INFO411 Memory Management on Mobile Devices

ISMM 2024 – Memory Management on Mobile Devices

Motivation

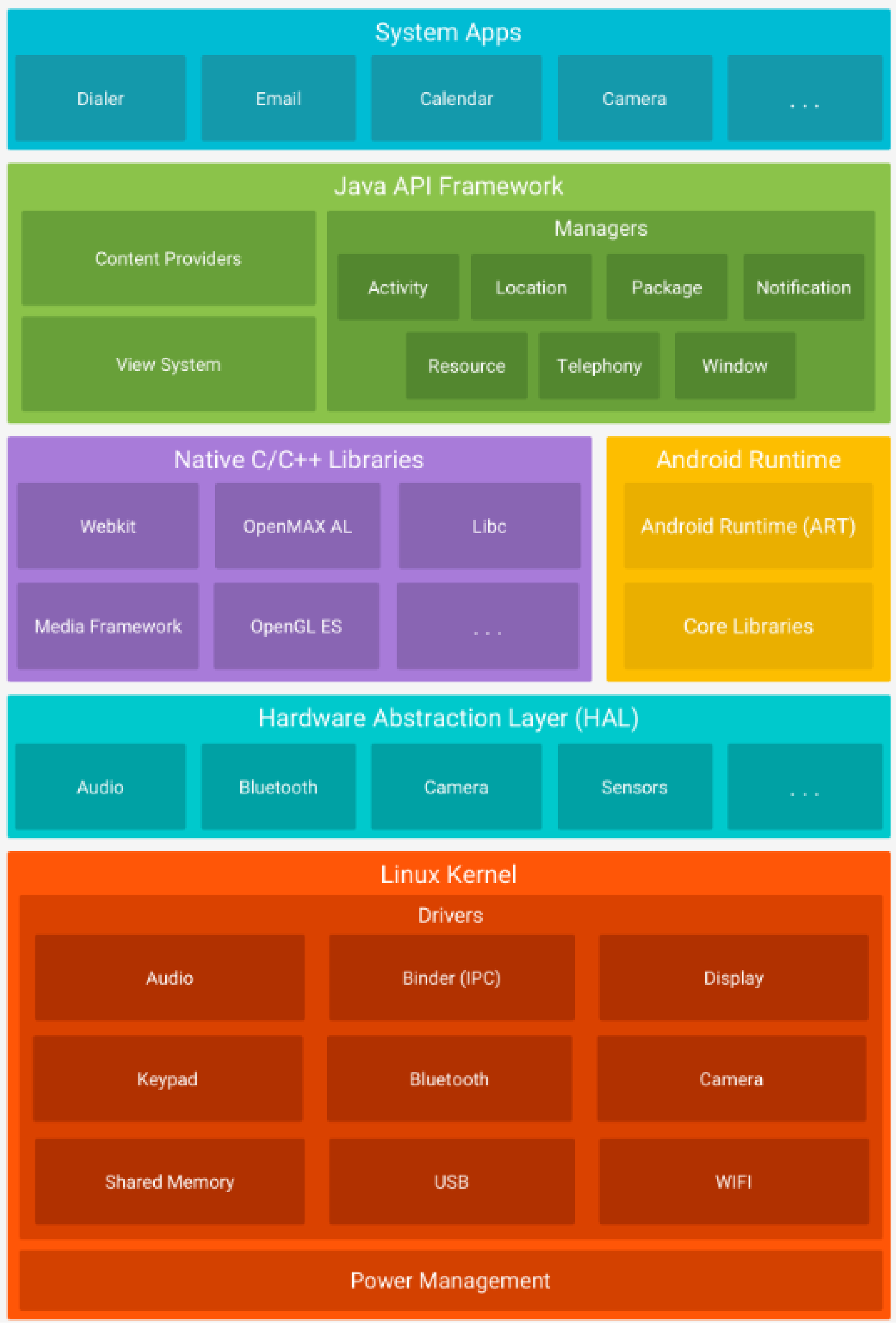
- Billions of mobile devices, yet **memory management** is understudied compared to servers/desktops.
- **Responsiveness (frame rate), energy (cpu/battery), and memory cost (heap size)** are critical to user experience.
- Android Runtime (ART), part of the **Android OS**, is:
  - Open-source
  - Garbage-collected
  - Runs across low- to high-end devices
- **?**How do OS garbage collectors behave on *real-world mobile apps***?**

⬇ Next

Background – ART Runtime

- **Android Runtime (ART):**
  - Zygote → forks every app process
  - Both **JIT** and **AOT** compilation available
  - Collectors: SemiSpace, Concurrent Copying, Concurrent Mark-Compact
- **OS level GC ≠ app-level GC**
  - Impacts *all apps* sharing the OS
  - Must measure **mutator cost** + **responsiveness**

Architecture



Challenges

- **Multi-tenancy**: Many apps/services share limited OS memory.
- **Lack of benchmarks**: No standard suite of open-source Android OS apps.
- **Non-determinism**: Network, GPS, UI events → reproducibility issues.
- **Heap size control**: Apps inherit from the OS Zygote → hard to tune per-app.
- **Heap introspection loops**: Apps adapt to OS memory pressure.
- **Closed-source apps**: Frequent updates + UI changes → flaky benchmarks.

?How can OS-level GC overheads be measured in a *controlled & reproducible* way**?**

Framework Design – Key Principles

- **Heap size control**
  - Hijacked **Zygote fork** to enforce per-app heap limits
  - First systematic mechanism for OS-level GC evaluation
- **GC cost attribution**
  - Extended ART to log **GC phases**
  - Collected **perf counters**:
    - CPU cycles
    - Task clock
    - **Instructions retired** ✅
    - Page faults
  - ⚠ Also measured wall-clock time, but discarded as *too noisy*
- **Responsiveness metrics**
  - Measured **frame jank & render times** via `gfxinfo`
  - User-visible latency, not just GC pause times
  - **Percentiles (P50, P99, P99.9)** for frame times to capture stutter

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Framework Design – Pipeline

App → **Modified ART** → **Mock APIs** → **UI Automator** → **Metrics**

- Controlled heap configuration at fork
- Mocked heap introspection APIs → stable values
- Automated user events via **UI Automator**
- Logged GC timings + frame stability

Framework Design – Challenges Addressed

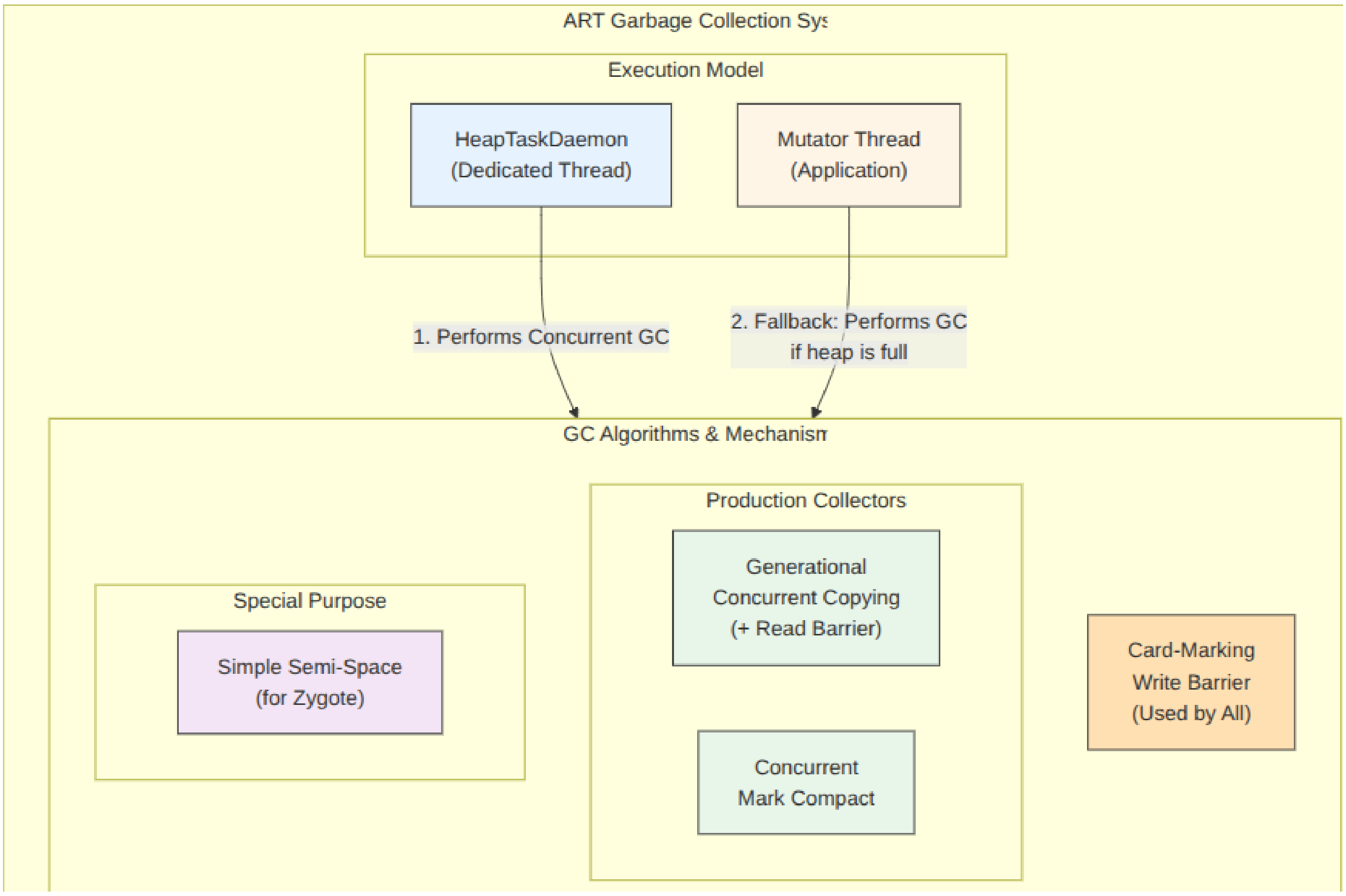
- **Heap introspection feedback loops**
  - Maps, Instagram adapt to “available memory”
  - Solution: Fake responses via modified ART
- **Non-determinism**
  - Cached TikTok feeds & fixed content
  - Forced **AOT compilation** → steady state
- **Idempotent benchmarks**
  - Cold-start every run

- Fixed app versions, reproducible UI scripts

Whitebox approach for analysis

- **Heap size control**: via Zygote hijack
- **Heap introspection**: ART returns fake values → prevent feedback loops
- **Network variability**: Pre-cached data, curated feeds
- **Compilation noise**: Forced AOT
- **App state**: Cold-start enforced

Garbage Collection



Cleaners (Collectors)

- **Generational Concurrent Copying Cleaner** 🧒
  - "Quick tidy-up kid"
  - Frequent, lightweight cleanups
  - Write barrier + read barrier ensure safety

Cleaners (Collectors)

- **Concurrent Mark-Compact Cleaner** 👵
  - "Deep-cleaning parent"

- Less frequent, re-organizes heap
- More space-efficient for long-lived workloads

Benchmarks – Design

- **Vanilla Java benchmarks**
  - DaCapo subset, GCBench
  - Controlled, stable workloads
- **Real-world apps**
  - Gmail, TikTok, Instagram, Maps, Acrobat, Airbnb
  - Represent actual OS-level stressors
- Excluded: browsers & games (too dynamic, non-reproducible)

Evaluation Framework

- Modified **ART** to:
  - Control heap per-app (Zygote fork)
  - Mock heap APIs (break feedback loops)
  - Automate UI input sequences
- **?**Can OS-level collectors be measured fairly for both **mutator cost** and **responsiveness?**

Evaluation – Methodology

- **Devices:** Pixel 7 Pro (12 GB), Pixel 4a 5G (6 GB)
- **Controls:**
  - Disabled SIM/Bluetooth/location
  - Fixed CPU frequency, pinned cores
  - Forced AOT warmup
- **Lower Bound Overhead (LBO):**
  - SemiSpace/NoGC as baselines
  - Reported results = empirical *lower bounds* on GC cost
- ⚖ **CPU cycles reported slightly higher overhead than task clock** → apps did extra work, not just slowing

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Evaluation – Vanilla Java Workloads

- **Optimized SemiSpace:** lowest mutator overheads (14–27%)
- **Concurrent Copying (CC):** 10–23%, cache-friendly at small heaps
- **Concurrent Mark-Compact (CMC):** 11–32%, more space-efficient
- **Takeaway:** No single collector dominates

Evaluation – Real-World Apps

- Overheads: **2% – 51%**, strongly app + heap dependent
- **Trends:**
  - SemiSpace (optimized) → best for mutator overhead
  - CMC → better for tight heaps (e.g., Maps)
  - Pause times ≠ responsiveness

Evaluation – Responsiveness

- Frame distributions (Gmail, Acrobat)
  - P50, P99, P99.9 → smoothness vs jank
  - 99.9th percentile → **stutter** despite short pause times
- Insight: Must use **frame stability metrics**, not just stop-the-world pauses
- Different apps show unique GC sensitivity patterns

Evaluation – Anomalies

- **Twitter/X:** highly unstable → discarded from results
- **Google Maps:** minimum heap size changed **daily** with updates
- **!** Highlights difficulty of reproducibility with closed-source apps

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Evaluation – Experimental Device

Pixel 7 Pro

Component	Specification
CPU	2× Cortex-X1 @2.85GHz 2× Cortex-A78 @2.35GHz 4× Cortex-A55 @1.8GHz
Memory	12 GB LPDDR5

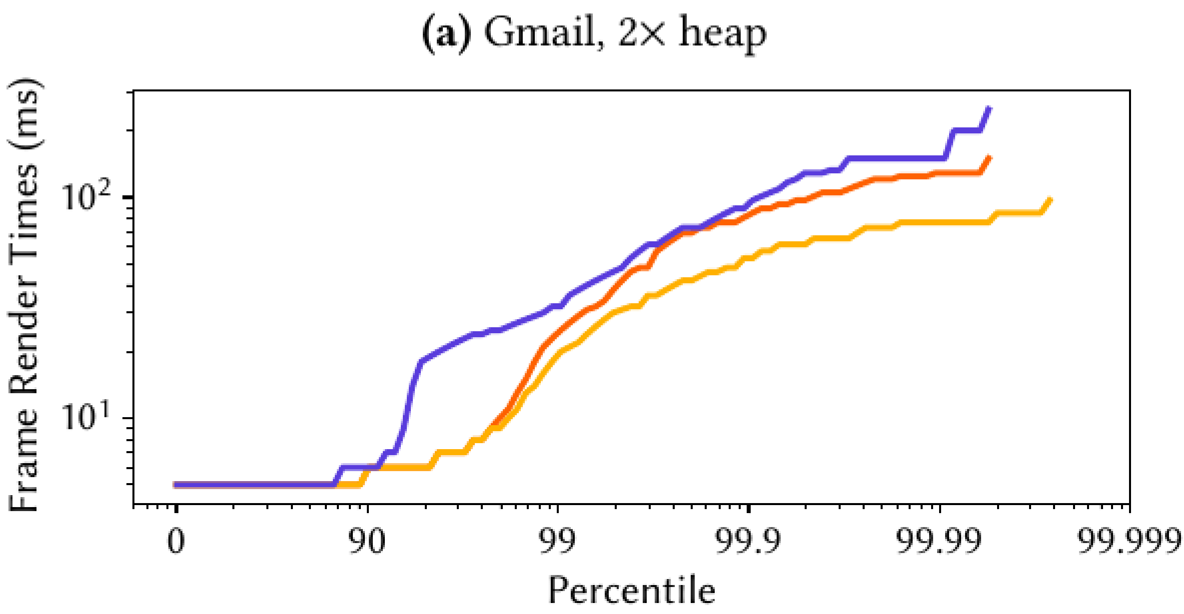
Evaluation – Heap Sizes (Apps)

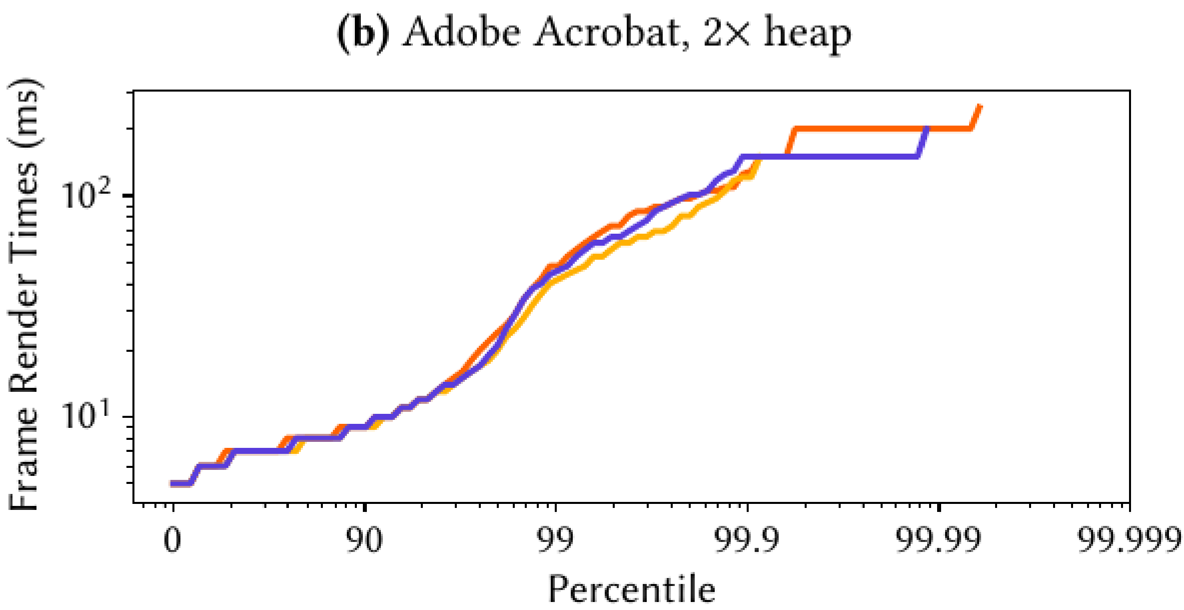
Minimum Heap Sizes (MB)

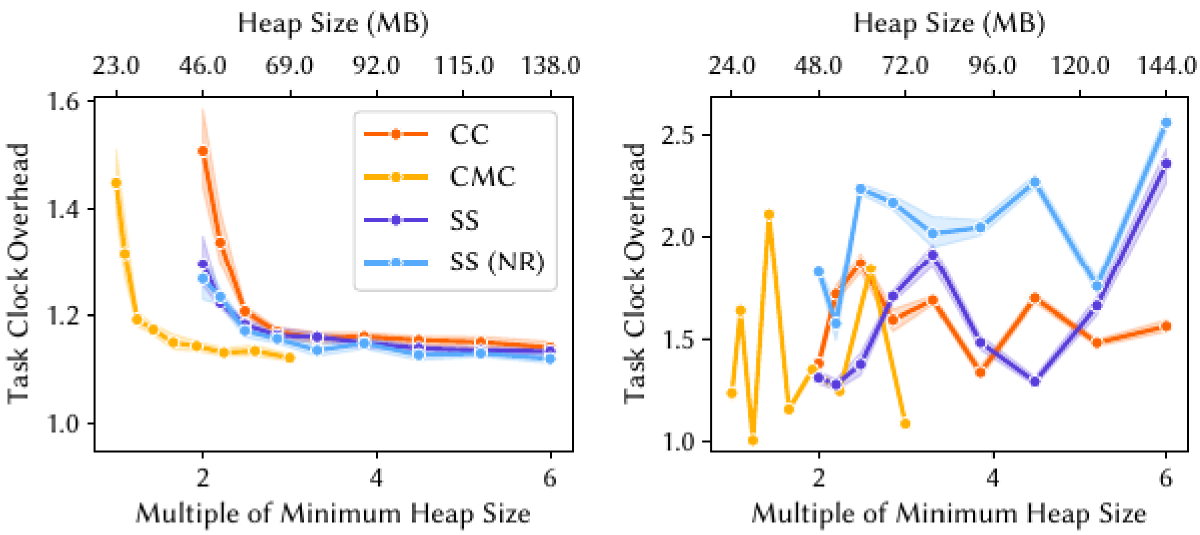
Benchmark	Pixel 7 Pro	Pixel 4a 5G
Acrobat	18	18
Airbnb	23	23
Discord	19	19
Gmail	14	14
Google News	14	17
Maps	65	65

Evaluation – Key Results

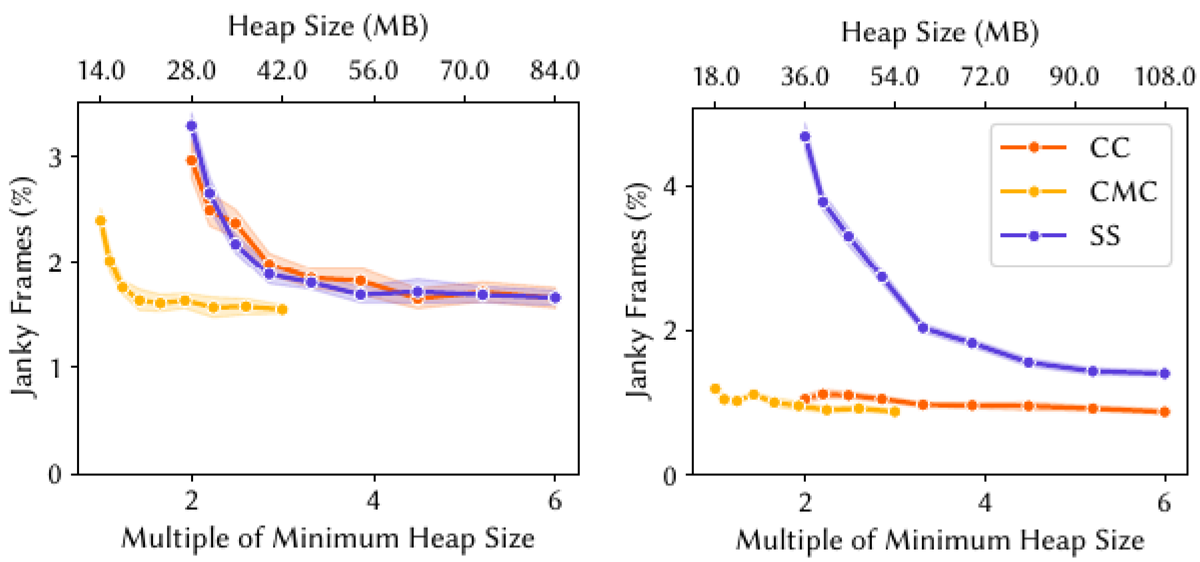
- OS-level GC overheads: **2% → 51%**
- **SemiSpace (optimized):** best mutator overhead
- **CMC:** most space-efficient
- **Responsiveness metrics:**
  - Pause times ≠ user experience
  - **Frame stability (percentiles)** = better predictor
- **Geometric mean overheads** and **LBO tables** used for fair comparisons







(a) Airbnb **(b)** X (Twitter)



Discussion – Time vs Space Tradeoff

- **SemiSpace:** low mutator cost, but higher heap demand
- **CMC:** space-efficient, but overhead increases with workload
- **Concurrent Copying:** good balance for smaller heaps
- ❌ No universal best GC across workloads

Discussion – What Surprised Us

- SemiSpace often outperformed concurrent collectors
- Pause time metrics failed as predictors of responsiveness
- Closed-source app volatility (heap growth, updates) complicates research

- Demonstrates **need for robust open benchmarks**

Summary Takeaways

- 📐 **Framework:** First systematic GC evaluation for Android
- 📊 **Evaluation:** Benchmarks across real apps + Java workloads
- ⚖️ **Tradeoffs:** SemiSpace → lowest overhead; CMC → most space-efficient
- 🎯 **Responsiveness:** Frame stability (P50/P99/P99.9) > pause times

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Future Improvements

- Build **open-source benchmark suite** for reproducibility
- Stronger solutions to **heap introspection loops**
- Improve reproducibility under **dynamic events**
- Extend framework to **other mobile OSes**
- Explore collectors optimizing **time-space tradeoffs** for small heaps

?What OS GC designs can sustain performance across *all tiers of devices***?**

Future Work

Broader Impact

- Provides **first reproducible framework** for GC research on Android
- Helps academia & industry evaluate collectors **under realistic mobile workloads**
- Paves way for **next-gen collectors** balancing mutator cost, responsiveness, and space efficiency