AZUL
SYSTEMS

Pauseless GC in the Azul JVM™

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Some Azul Background

- Azul is building an appliance that runs Java
- The Networked Attached Processing idea:
  - JVM proxy or shim runs on host
  - Bytecode execution on appliance
  - Security, visibility, file access, firewalls, etc on host
- Custom CPU
  - Core is classic 3-adr RISC, 32 regs, 64bit datapaths
  - Read & Write barrier instructions
  - Easy JIT target but no direct bytecode execution
  - Per core 16K I+16K D cache, 8 cores share 1Meg L2
  - 3 8-core clusters per die (24 cores/die)
  - 16-way SMP x 24 cores/die = 384 cores

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Outline

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- **Major Phases**
- Marking Phase
- Relocation phase
- Remap phase
- Current Status

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GC Phases

- GC runs in 3 phases: Mark, Relocate, Remap
- Fully parallel & concurrent during all phases
- No rush to finish any given phase
  - No cost beyond *read barrier* in steady state of any phase
  - Mark phase **will** finish despite busy mutators
  - Can produce free memory at any time
- "Self-Healing" - Mutators help when blocked by GC
  - Mutators test each loaded OOP with a *read barrier*
  - If *read barrier* traps, mutator does a little work
  - Loading same OOP won't trap again
  - Once working set is handled, no more traps

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Mark – Relocate – Remap

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- Marking
  - Flip marking bit on all mutator thread roots
  - Follow & mark all live objects
  - Compute per-page liveness
- Relocation
  - TLB protect relocating 1M pages, move roots
  - Relocate remaining live objects out of protected pages
  - Free physical memory
- Remapping
  - Change all pointers to relocated objects
  - Free virtual memory

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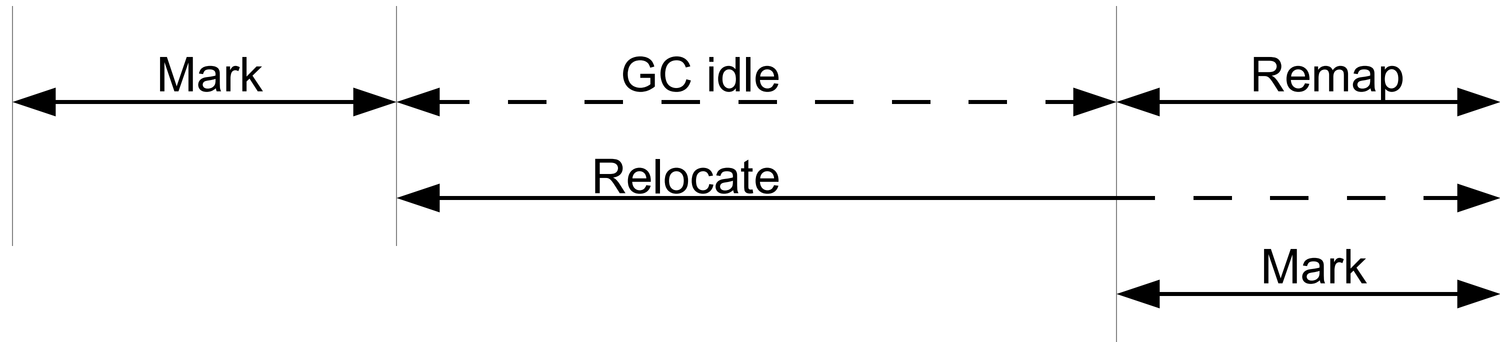
Mark – Relocate – Remap



- Always parallel & concurrent
- Next cycle Mark phase overlaps with Remap phase
- Can relocate (and free!) pages anytime after Mark
- Relocate stops at next Mark phase
- Future work: could relocate during Mark

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Marking

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- Flip marking bit on all roots
  - Initialize worklists
- Mark all live objects
  - Standard parallel work-stealing algorithms*
  - New objects marked live
  - Also compute per-page liveness
- Mutators *read barrier* loaded OOPs
  - 1 instruction, 1 cycle common case
- Finish Marks
  - Classic race with mutator discovery of large root removed

*Flood, Detlefs, Shavit, Zhang, JVM02,
"Parallel Garbage Collection for Shared Memory Multiprocessors"

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Read Barrier and the NMT bit

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- Steal 1 address bit (out of 64) from every OOP
  - The *Not-Marked-Thru* (**NMT**) bit
- *Read barrier* checks NMT bit
  - Traps if set wrong to fast user-mode handler
  - Trap handler informs Marker directly
  - Trap flips NMT bit in register to avoid propagating
  - Loaded value in Mutator working set, likely to load it again
  - Trap flips NMT bit in memory to avoid re-trapping
- "Self-Healing"
  - Once working set is marked, no more trapping

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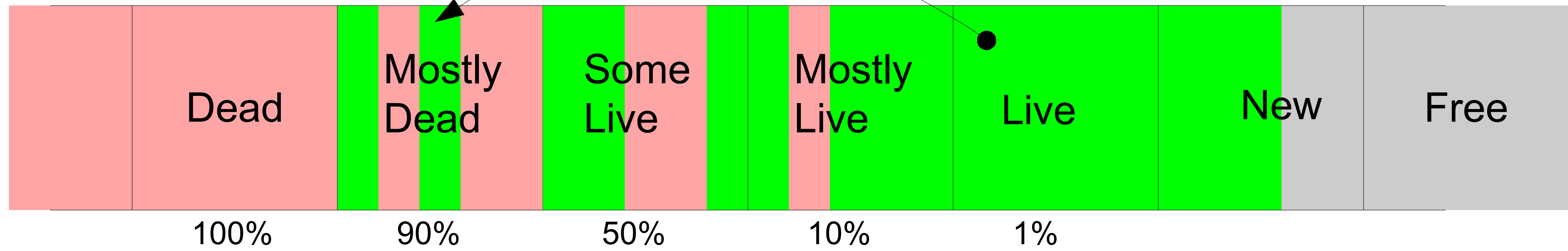
Relocation #1



1. **Choose sparsely populated 1M pages**
   - **Marking phase found per-page free space**
2. Build side arrays to hold forwarding pointers

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Relocation #2

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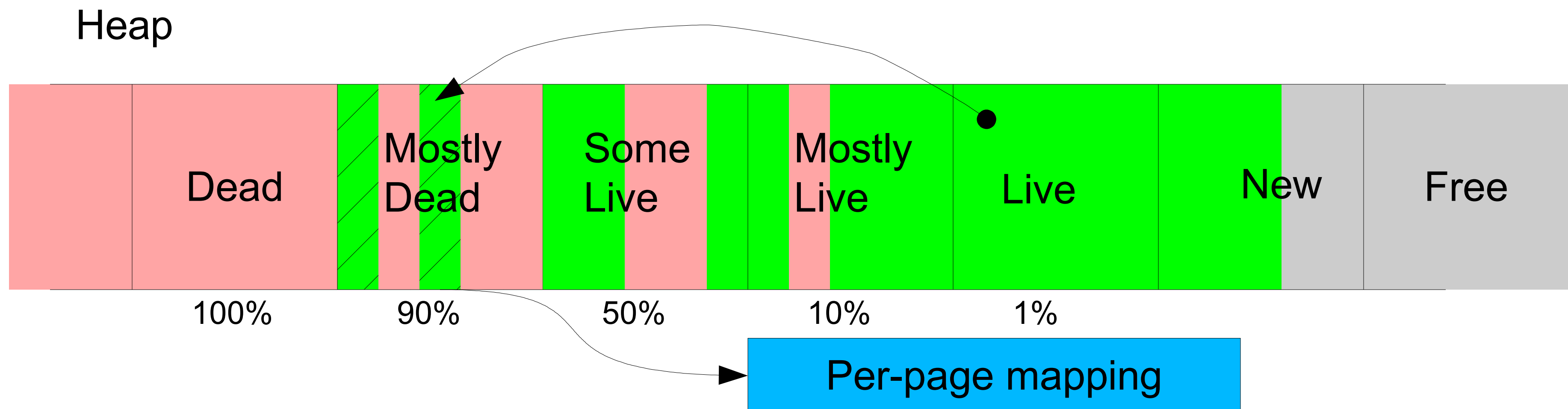

1. Choose sparsely populated 1M pages
   – Marking phase found per-page free space
2. **Build side arrays to hold forwarding pointers**
3. TLB-protect pages

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Relocation #3

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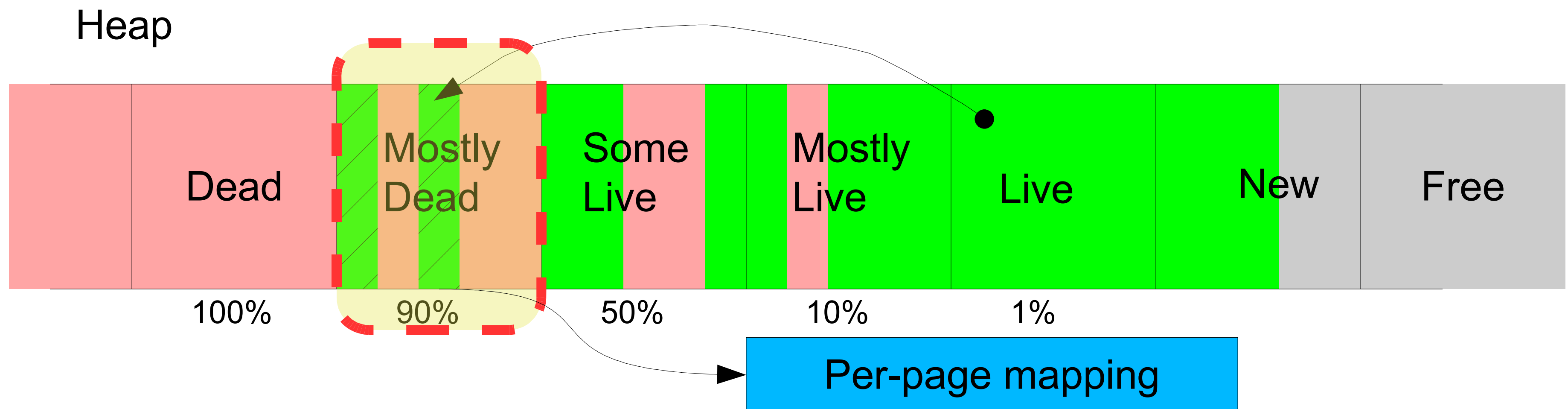

2. Build side arrays to hold forwarding pointers
3. **TLB-protect pages**
4. Copy live objects out
   – Leave dangling pointers for remap phase

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Relocation #4

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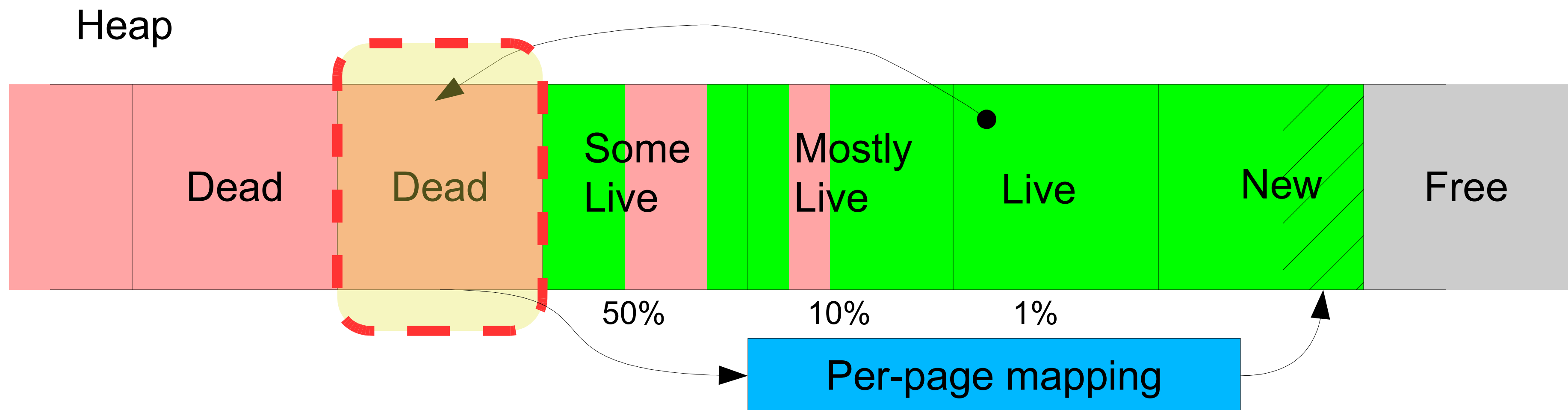

3. TLB-protect pages
4. **Copy live objects out**
   - **Leave dangling pointers for remap phase**
5. Free physical memory – OS immediately recycles

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Relocation #5

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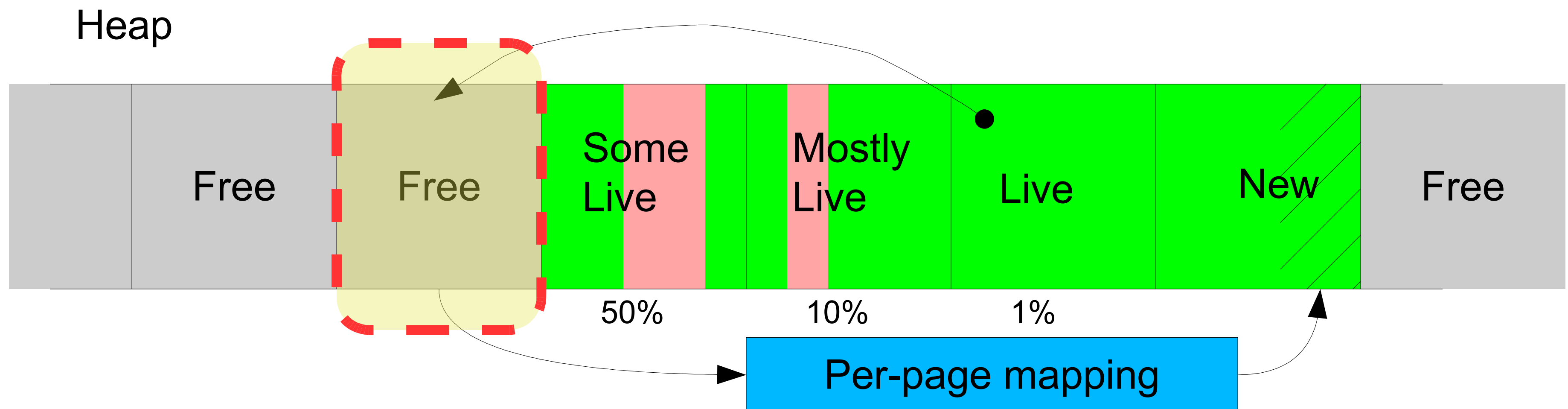

4. Copy live objects out
   – Leave dangling pointers for remap phase
5. **Free physical memory – OS immediately recycles**
   – Mutator *read barrier* prevents propagating stale oop

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Relocation and Self-Healing

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- Mutator might load stale OOP to protected page
  - Then propagate it
- Instead, *read barrier* traps
  - Trap handler finds forwarding pointer, replaces in register
  - If object not yet copied,
    - Mutator copies it just like a GC thread would
- Loaded OOP is in Mutator working set
  - Mutator likely to load it again
  - Trap updates memory to avoid re-trapping
- “Self-Healing”
  - Once working set is relocated, no more trapping

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Relocation Phase

- No “rush” to finish any relocation
  - Just run a little faster than allocation rate
- Relocated pages are mostly empty
  - Unlikely a mutator stalls on a page
  - Virtual memory is freed later, but we have lots of that
- Future work: could Relocate during next Mark phase
- Relocation needs valid mark bits
  - During Marking, mark bits are in flux
  - So use prior Mark phase bits
  - Need two sets of Mark bits

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Remap Phase

- Remap all OOPs to their forwarded locations
  - Physical memory is long gone
  - Forwarding pointers kept in side arrays
- Runs completely inside the next cycle's Mark phase
  - Or continuously via mutators' trap handlers
- Just execute a *read barrier* on each OOP
  - Will trap if not marked-through
  - Will trap if relocated
- At end no un-forwarded pointers remain
  - Deallocate virtual memory

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Remapping

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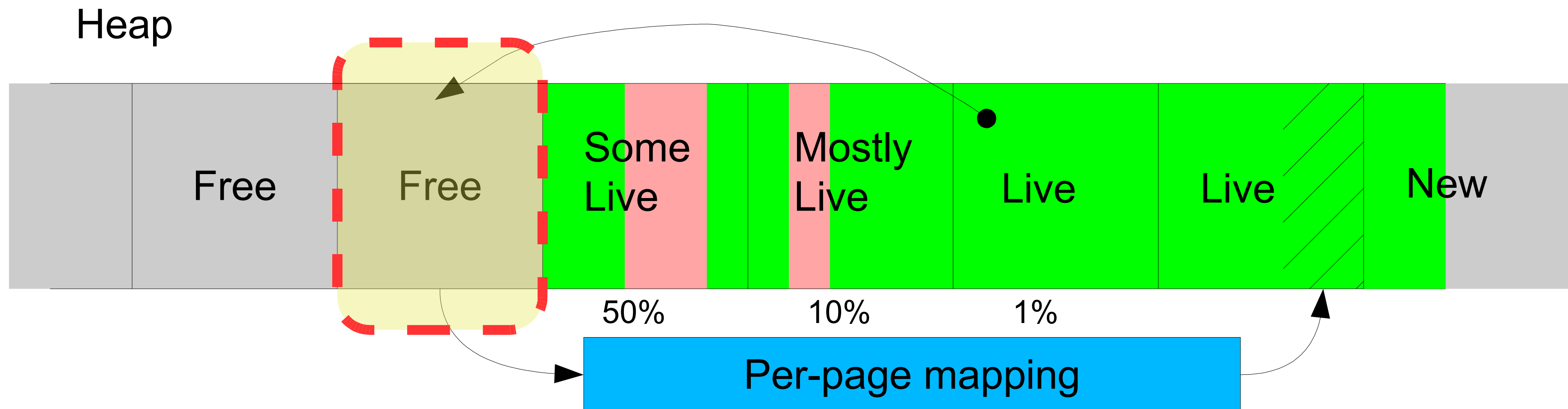

- **Either mutator or GC finds dangling pointer**
  - **Mutator does it via *read barrier* trap**

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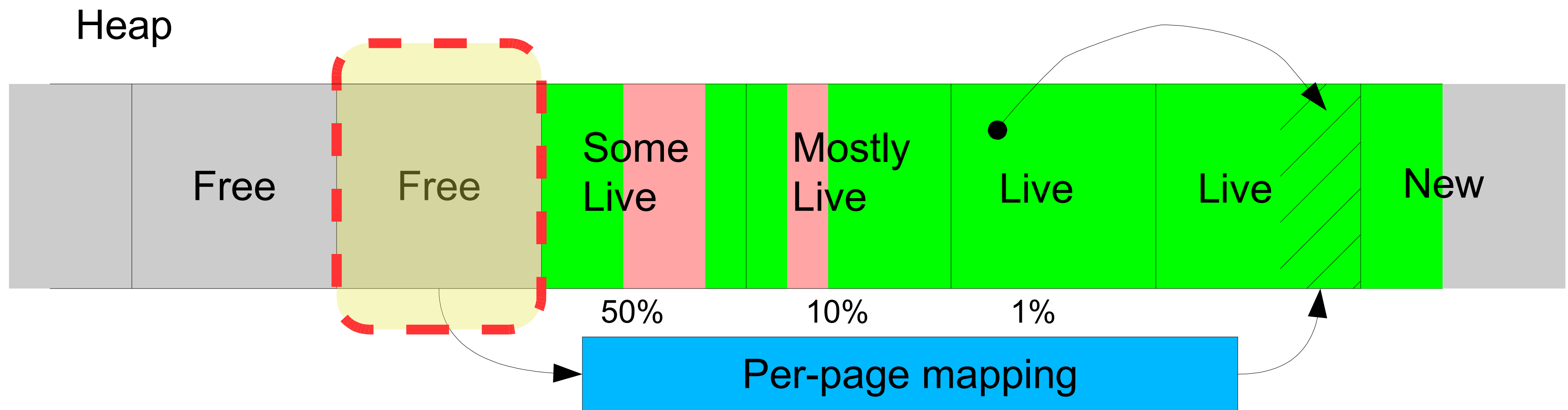
Remapping



- Either mutator or GC finds dangling pointer
  - Mutator does it via TLB trap
- **Consult mapping, forward pointer**

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Remapping

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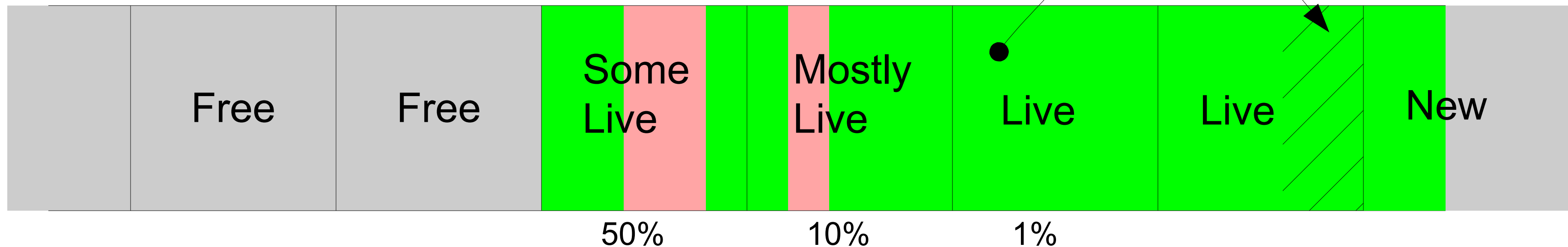

- Either mutator or GC finds dangling pointer
  - Mutator does it via TLB trap
- Consult mapping, forward pointer
- **At end, no dangling pointer**
- **Free virtual memory, side mappings**

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Some preliminary data

- 24 warehouse JBB with 4Gig heap, 20min run
- GC keeps up with 200Meg/sec allocation rate
- Max pause time: 37ms
- 3 STW pauses in current implementation
  - Initial marking STW (clear marks, flip roots)
  - Final marking STW (finish marks, mark code, sys dict, etc)
  - Relocation STW (TLB protect, relocate roots)
  - All have solutions worked out, being implemented

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Trap "Storms"

- After a desired-NMT flip or TLB protection
  - Mutators start trapping
- Mutators slow down in a "trap storm"
- But slowdown currently not measurable
  - Gross pause times dominate
  - No ticks in the profiler
- See ~1000 traps @ ~1000 clks each per "storm"
  - This is a tiny slowdown
  - Will need very low STW pauses to see effect

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Read Barriers

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- Expensive in Software*
- So done in hardware!
- 1 extra instruction per Load
- "Looks like" a dead load but
  - with fancy TLB mappings
  - no L1 pollution on a hit
  - No trap on a NULL
  - fast user-mode trap handler
- Mutator thread pays load-use penalty
  - compiler can schedule around it

*Blackburn & Hosking, 2004, "Barriers: Friend or Foe," conditional read barriers cost 7-21%

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Future Work

- Generational version is planned
  - Will use *write-barrier* op
  - Includes cross-generation check
- Remove expensive STW pauses
  - Actually most STWs already meet goal of OS timeslice
- General tuning work
  - It's all in the implementation details
  - No interesting algorithmic work

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