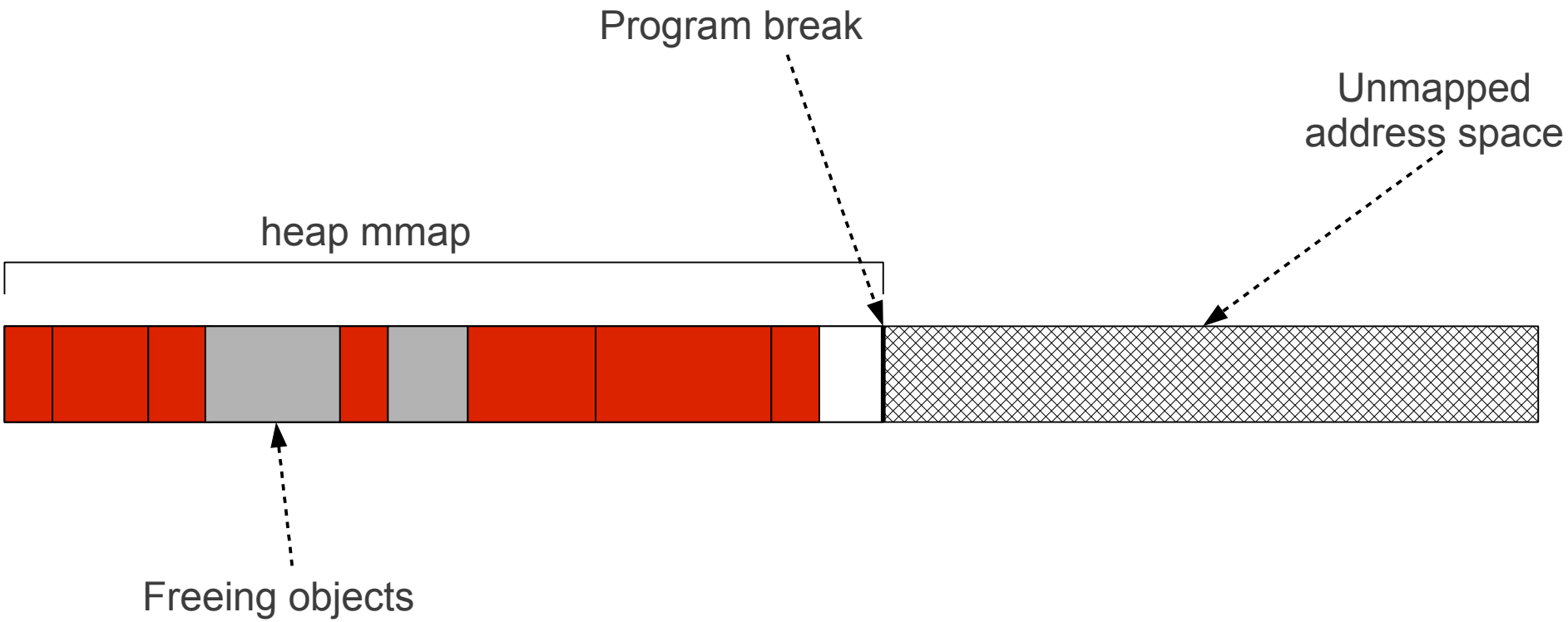

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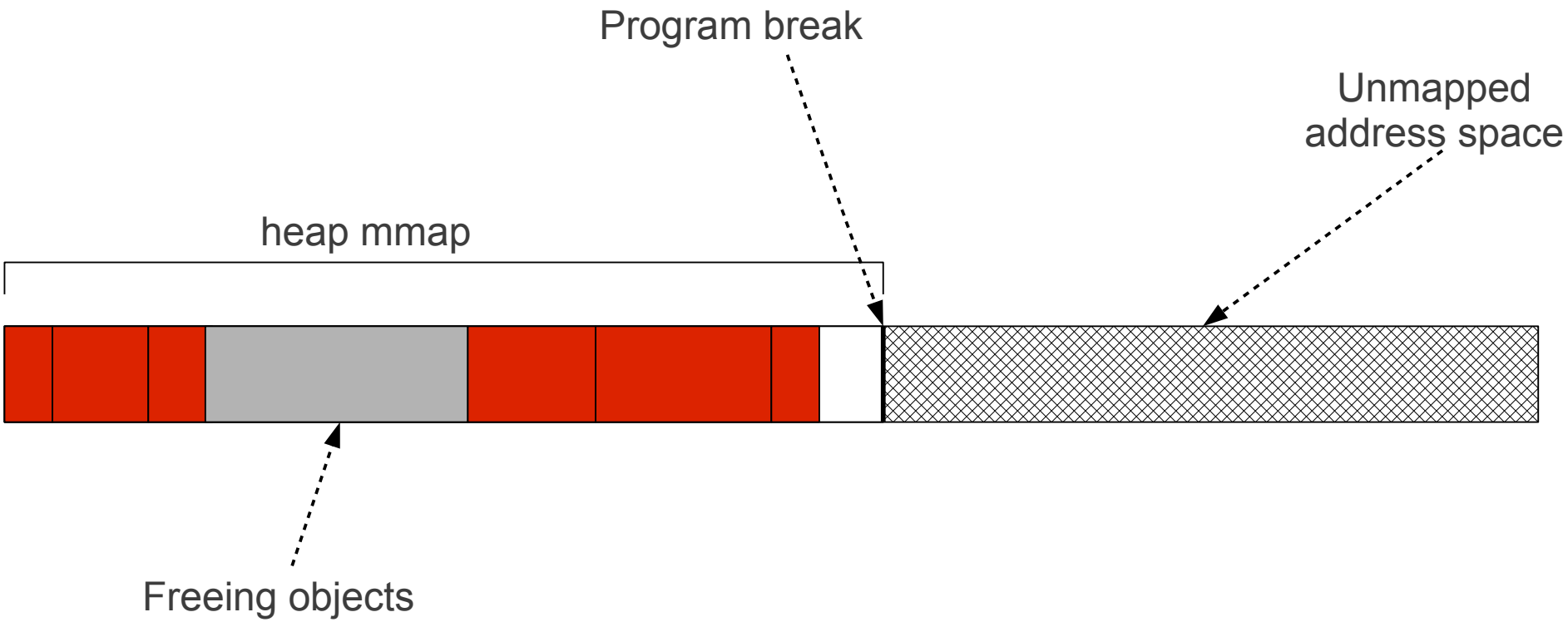

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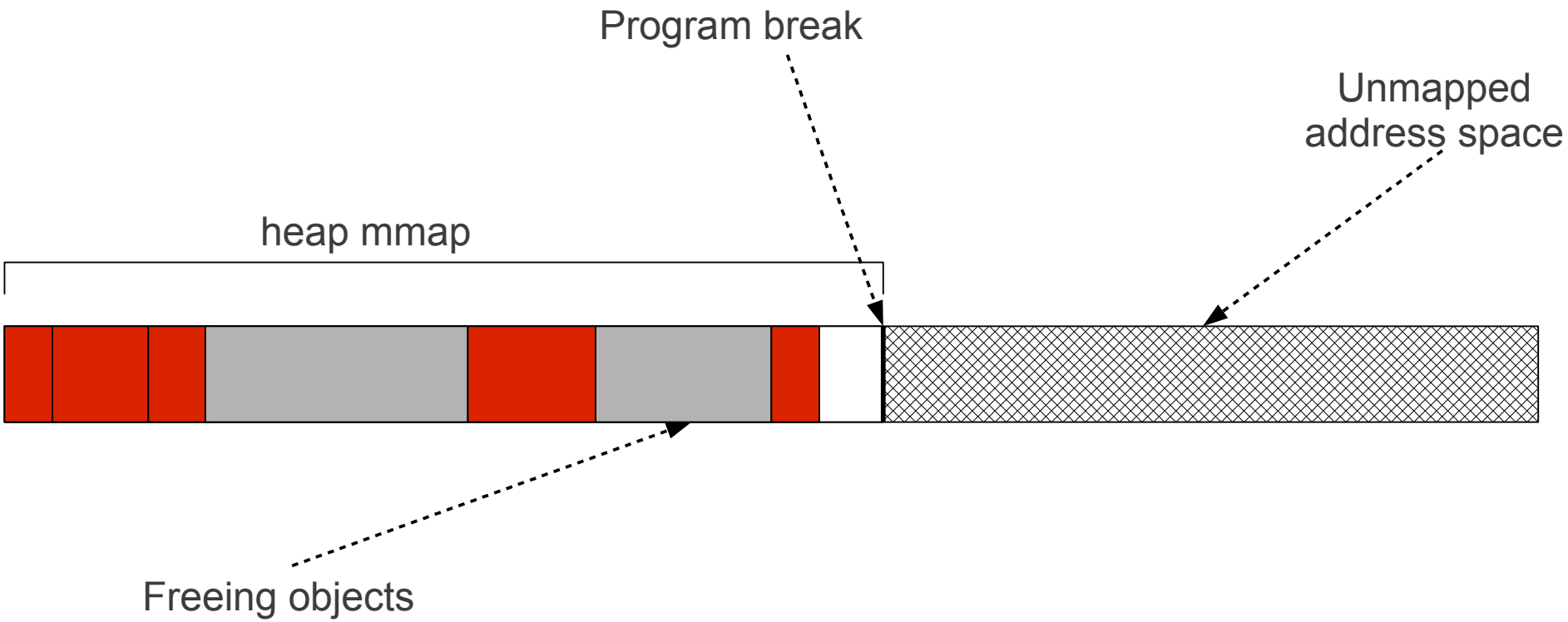

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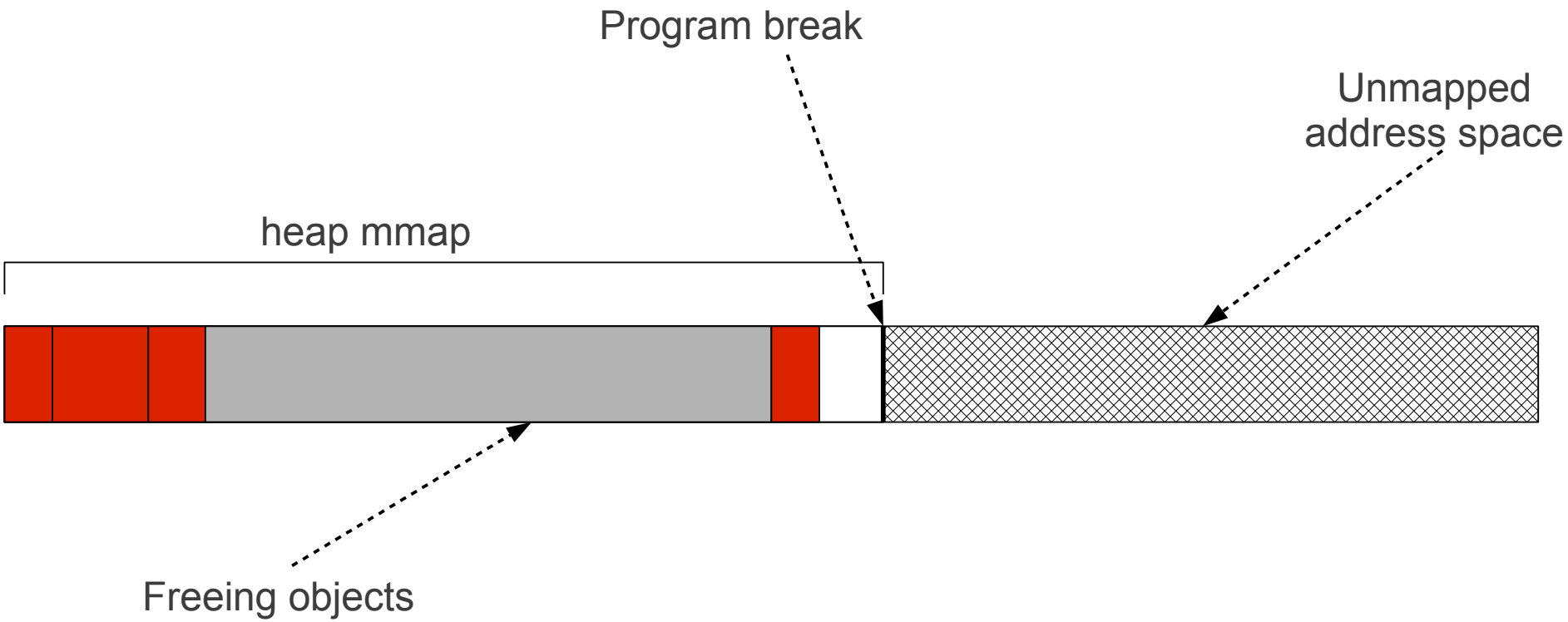

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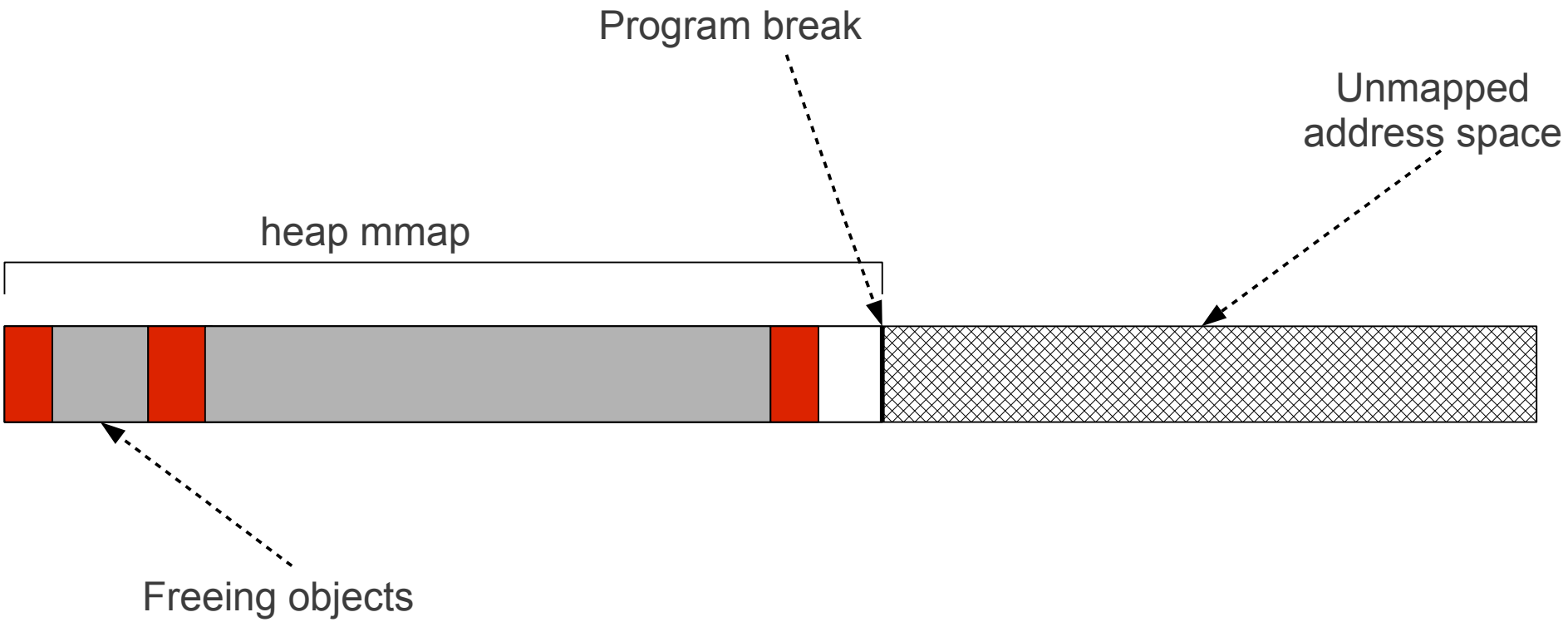
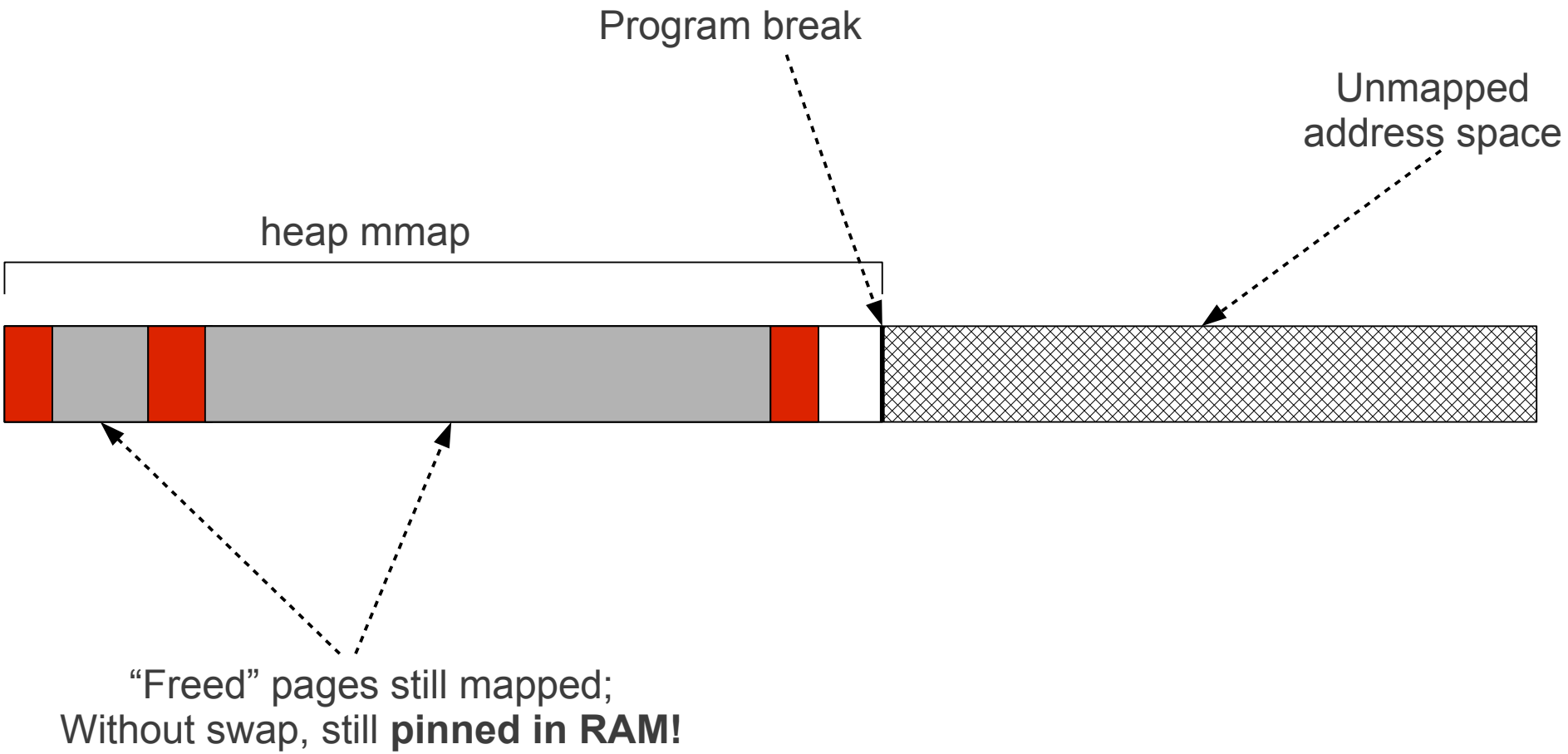
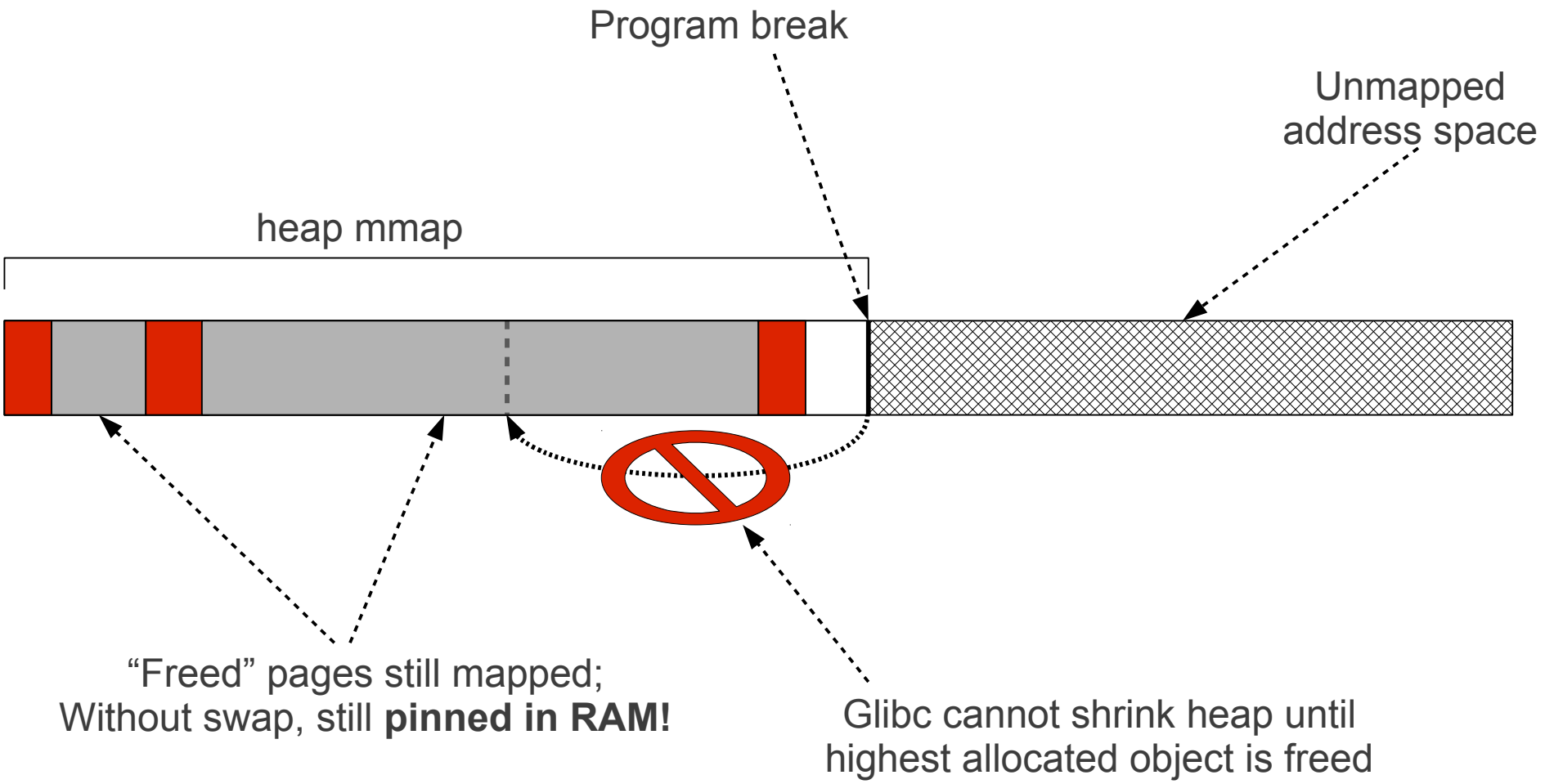


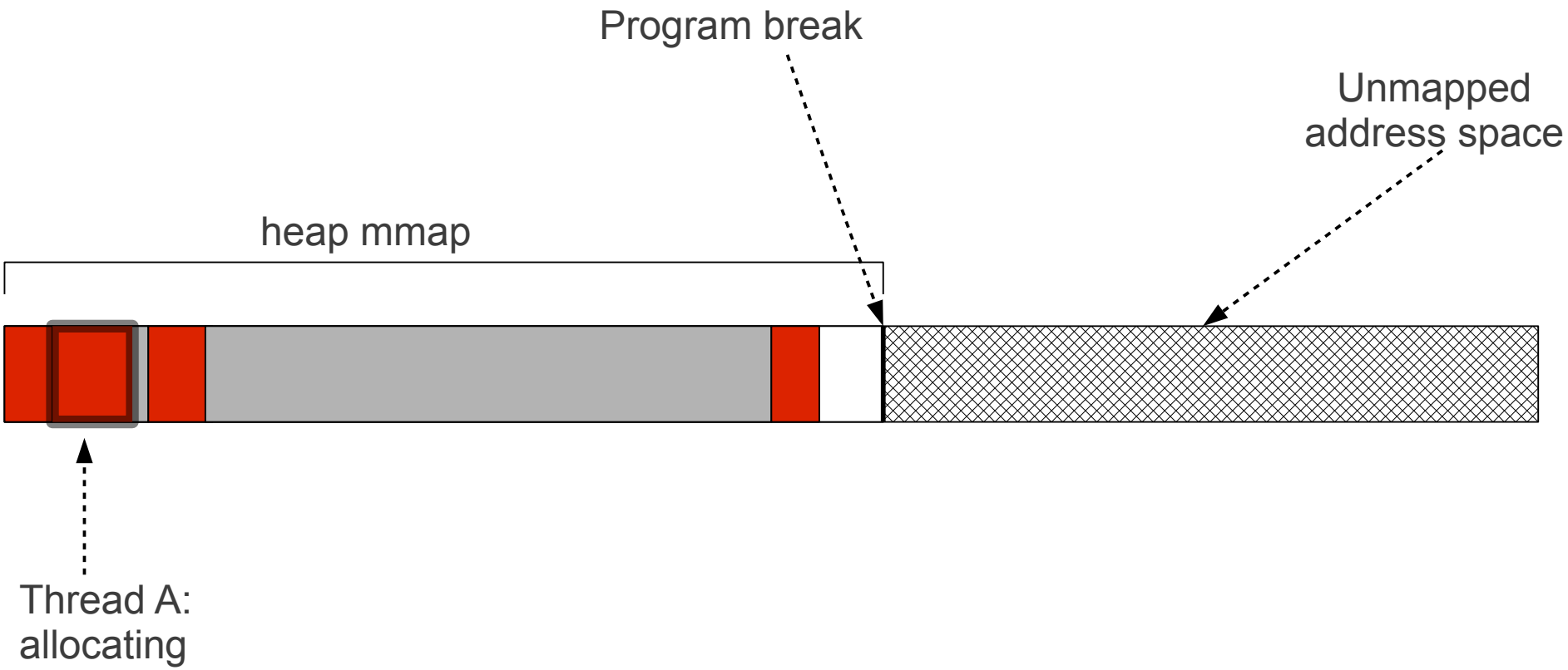
glibc heap – freed pages still pinned!



glibc heap – cannot shrink heap



glibc heap – concurrent allocation



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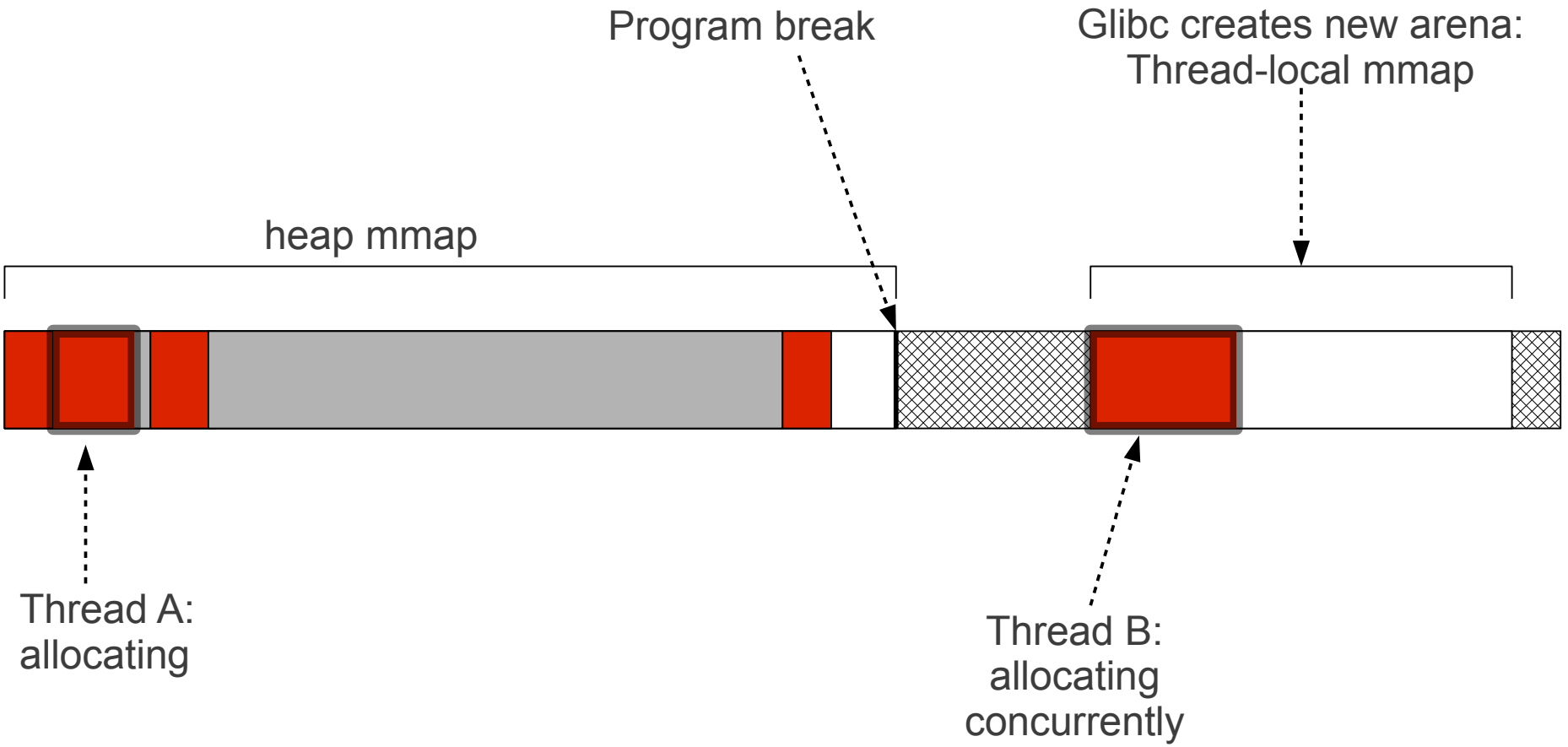
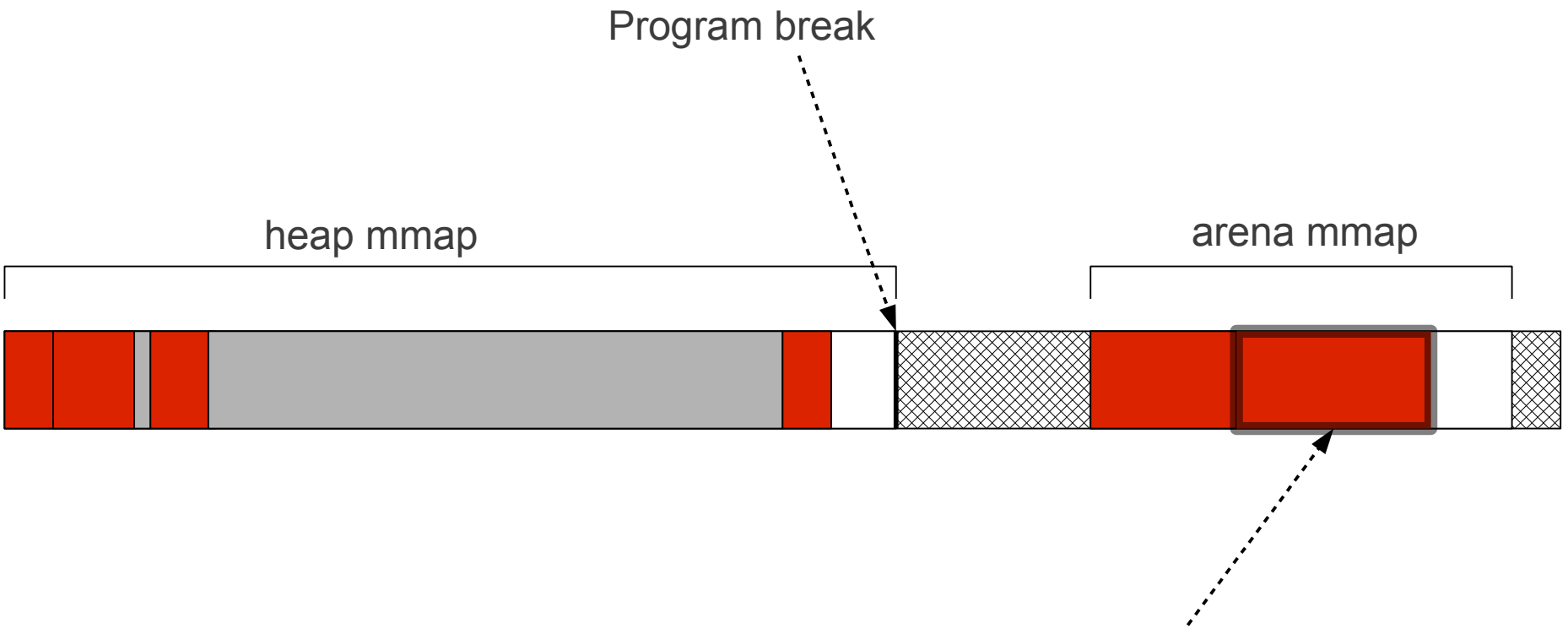


glibc heap – alloc from arena



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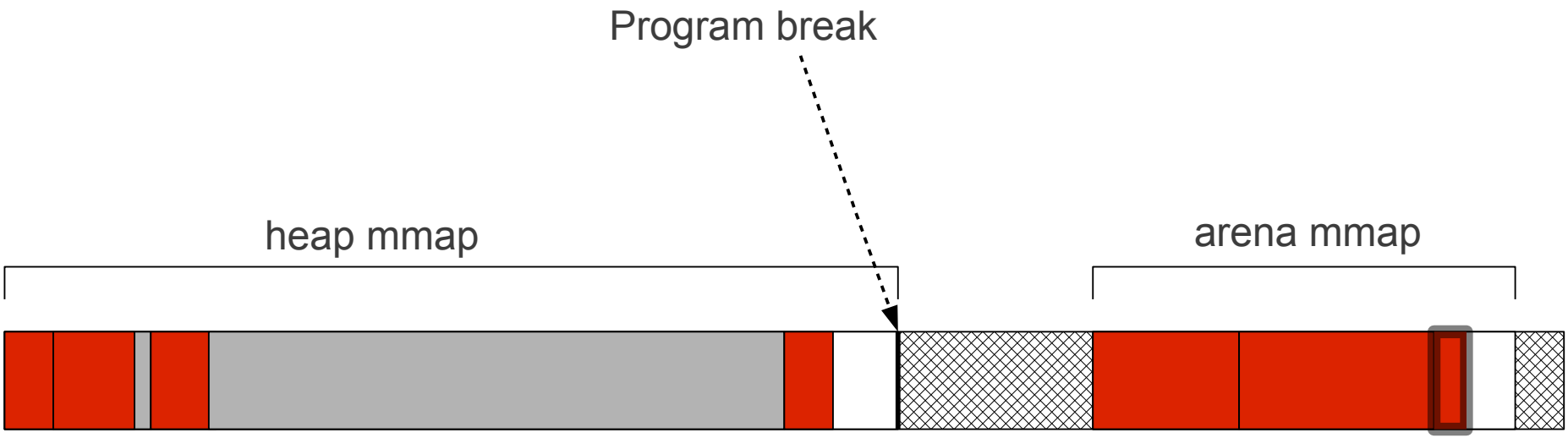
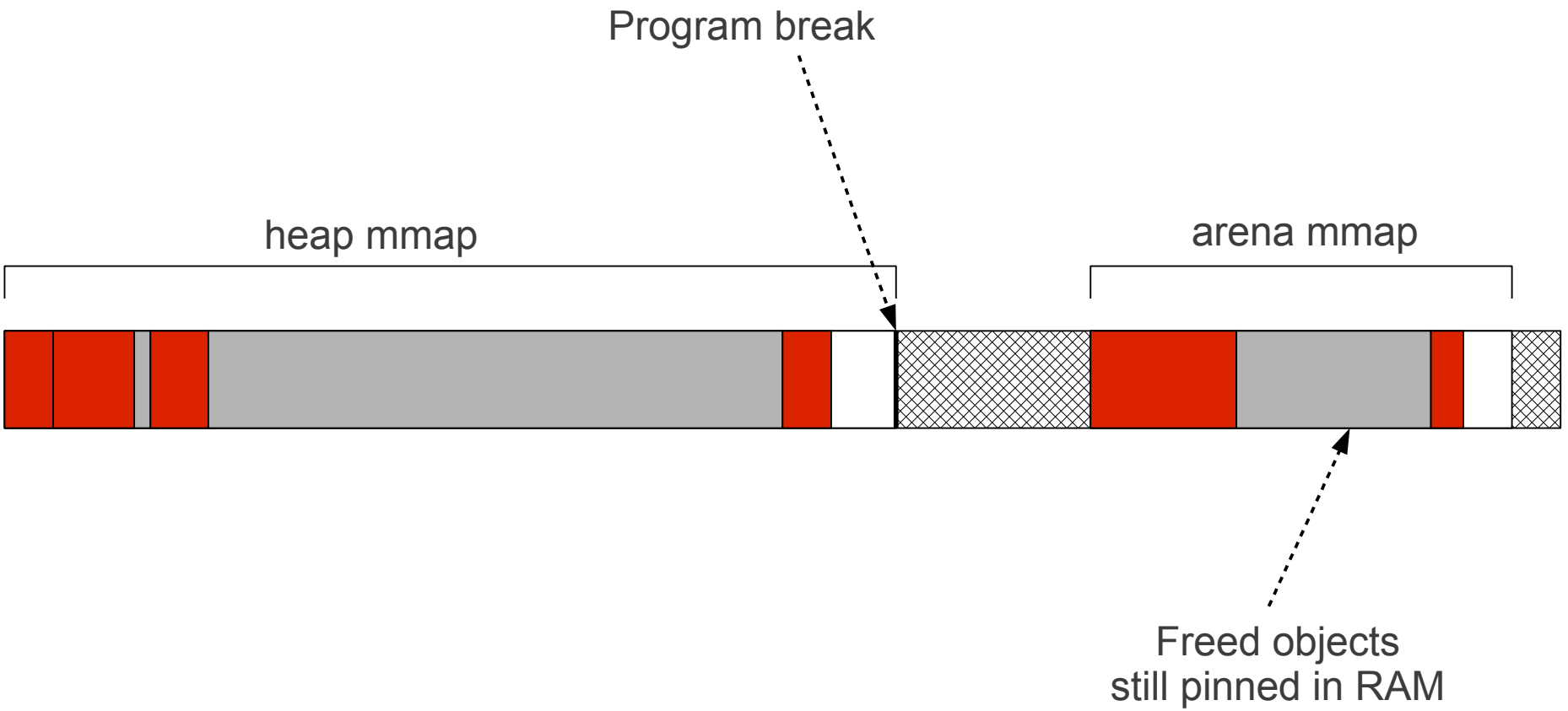
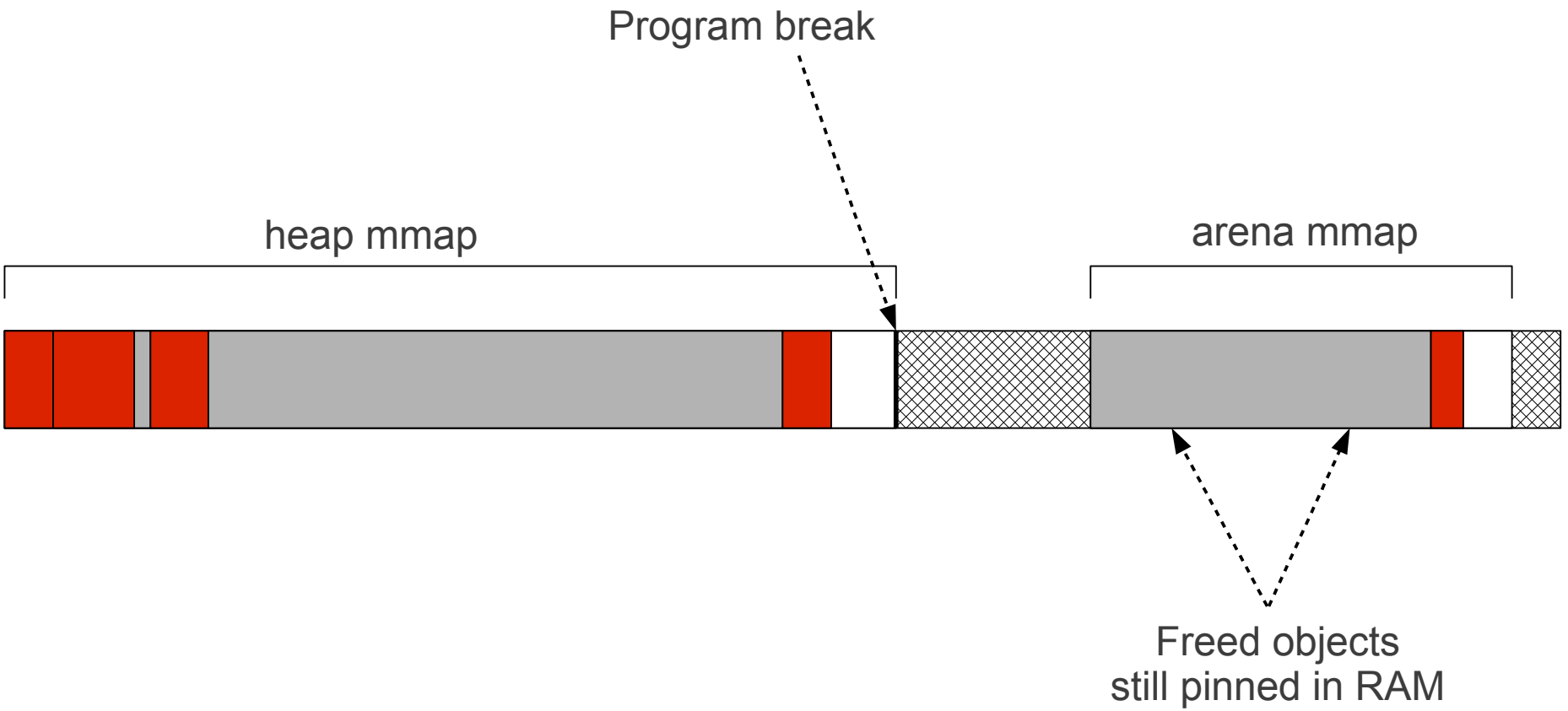


glibc heap – free within arena



glibc heap – free within arena (pinned!)



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membroker

- Service from which apps can cooperatively negotiate memory "quota" system-wide.
- Does not physically manage memory
  - kernel does that.
- Reads from .conf file, which sets limit
  - For Lexmark, the .conf file is generated by a script, based on static tuning and amount of installed RAM.

Membroker is published under LGPL 2.1
https://github.com/lxkiwatkins/membroker.git

membroker – components

- mbserver – long-running service
- Clients communicate via socket – simple protocol
- libmbclient.so – Client library handles communication
  - libmbclient does no memory allocations

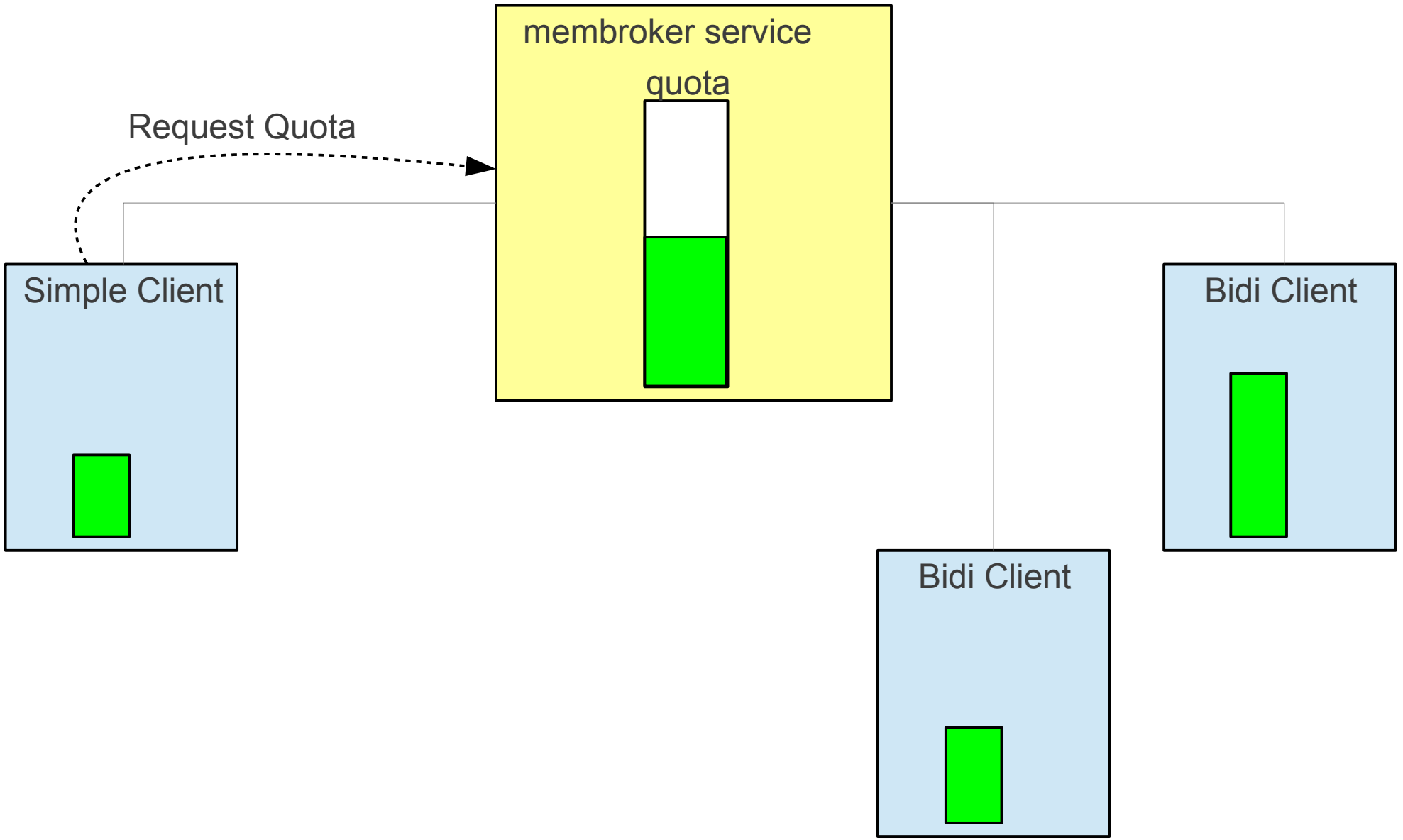
membroker - interactions

- Membroker maintains:
  - Global “available quota”
  - A list of currently connected clients
  - How much quota is owned by each client
- Client asks for quota
  - Membroker decrements available quota and gives to client
  - If quota not available:
    - Ask other clients if they can give back quota
    - Can stall client request until gets enough or gives up and rejects

membroker – two types of clients

- Simple client
  - Only client can initiate a membroker transaction
  - Two kinds of transactions:
    - Ask for quota
    - Return quota when no longer needed
- Bidirectional client
  - Can also receive a request from membroker to “give back”
  - Give back request can normal or urgent.
  - Client may free caches, do a garbage collection, wait for some operation to finish, etc.

membroker in action



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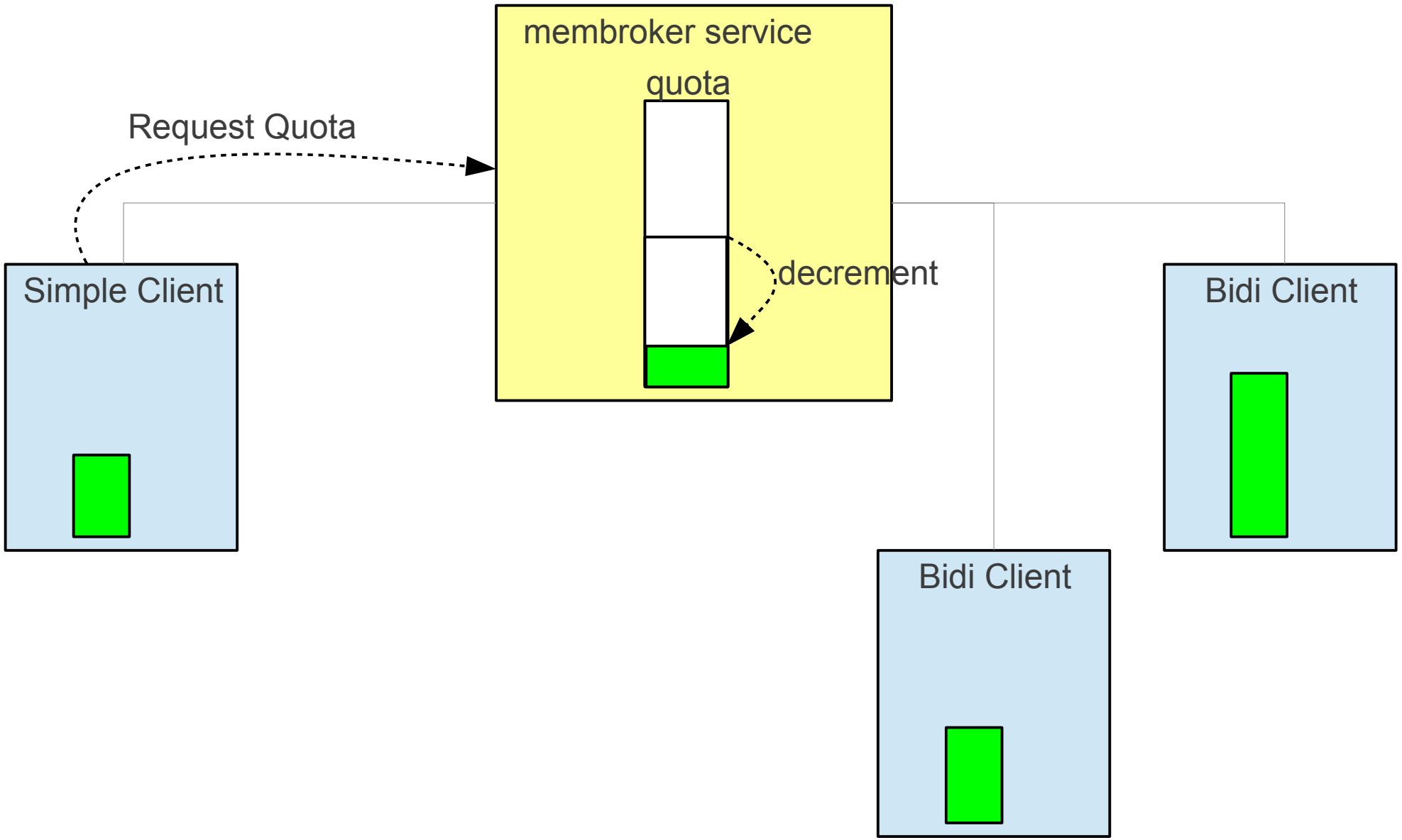

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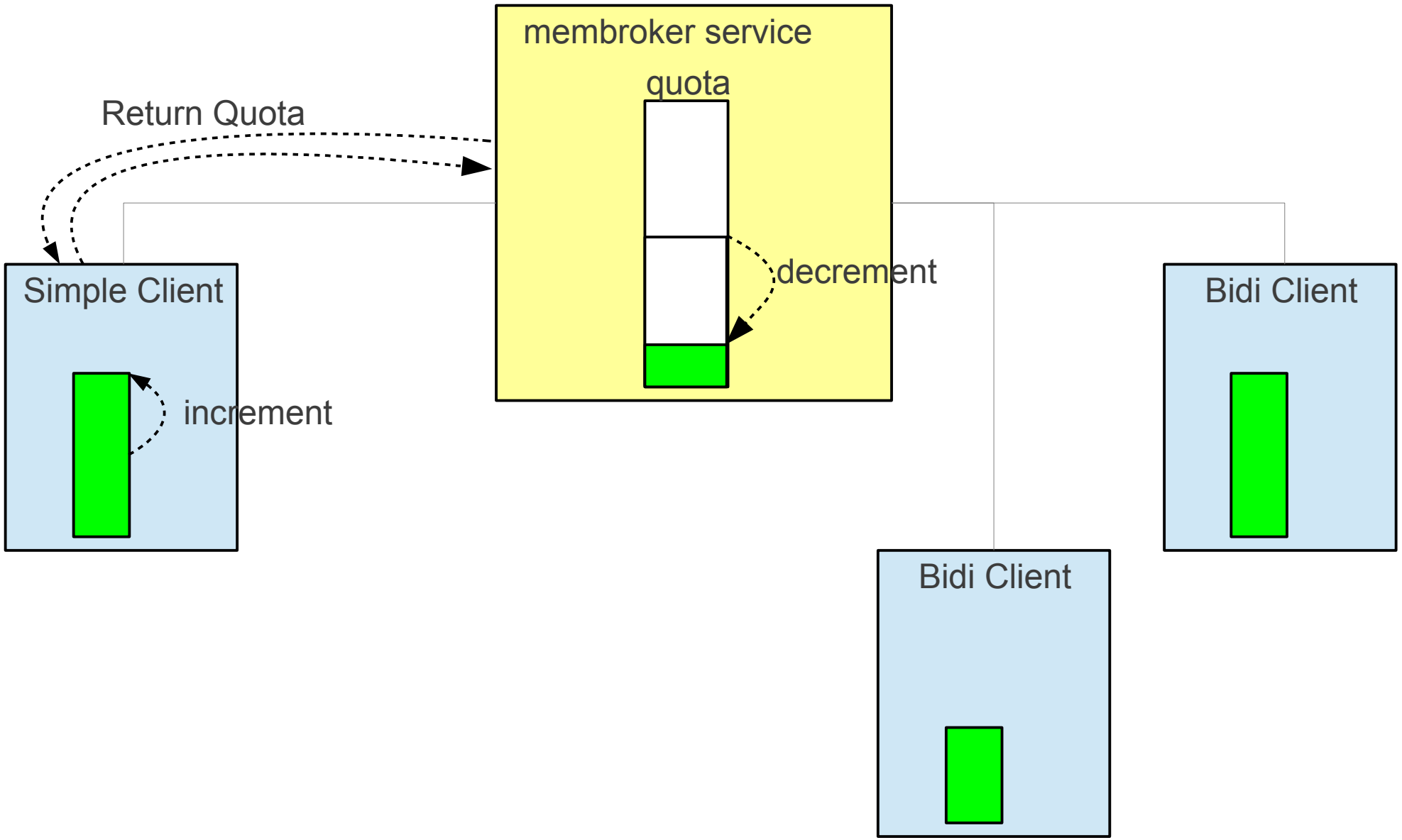

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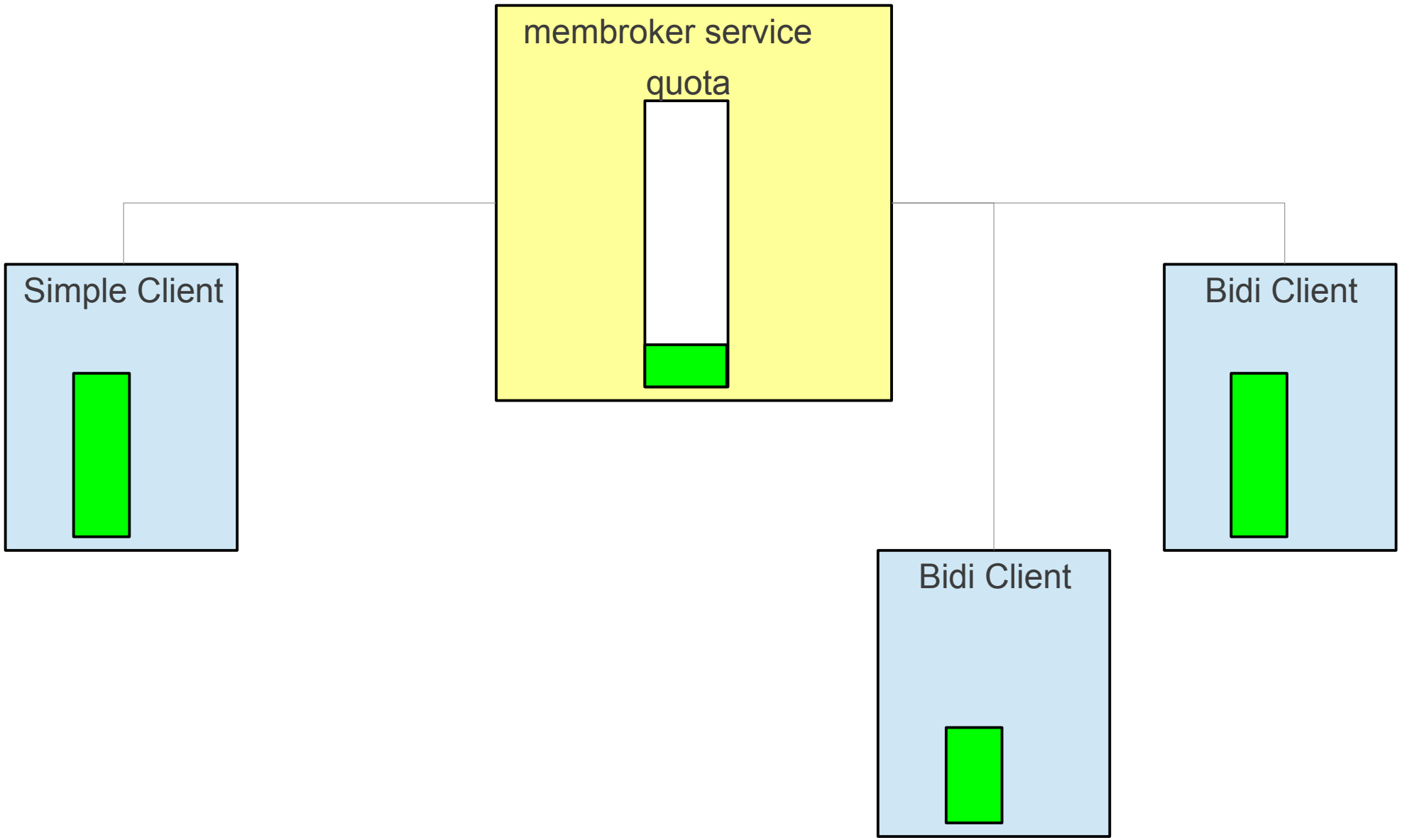

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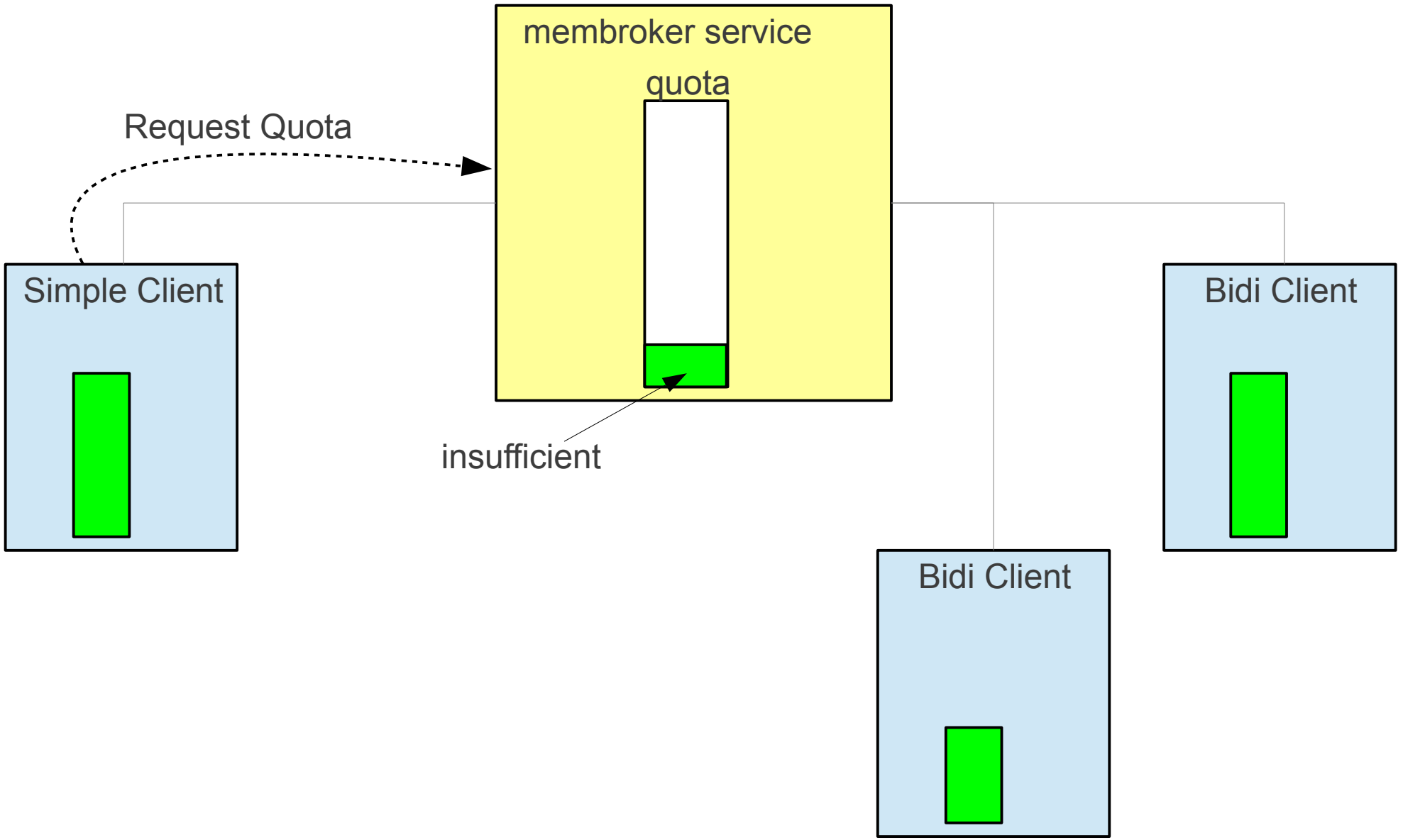

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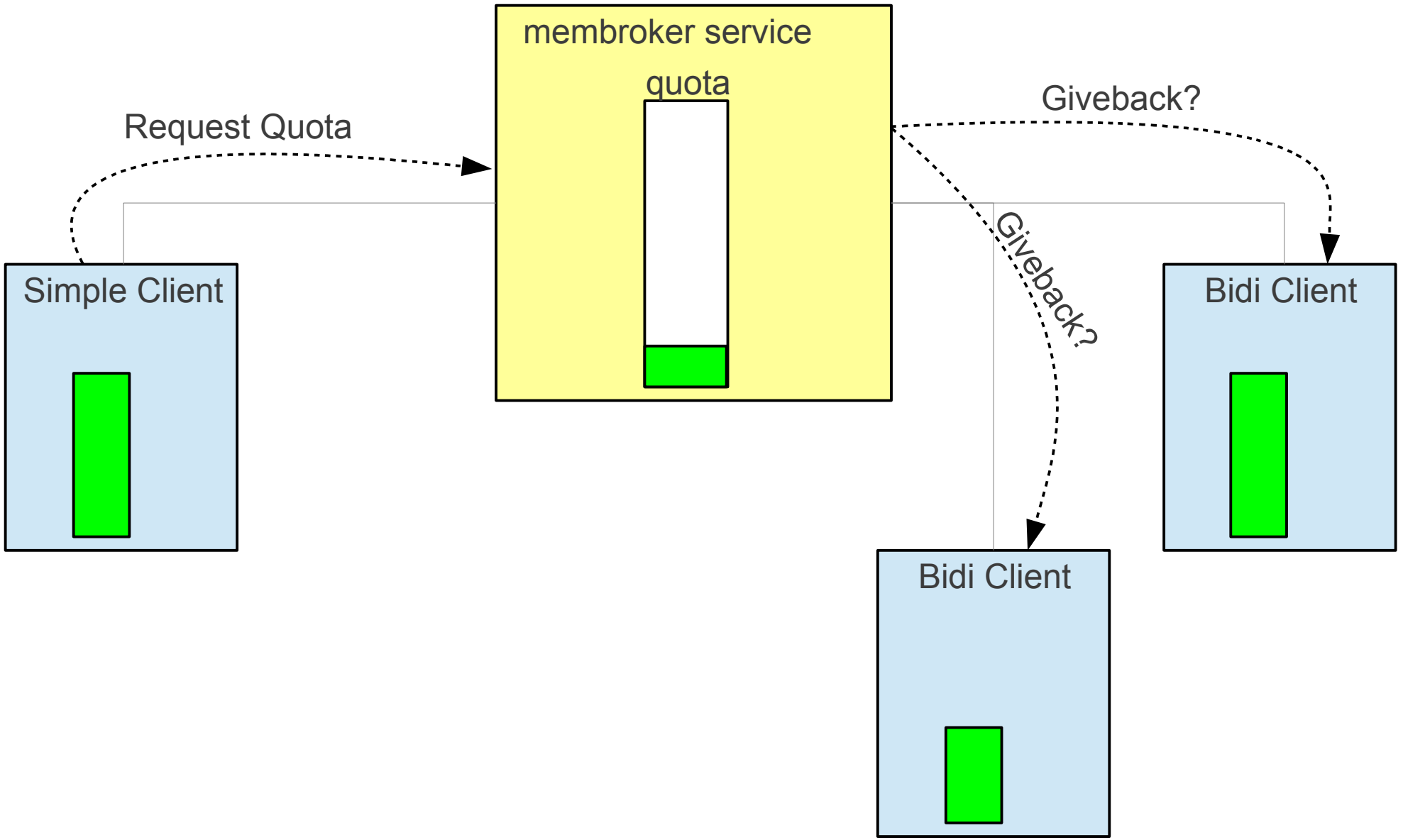

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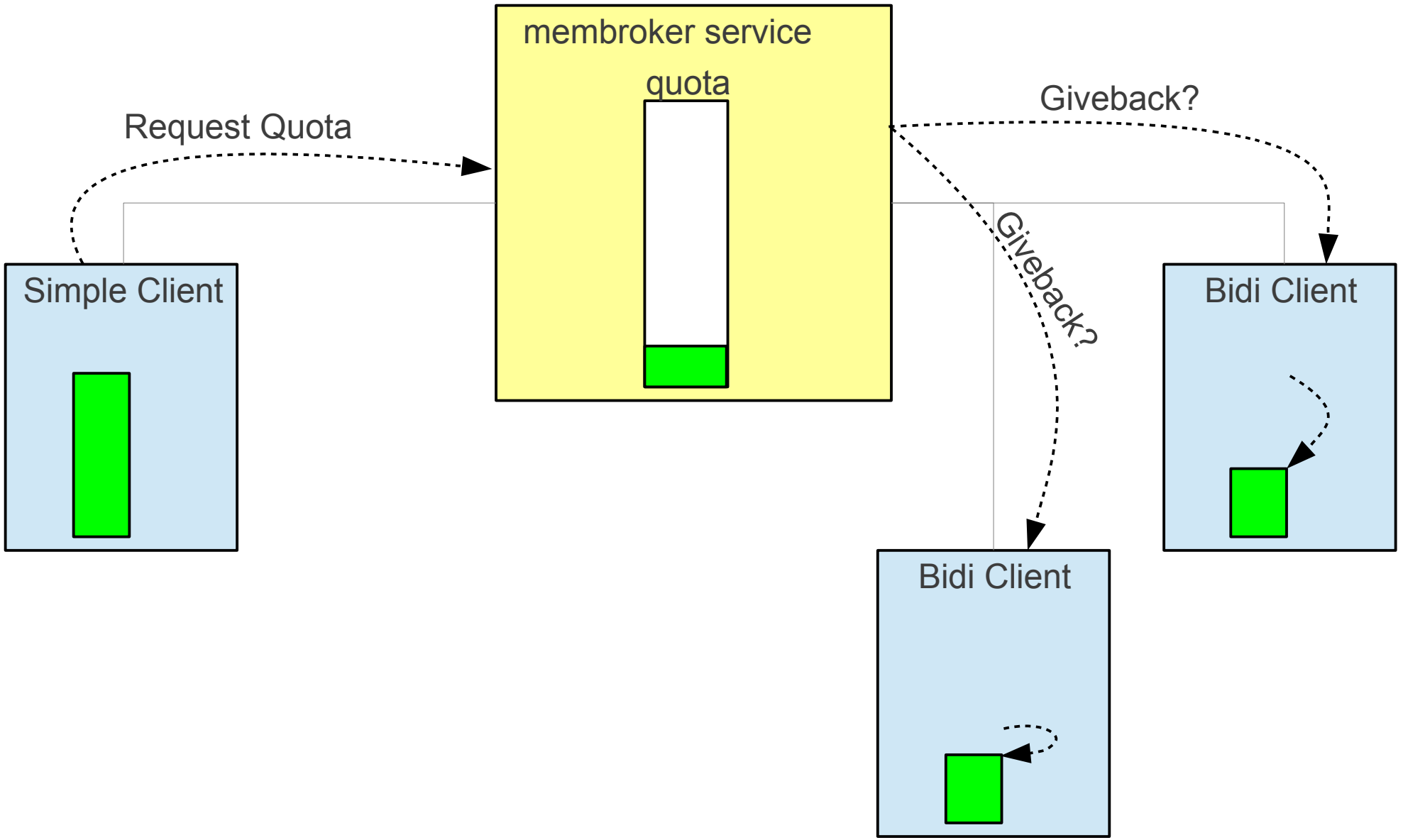

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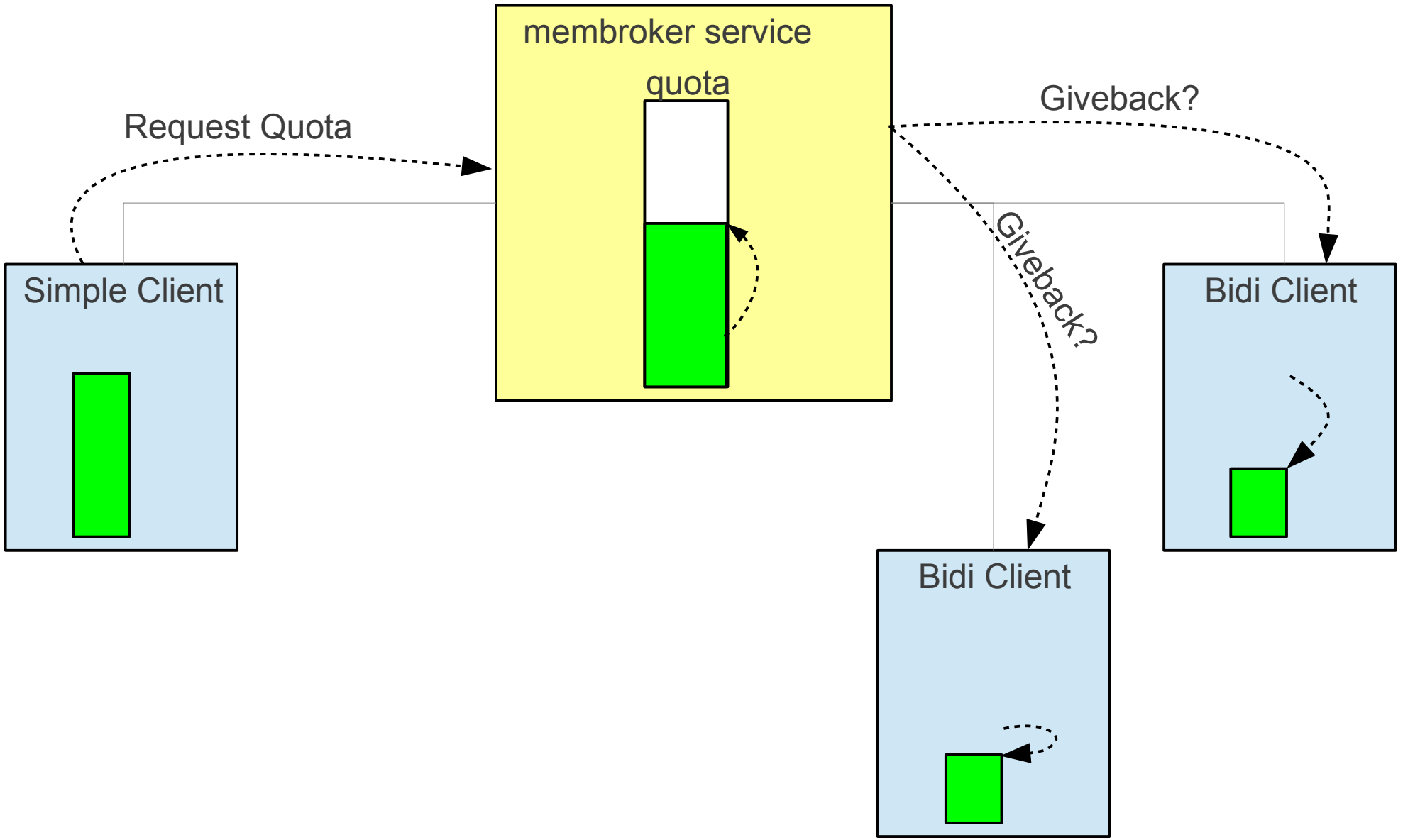

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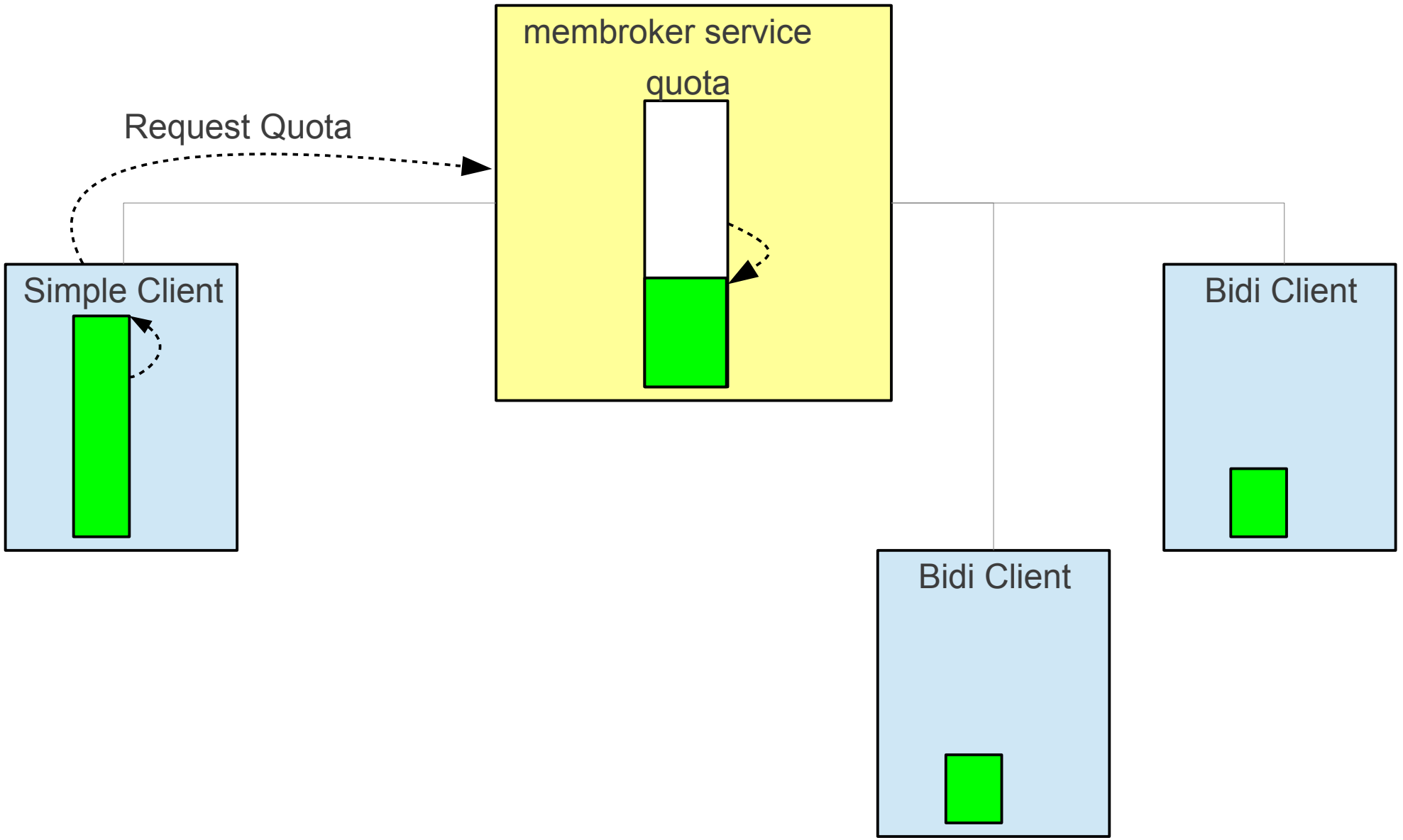

membroker – two levels of urgency

Low urgency (aka “REQUEST”)

- May block while membroker sends Low-urgency giveback request to bidi clients.
- Does not wait indefinitely.
- May return fewer pages than requested.

High urgency (aka “RESERVE”)

- May block indefinitely.
- Will send giveback “RESERVE” message to bidi clients.
- Only fails if all bidi clients refuse giveback.
- Returns either all of requested quota or none of it.

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Acknowledgement

membroker and anrmalloc written by:

Ian Watkins

iwatkins@lexmark.com

ANR malloc - A new allocator

Crucial "embedded-friendly" features:

- Return unused pages to system when possible
  - madvise(MADV_DONTNEED)
- Avoid changes to process's memory map
  - i.e. Friendly to real-time threads in same process
- Client can set limit on memory use.

anrmalloc is published under LGPL 2.1
https://github.com/lxkiwatkins/anrmalloc.git

ANR malloc – Why the name “ANR”?

Author, **Ian Watkins**, didn't want to call it “iwmalloc”, so...

The three letters most commonly occurring in the last names of its designers are A, N, and R...

- Ian Watkins
- Scott Arrington
- Steven Walter
- Howard Cochran

ANR malloc - Additional Features

Good space efficiency

- Small allocations use slabs
  - avg 2-3 bits overhead
- Larger allocations use DL-malloc-like algorithm
  - ~1 word overhead
- Slab sizes are controlled by a .conf file

Good speed

- In malloc-heavy real app tests, indistinguishable from glibc.
- In synthetic, pure malloc test, noticeably slower

Optional mark & sweep garbage collection

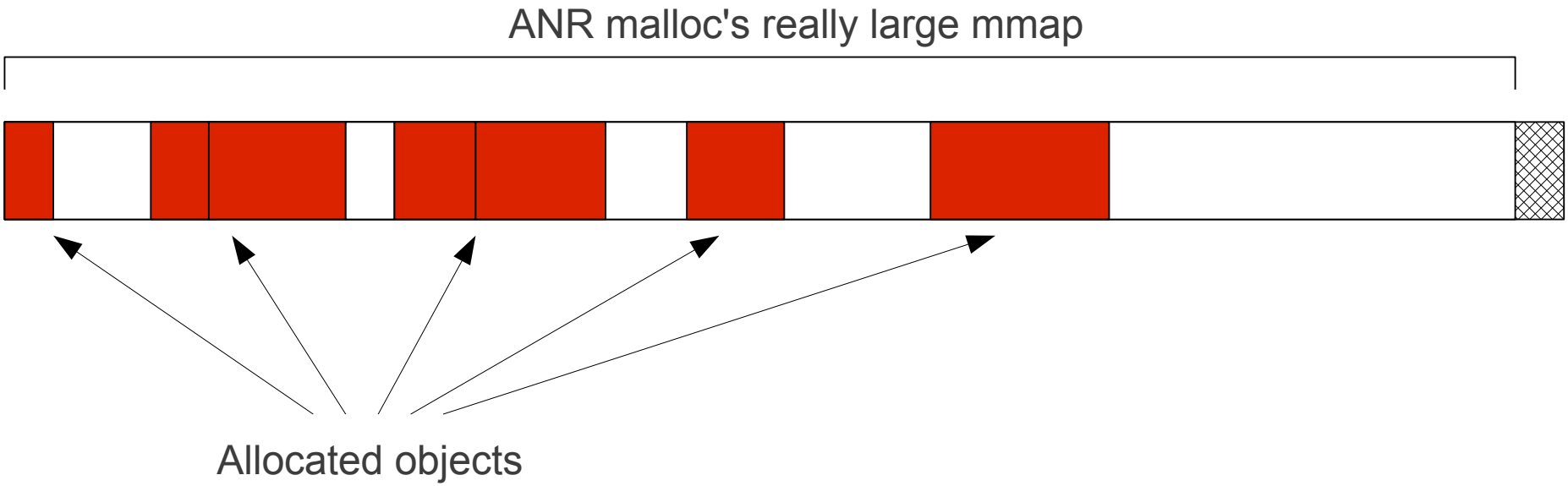
ANR malloc – Debug Features

- All of these are optional and run-time configurable:
- “Flight Data Recorder” - last N client operations
- Guard word at top and bottom of each object to detect overruns
- Store N levels of call stack with each allocation
- Allow client code to stuff additional debug info in each allocated object.
- Debug socket to dump debug data
- Compatible with valgrind on x86
- Fill-with-trash on free

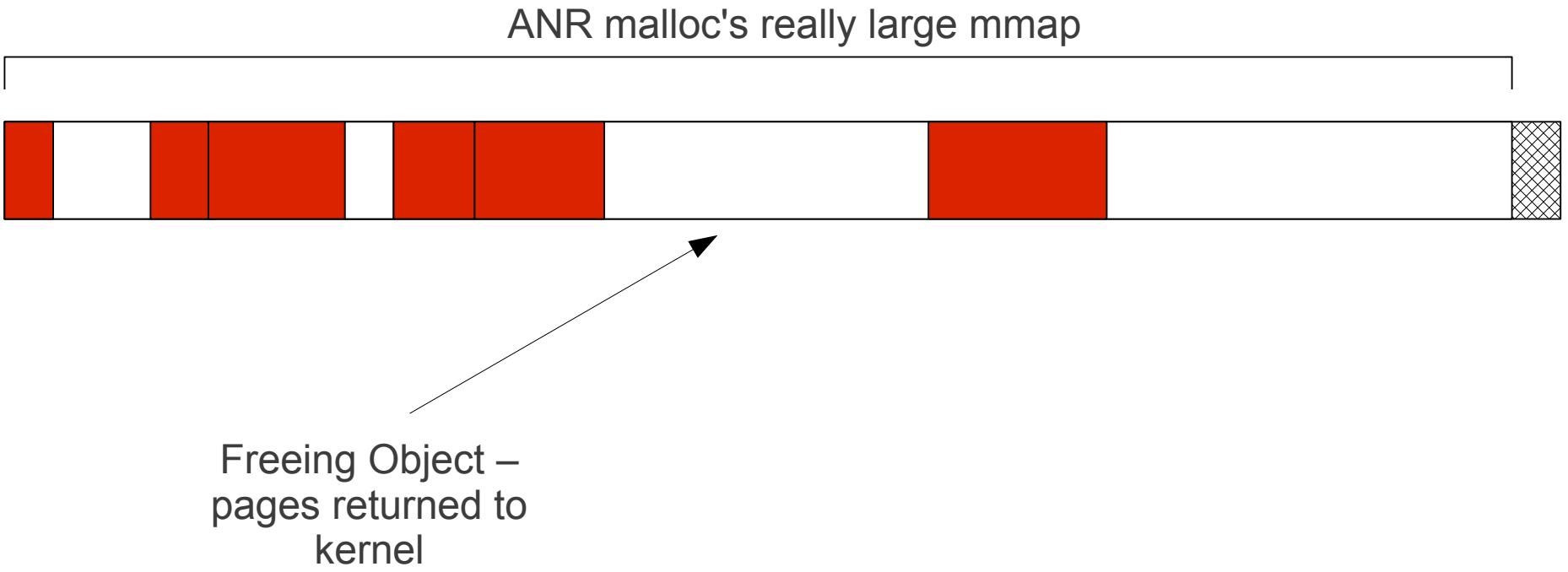
ANR malloc - Returns RAM to linux

- Maintains a bitmap of which pages in its mapping are in use.
- During free:
  - If possible, combine with adjacent free area
  - Mark in bitmap any pages newly made unused.
  - When a threshold of freeable pages reached:
    - Use madvise(MADV_DONTNEED) to return them to the kernel
    - Hysteresis avoids thrashing madvise + page fault
- Volatile Ranges?
  - anrmalloc might become a basis for taking advantage of upcoming Volatile Range kernel support.
  - See http://lwn.net/Articles/518130/

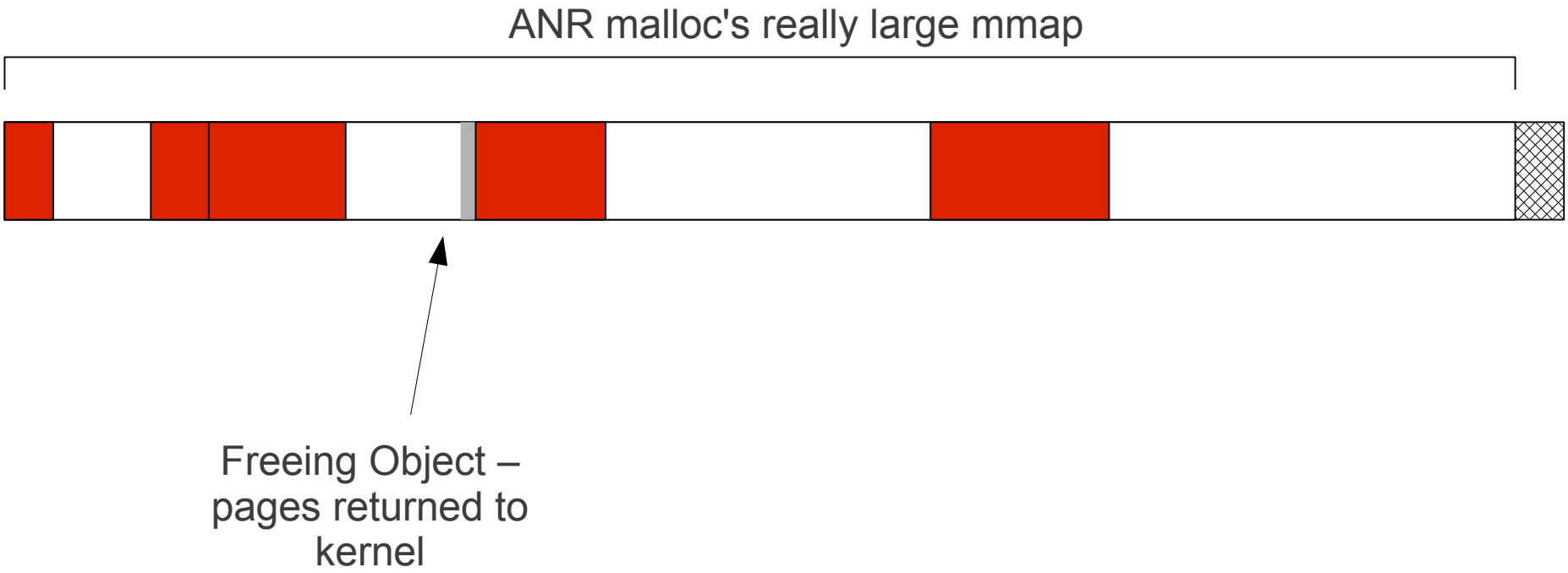
ANR malloc



ANR malloc


ANR malloc's really large mmap
Freeing Object –
pages returned to
kernel

ANR malloc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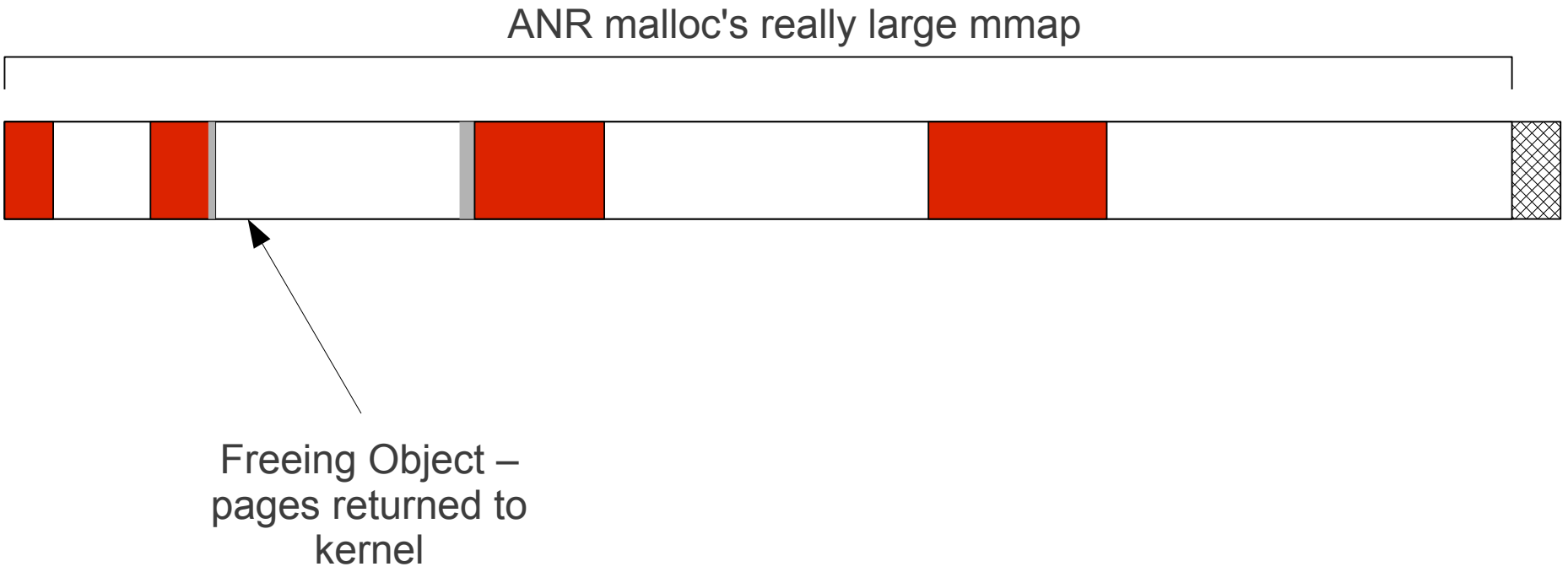
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ANR malloc - Antifeature!

Access is serialized via mutex.

- Why? To avoid having to dynamically create "arena" mapping when concurrent allocation occurs
  - Would cause RT misses in other threads
- free() will not block
  - If lock held, actual free is deferred.
- It is still thread-safe.

ANR Malloc - Two APIs

gmalloc

- A transparent replacement for glibc malloc

anr_malloc

- "Full featured" API for clients who need everything.

anr_core

- "Base class" for both of the above.

gmalloc - Replace glibc malloc

- Use dynamic linker to override glibc functions
  - malloc, free, calloc, realloc, posix_memalign
  - Can use LD_PRELOAD to affect unmodified app
  - Reads configuration from .conf file or the environment
- What you get:
  - Gives freed pages back to kernel
  - Never modifies process's memory map behind your back (for Realtime safety)
  - Automatic membroker integration (Optional)
    - Block malloc while ask membroker for quota.
    - Returns unused quota to membroker (w/ hysteresis)

gmalloc

- Configurable fixed max limit
  - Will not exceed, even if membroker could provide quota.
- Can force abort when app exceeds limit.
  - Or just return NULL
- Can enable call-stack debug data per allocation

gmalloc – What you don't get

- Does not allow membroker to ask it to “give back”
  - i.e. not a “bidi” client
- Does not provide garbage collection support
- App cannot make allocations with different level of urgency

anr_malloc interface (1/3)

- Much more control; must customize app
- App must call anr_* functions instead of malloc, free.
- Optional support for mark & sweep Garbage Collection:
  - App initiates G.C. when desired.
  - All subsystems that use anr_malloc register for a “mark your stuff” callback
  - During G.C., anr_malloc calls all registered marking functions.
  - When done, any objects not marked are garbage:
    - Optionally, it can free free them.
    - Optionally generate a “leak report”

anr_malloc interface (2/3)

- Register for “need more memory” callback
  - This callback may do any of these:
    - Free cached objects.
    - Initiate an ANR garbage collection.
    - Ask membroker for quota
  - OK to stall indefinitely.

anr_malloc interface (3/3)

- Variations of malloc:
  - anr_malloc() – normal.
    - May call “need more memory” callback.
    - May block indefinitely.
    - If fails, returns NULL.
  - anr_malloc_if_available() –
    - Succeeds if quota readily available, or fails fast.
    - Not allowed to call “need more memory” callback.

Agenda

- The Problem:
  - How Linux kernel manages memory
  - Memory challenges in Lexmark devices
  - Limitations of glibc malloc for embedded
- Our Solution:
  - membroker service
  - ANR malloc & gmalloc
  - track_fs
  - Configuration
- Q&A

track_fs – membroker aware tmpfs

- FUSE filesystem
- Layers on top of tmpfs
- During write, compares quota with what devstat says
- If needed, requests more quota from membroker
- Returns ENOSPC if membroker cannot give quota
- Very simple – file ops serialized via mutex
- During unlink, gives quota back to membroker
- Modularized – could membroker interaction is in separate shared object easily replaced.
- Does not support mmap.

track_fs is published under GPLv2
https://github.com/...

Agenda

- The Problem:
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Typical Configuration

- Make mapping for anr_malloc or gmalloc be twice as large as the most quota that you expect to have.
  - Internal limit (quota) can change, but can keep mapping the same.
  - Reduces fragmentation.
  - Extra large mapping is almost free due to madvise().
  - .conf file or app controls mapping size.

Typical Configuration – membroker

- Set membroker's quota to most of RAM
  - Exclude page cache working set, kernel pages, DMA buffers, thread stacks.
  - Tune this limit by trial and error
    - Stress test device
    - Watch /proc/meminfo, /proc/vmstat – pgmajfault for signs of heavy memory pressure
    - Slowly give membroker more quota until see pressure, then back off a bit.

Thank You!

- Acknowledgements:
  - **Ian Watkins**, iwatkins@lexmark.com
    - Author, anrmalloc & membroker
  - **Scott Arrington, Steven Walter** – design
  - **Randy Witt** – author, track_fs.
- Contact:
  - Howard Cochran cochran@lexmark.com
- Source Code:
  - https://github.com/lxkiwatkins/membroker.git
  - https://github.com/lxkiwatkins/anrmalloc.git
  - https://github.com/zedian/track_fs

Bonus Slides...

Future Work

- membroker:
  - Different classes of clients with independent quotas
  - Utilize low-memory notification from kernel
- anr_core
  - Support 64-bit architecture
  - Optional “arena” concurrency for apps with no RT code
- Other
  - Provide library to add membroker integration for anrmalloc client.
- track_fs
  - Add concurrency
  - Support mmap
  - Optional “non-urgent”-only membroker integration.

Alternative – RT safety only

- glibc malloc doesn't call brk() directly, but a __morecore() function that your app can override.
  - App can make a large brk() call at startup, and never grow it.
- Avoid arena creation
  - Use dynamic linker to override all glibc malloc functions
  - Simpler wrapper
  - Lock a mutex, then call the real glibc function, then unlock.
  - Use mallopt(M_MMAP_MAX, 0) to prevent separate mmap for large allocations.

Alternative – Tracking without gmalloc

- What if?:
  - You want to use glibc malloc, not a custom allocator.
  - You only need to roughly track memory usage
  - You don't care about returning unused pages to linux
- Override glibc's __morecore
  - Normally __morecore is sbrk()
  - Your __morecore could:
    - Request or return quota from membroker
    - Call sbrk()
- Use techniques on previous slide to prevent mmap or arena creation in glibc malloc.

Handling OOM Crash

- Out of Memory failures are hard to debug
  - For our devices, any actual OOM task kill is a crash.
    - We must reboot
  - Generally, shell is unresponsive.
  - Cannot fork() tools to read information from /proc, etc.

Handling OOM – Kernel Hack Method

- Hack out_of_memory():
  - Make out_of_memory() simply return unless it has been called many times in short period (i.e. “try harder).
  - Make it panic instead of kill a process
  - Make panic path to dump some info to flash storage:
    - /proc/meminfo
    - For all /proc/pid/smaps, dump sums of writable private dirty (i.e. unevectable) pages
    - Dump maps for the “largest” process in the system
- Disadvantages:
  - Hacky, maintenance burden
  - limited to only what you chose ahead of time to collect

Handling OOM – Sacrificial Lamb Method

- Force kernel to select a specific process to kill
  - Use /proc/pid/oom* nodes to accomplish this
- Parent is debug monitor – receives SIGCHLD
  - Parent can use freezer control groups to halt most activity
  - Let parent be SCHED_FIFO
  - Parent may collect more debug data
  - May allow debug shell to operate for leisurely debug

Memory Control Groups, oom_notify

- Put most processes in a large memory control group
- Have debug processes live in a smaller control group
- A debug process can listen for oom_notify event
  - Kernel will suspend allocations from main group for you
  - Debug process can leisurely collect debug data
  - Might could even implement a non-fatal recovery strategy
- We have not tried memory controllers yet:
  - The code appears fairly heavy-weight
  - It broke the “lumpy reclaim” algorithm on ARM
    - Lumpy reclaim was crucial for us
    - No longer an issue since Mel Gorman replaced lumpy reclaim with page COMPACTION.

Recap: Problems with glibc malloc

- Uses sbrk() to increase size of heap mapping
- The only way it can return heap to kernel is by shrinking the heap mapping via sbrk().
  - Even one extant allocation near end of mapping prevents shrinking.
  - Cannot return unused pages in middle of heap
- Achieves thread concurrency by creating a new mapping for second thread (arena).
  - These are sticky; may never unmap these
- Not Realtime-safe: Use of mmap, sbrk will break any RT threads within the process!