End the Senseless Killing: Improving Memory Management for Mobile Operating Systems

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Disclaimers

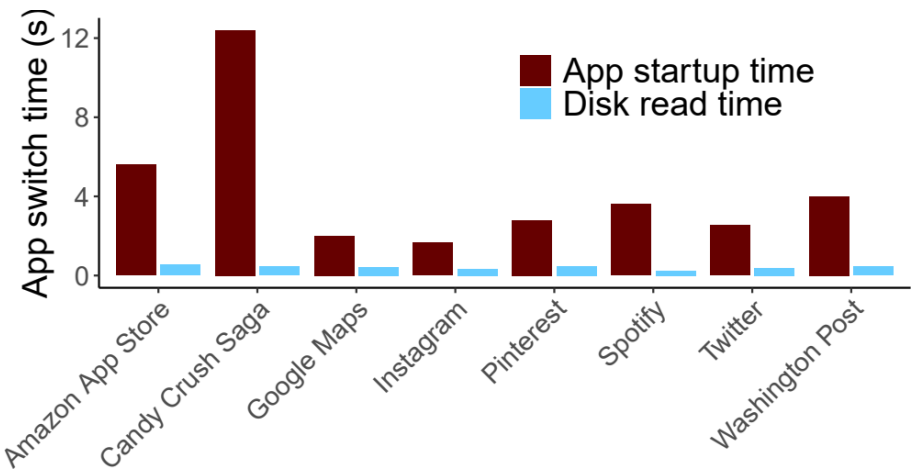
- I currently work at Google (not on Android)
- This work is not connected with Google
  - Research was done while I was a graduate student at UW
  - All data is from our experiments or open-source resources
  - All opinions are our own

This talk

- Motivation
- Key insight and Marvin
- Marvin’s mechanisms
- Marvin’s features
- Implementation and evaluation

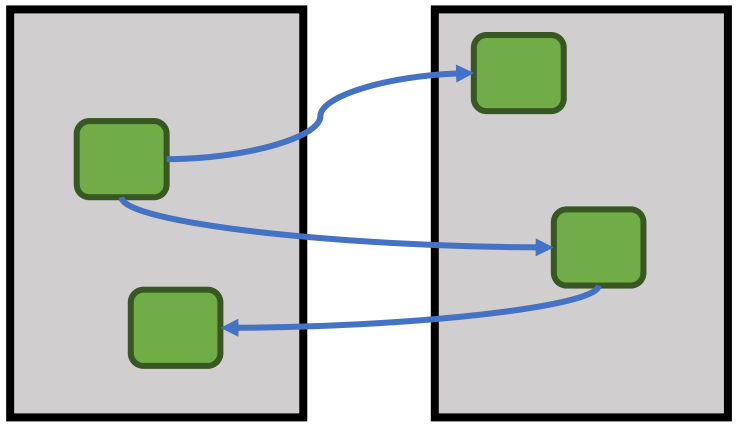
Today's mobile memory management is bad for users and applications

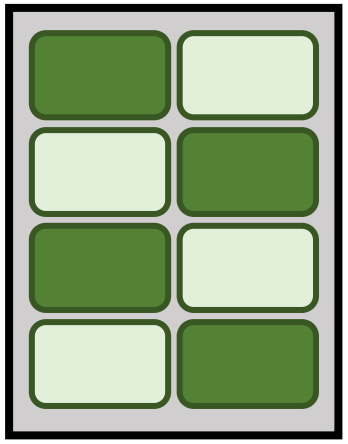
- Each app gets a fixed maximum memory budget
- Mobile OS kills apps when the device runs out of memory
  - Even if apps are not actively using their memory
- Restarting apps takes time
- Developers must optimize app memory usage

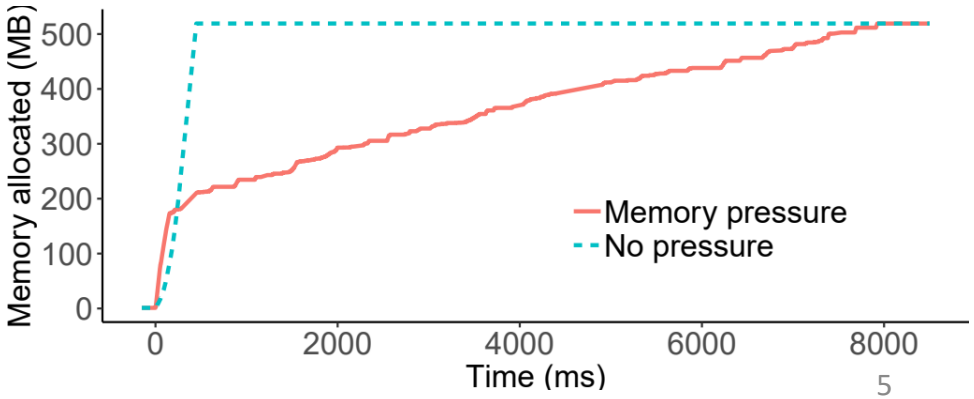


Traditional swapping is not a solution

- Not suited to managed languages (e.g., Java)
  - Garbage collection causes swapping, confuses working set estimation (WSE)
  - Page-granularity swapping and WSE do not fit variable-sized objects
- Not suited to latency-sensitive touch devices
  - On-demand swapping causes stuttering and delays







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Key insight

- We can ***co-design the runtime and OS*** to improve mobile memory management
- Possible because modern mobile platforms require all apps to use the same runtime

Marvin

- Android memory manager co-designed with Android's Java runtime
- Reintroduces swapping to the mobile environment

Marvin

- Marvin has three main features:
  - Ahead-of-time swap
  - Object-level working set estimation
  - Bookmarking garbage collector **[Hertz 05]**

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  - Stubs
  - Reclamation table
  - Object access interposition
- Marvin's features
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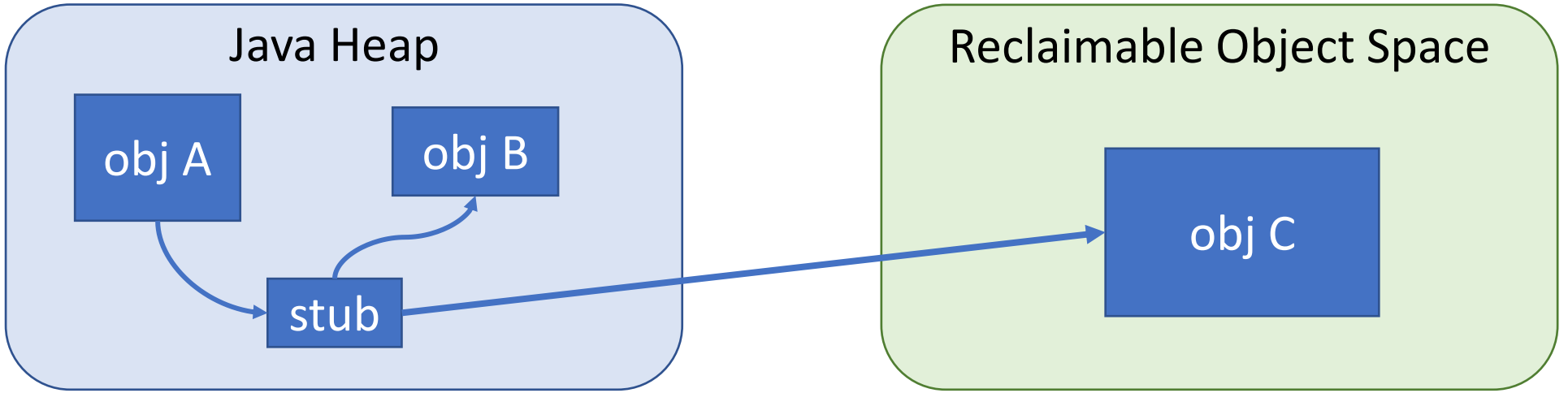
indirection layer between objects
allows the runtime and OS to coordinate
lets the runtime transparently take action

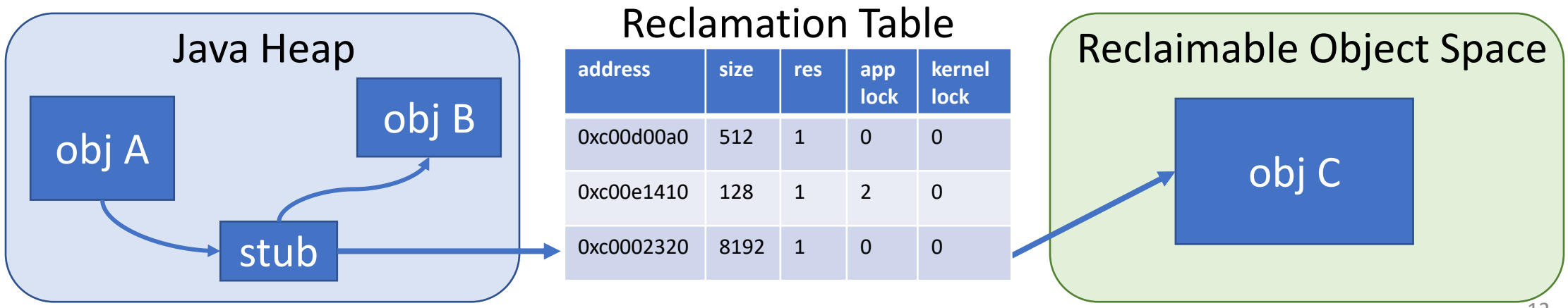
Stubs

- We need an indirection layer between objects referencing each other
  - Catch accesses to swapped-out objects
- ***Stubs*** provide that indirection layer
  - Small pseudo-objects that sit in the Java heap and point to the “real” object
  - Store copies of the real object’s references



Reclamation table

- We need a way for the runtime and OS to coordinate
  - Tell OS which objects can be reclaimed
  - Prevent OS from reclaiming an object being used by the runtime
- A shared-memory ***reclamation table*** allows that coordination
  - Stores an object's location and size, and has metadata bits for locking



Object access interposition

- The runtime needs a way to transparently act when app code accesses objects
  - Restoring swapped-out objects
  - Update working set metadata
- ***Object access interposition*** is a set of paired interpreter and compiler modifications implementing those actions
  - Interpreter directly acts when performing object accesses
  - Compiler generates additional ARM64 instructions around object accesses

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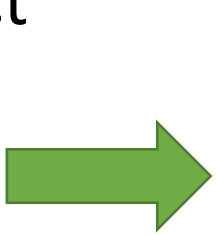
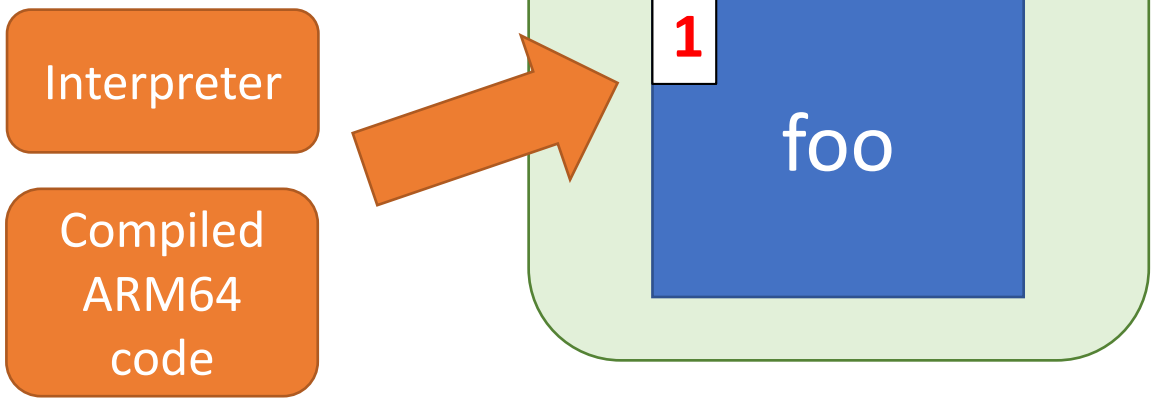
Ahead-of-time swap

- Runtime uses **object access interposition** to set dirty bit in object header
- Runtime clears dirty bit after saving an object
- Kernel checks dirty bit before reclaiming an object

```
foo.setX(42);
```





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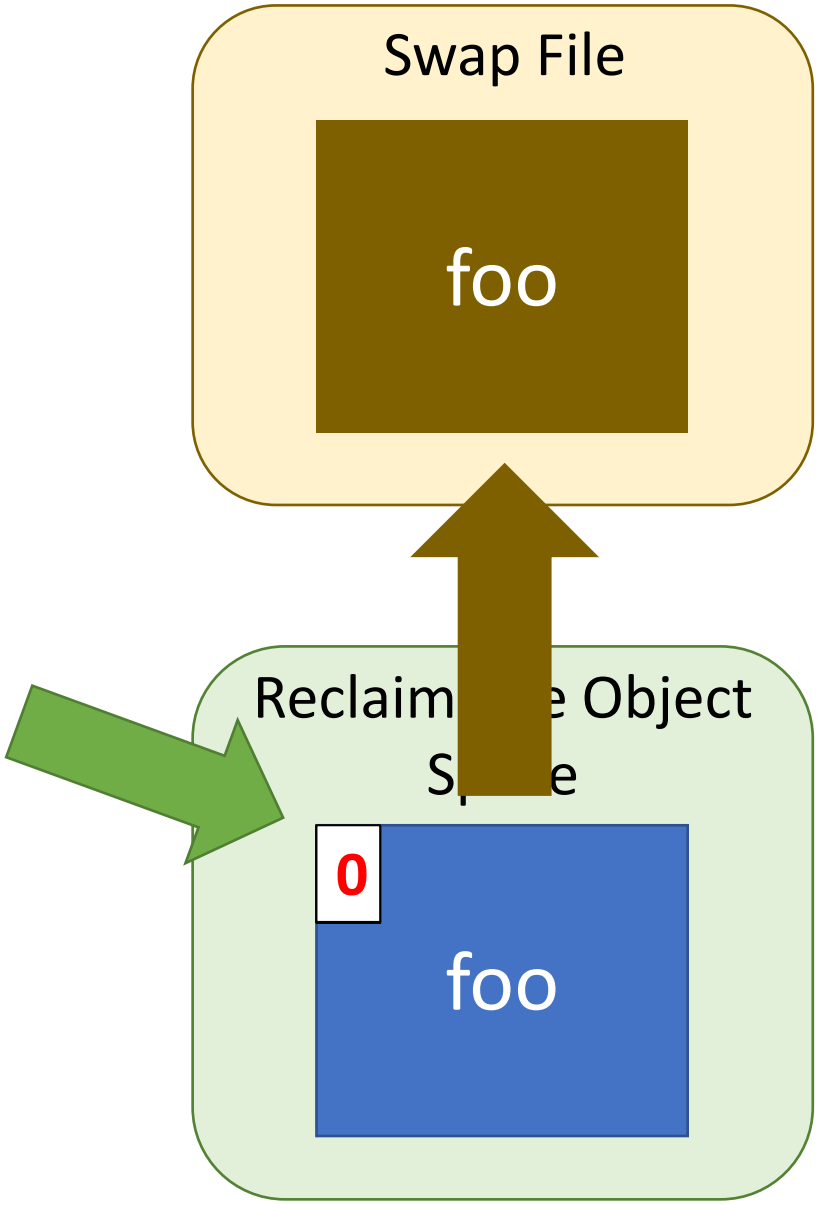

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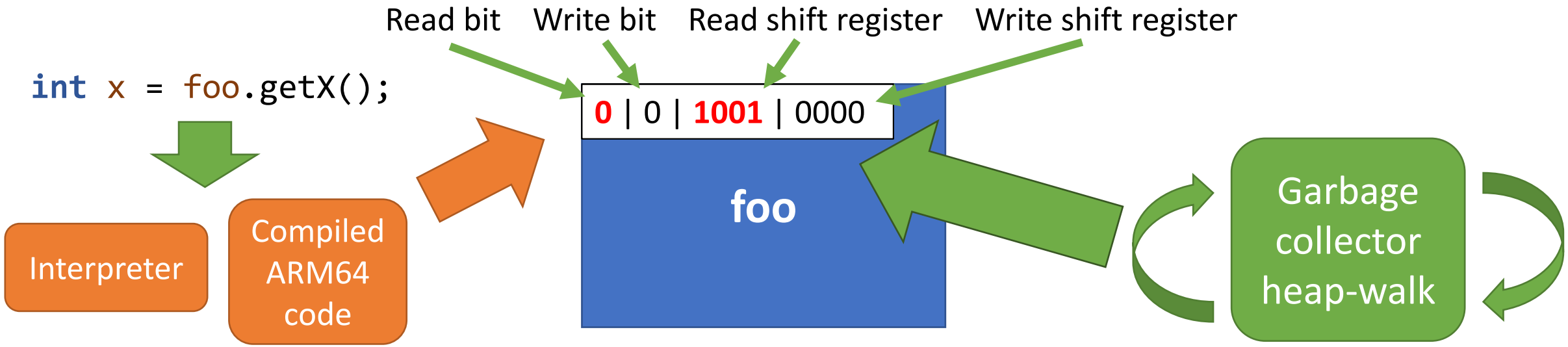
Object-level working set estimation

- Runtime uses **object access interposition** to set access bits
- Runtime scans access bits and updates longer-term WSE metadata



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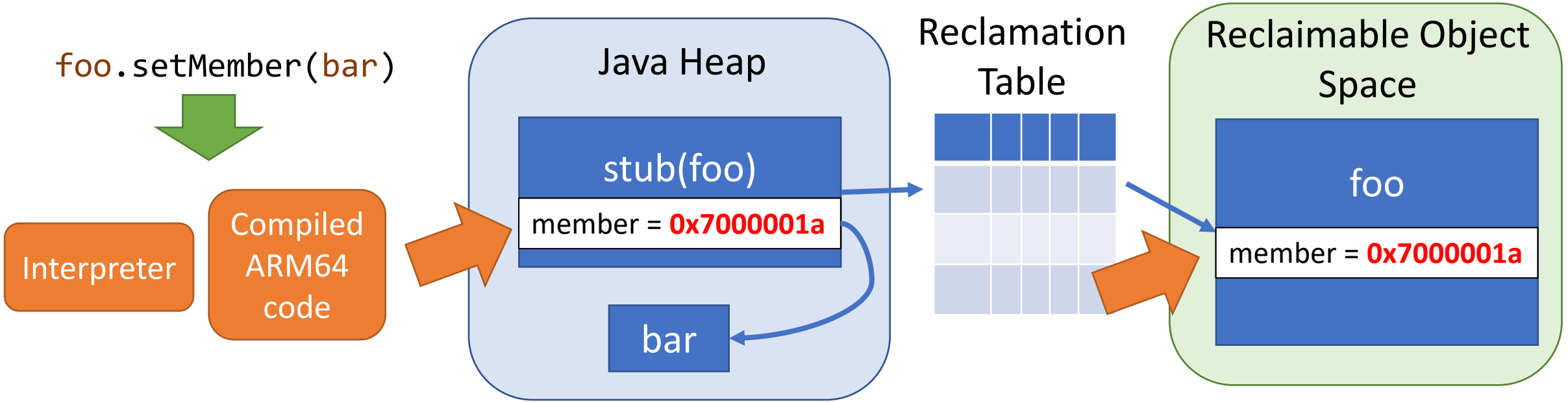
Bookmarking garbage collector

- Runtime uses **object access interposition** to maintain stub references
- GC detects **stubs** and reads references without touching underlying objects



Bookmarking garbage collector

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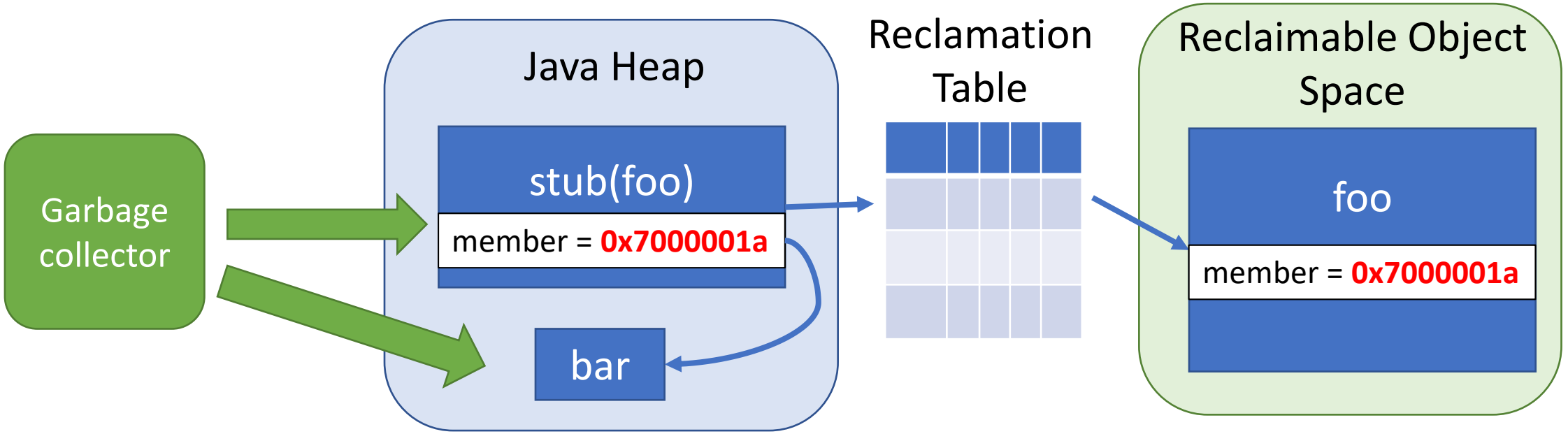

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Marvin implementation

- We modified the Android Runtime (ART) to implement Marvin
- Default policy keeps the foreground app's objects in-memory
- For experiments, we trigger reclamation in the runtime

Evaluation

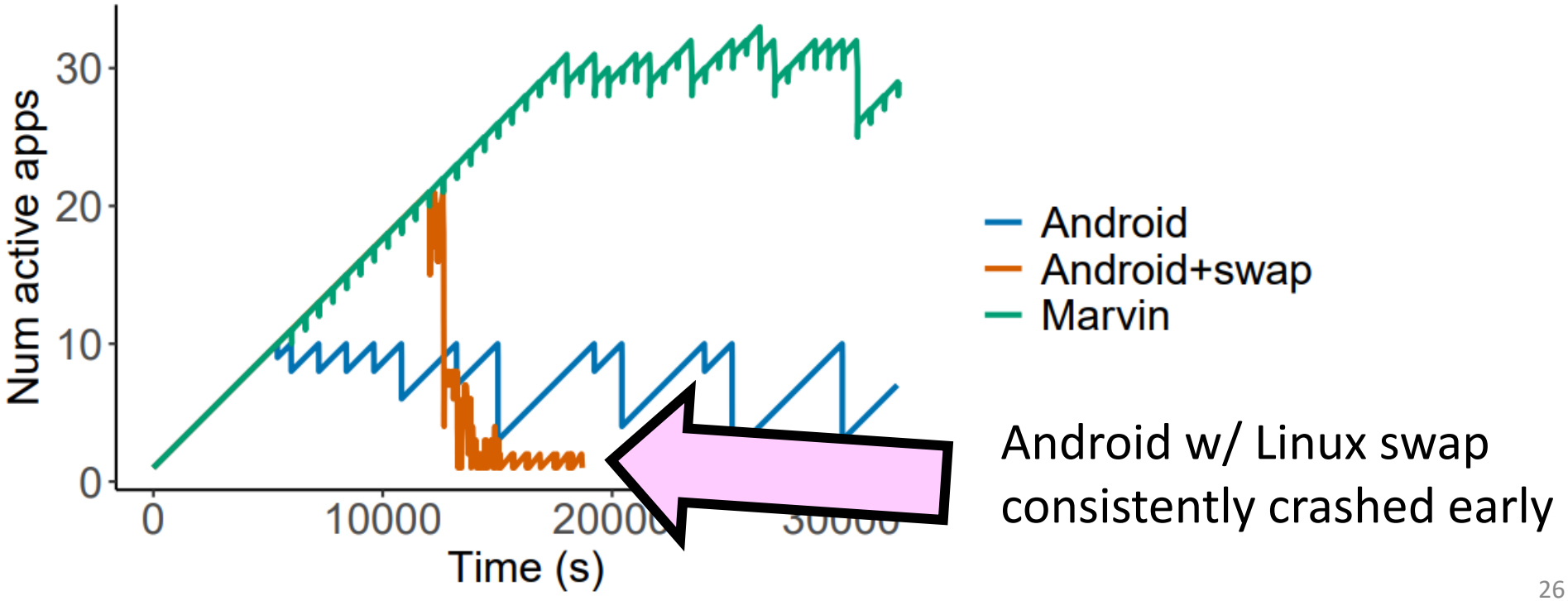
- Experimental setup:
  - Pixel XL phones
  - Android 7.1.1 (or our modified build)
- Questions:
  - Does Marvin let users run more apps?
  - Does ahead-of-time swap work?
  - What is Marvin’s overhead?

Does Marvin let users run more apps?

- We periodically started instances of a benchmark app
  - Initializes a 220MB heap with a mix of 4KB and 1MB arrays
  - Deletes and re-allocates 20MB of those arrays every 5 seconds
- We measured the number of ***active apps***: apps that are alive and making progress on their workloads

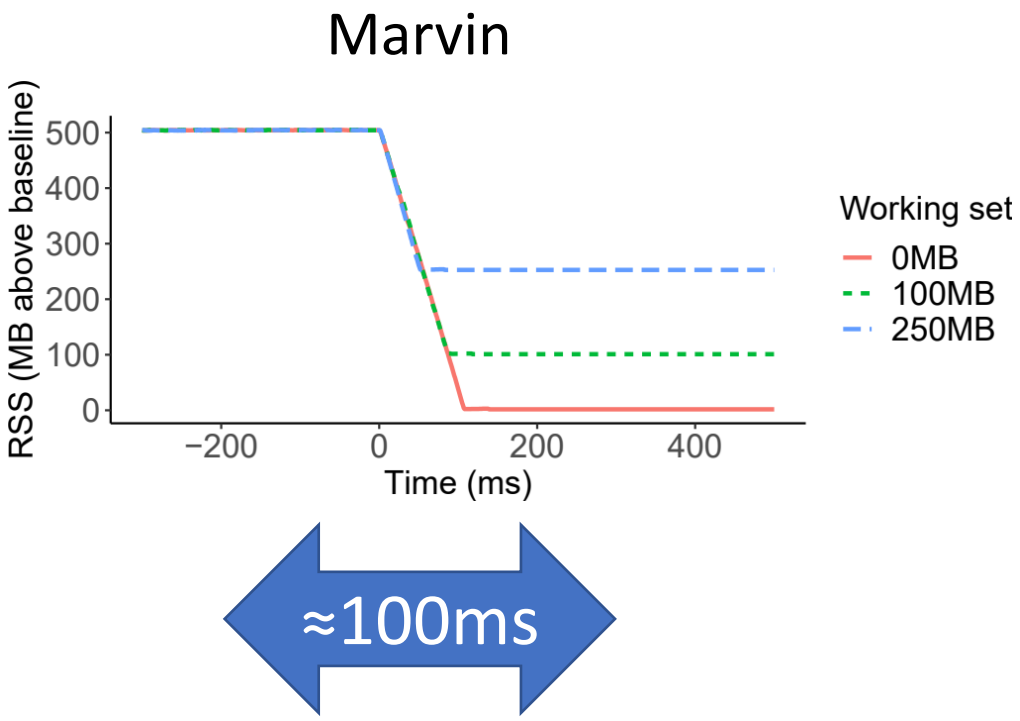
Does Marvin let users run more apps?

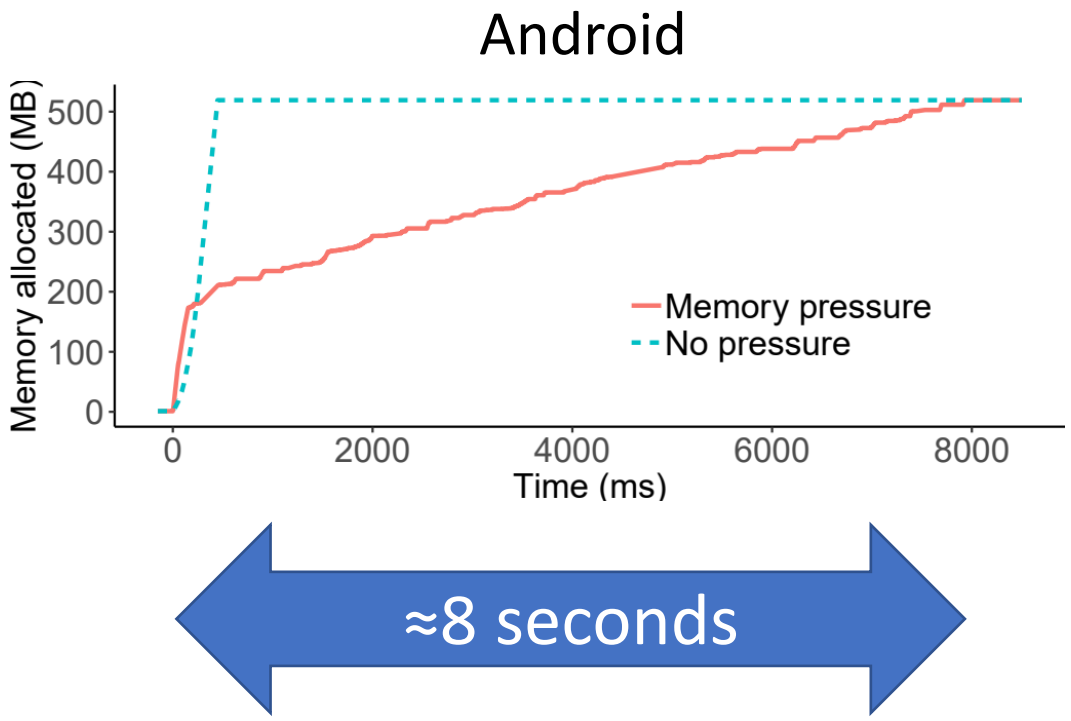
- Marvin can run over 2x as many apps as stock Android
- On Android w/ Linux swap, a little allocation makes apps unusable



Does ahead-of-time swap work?

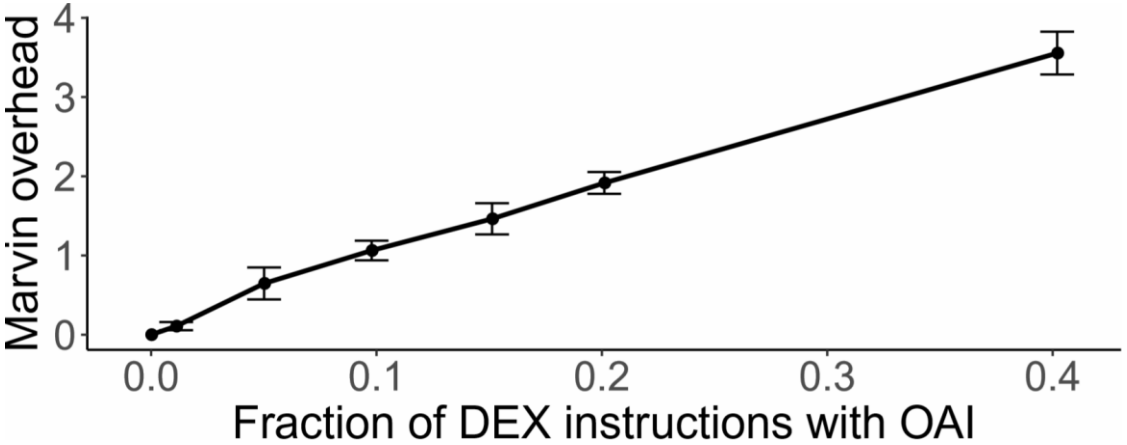
- Marvin reclaims memory much faster than Android w/ Linux swap



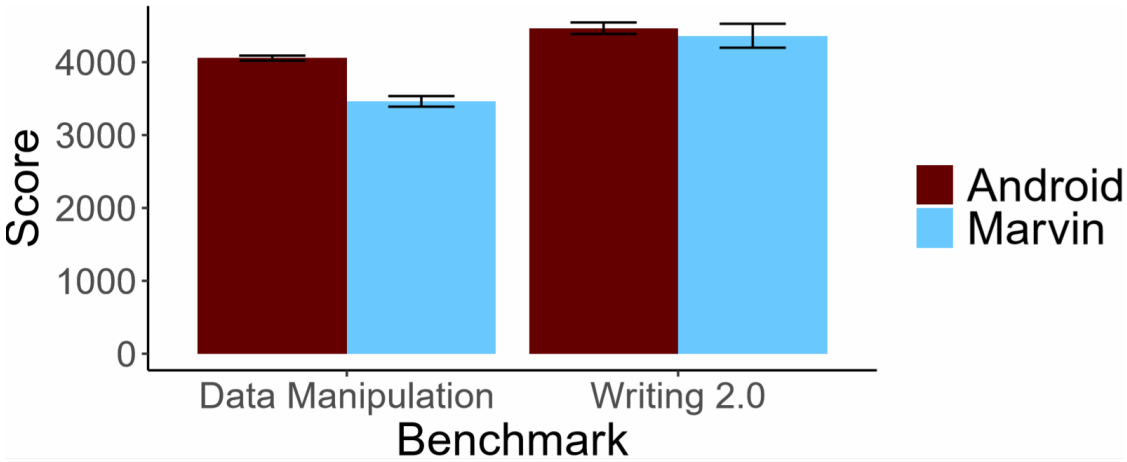


What is Marvin's overhead?

- When objects are memory-resident, execution overheard depends on proportion of object accesses



- Overhead is reasonable (15%) on PCMark benchmark



Related work

Similarities with Marvin

Acclaim **[Liang 20]**

SmartSwap **[Zhu 17]**

A2S **[Kim 17]**

MARS **[Guo 15]**

Policies distinguish between foreground and background apps

Related work

Similarities with Marvin

Acclaim **[Liang 20]**

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MARS **[Guo 15]**

Addresses incompatibility of garbage collection and kernel-level swap

Related work

Differences from Marvin

Acclaim **[Liang 20]**

SmartSwap **[Zhu 17]**

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MARS **[Guo 15]**

Perform swapping at the kernel level rather than the runtime level

Conclusion

- **Problem:** Today's mobile memory management is inadequate
- **Insight:** We can co-design the runtime and OS to improve memory management
- **Solution:** Marvin improves mobile memory management with three co-design features
  - Ahead-of-time swap
  - Object-level working set estimation
  - Bookmarking garbage collection

Thanks!

- Marvin source code is available on GitHub: https://github.com/UWSysLab
- Contact: nl35@cs.washington.edu