Runtime Integrity Checking for Exploit Mitigation on Embedded Devices

Matthias Neugschwandtner
IBM Research, Zurich
eug@zurich.ibm.com

Collin Mulliner
Northeastern University, Boston
collin@mulliner.org

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Embedded Devices?

Internet of Things!

Embedded Devices

- Produced in large quantities
  - not a computer, but actually a computer
- Mostly low cost/power/end RISC-based CPUs
  - exceptions, e.g. CPUs for smartphones
- Devices run open/free software such as Linux
  - light software stacks, for example uClibc

Embedded Device Security

- Valuable targets
  - always on
  - contain interesting personal data
  - control important things

- Contain software vulnerabilities
  - e.g. memory corruption
  - exploited like desktops and servers

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- Contain software vulnerabilities
  - **e.g. memory corruption**
  - **exploited like desktops and servers**
- **Mitigations not state of the art!**

Exploit Mitigation - State of the Art

Exploit stages:

- Inject payload
- Hijack control flow
- Run payload

Exploit Mitigation - State of the Art

- Inject payload
  - Data Execution Prevention
  - Address Space Layout Randomization
- Hijack control flow
  - Control Flow Integrity
- Run payload
  - Policies for system call usage
  - System call based IDS

Exploit Mitigation - State of the Art

- Inject payload
  - Data Execution Prevention
    - MMU hardware support required (SW emulation slow)
  - Address Space Layout Randomization
    - limited address space on embedded devices

- Hijack control flow
  - Control Flow Integrity
    - source code beneficial
    - high overhead
    - hardware support only for next-gen Intel processors

- Run payload
  - Policies for system call usage
    - requires writing policies for every application
  - System call based IDS
    - mimicry attacks, overhead

Goal: SotA Mitigations for embedded RISC devices

- Leightweight exploit mitigation
  - also suitable for “budget” SoCs

- Use RISC hardware features

- Tailor for “binary only” / COTS
  - source code is not always available

RISC Architecture Features

- Register only operations
  - load / store architecture
- Many registers and specialized registers
  - e.g. control flow
- Fixed instruction length
  - easier disassembly
- Instruction / address alignment
  - no jumping into the middle of an instruction

Exploits revisited

- Exploits use OS functionality
  - read/write data, launch process, …
- Exploit OS usage differs from original program
  - different syscall, different parameters, ...

Exploits revisited

- Exploits use OS functionality
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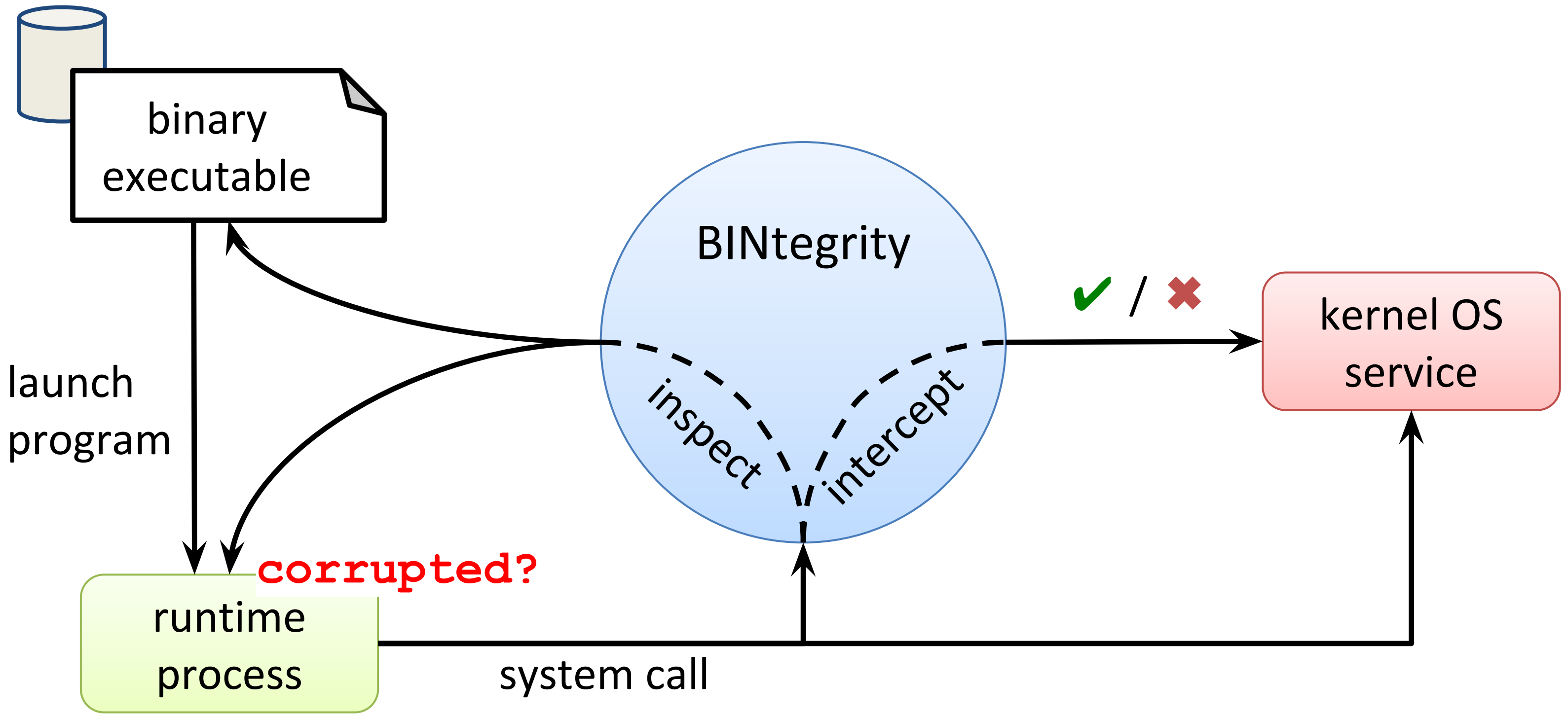
  - different syscall, different parameters, ...
- **Ensure that <u>runtime</u> OS usage is coherent with OS usage in <u>binary executable</u>**

⇒ BINtegrity

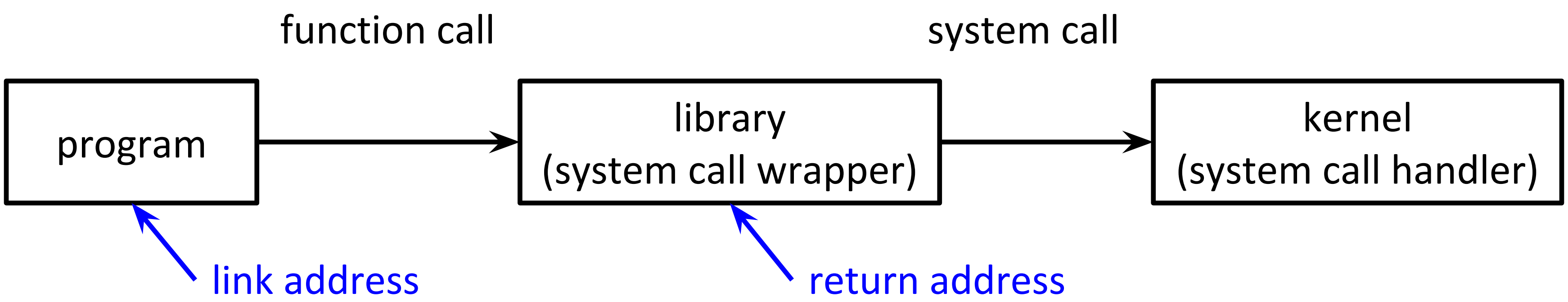
Threat Model

- Trusted kernel ✓
  - we protect user space code
- Trusted binaries on disk ✓
  - executable and libraries not modified by attacker
- Memory is untrusted ✗
  - we try to fight off memory corruption attacks!

BINtegrity Overview



Process Runtime State

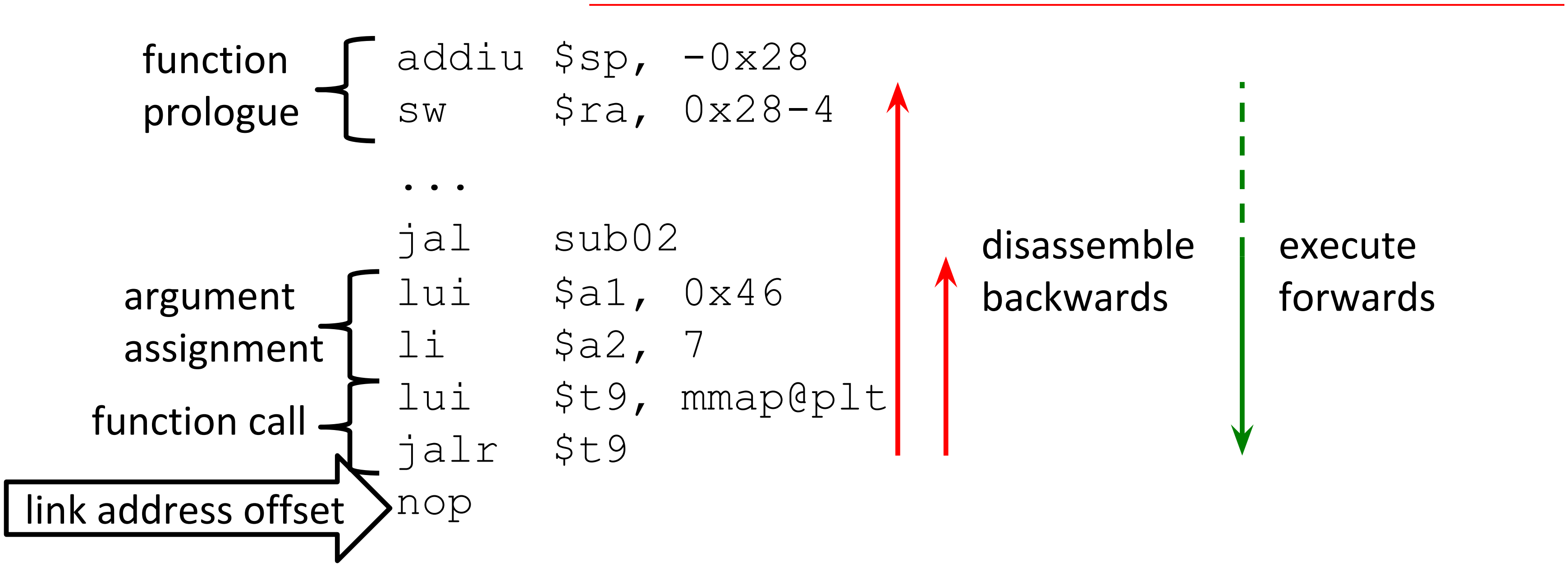


- System call return address $\texttt{ret}_{\texttt{sc}}$
- System call information
  - System call number
  - System call arguments

- Link address $\texttt{ret}_{\texttt{lr}}$
  - specific to RISC
  - register containing return address of last function invocation

- Indirect jump target (on MIPS)

Code Invariant Extraction



- Leightweight execution state (only registers)
- Invariants = concrete values at end of execution
- Static analysis on the binary executable on disk

Enforcing Integrity

1. Code Provenance
   - where do function invocations originate from?
   - only allow legit locations
2. Code Integrity
   - is the call chain reflected by the binary?
   - do the system call arguments match the invariants?
3. Symbol Integrity
   - are called system call wrappers actually imported?

Enforcing Code Provenance

- Trusted Application Code Base (TACB)
  - valid code regions of the process runtime image
    - mapped text segments of a running process
    - includes text segments of libraries
  - fixated after linking stage

- Call chain has to originate from the TACB
  - return addresses: both $\texttt{ret}_{\texttt{sc}}$ and $\texttt{ret}_{\texttt{lr}}$
  - everything outside TACB is invalid

Enforcing Code Integrity

program code

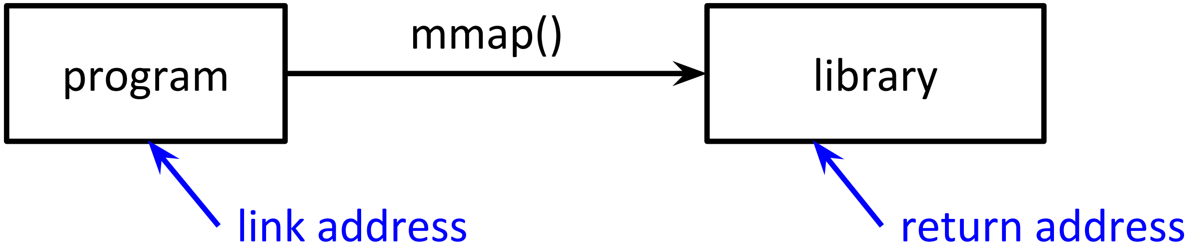
```
...
lui     $a3, 0x46
li      $a0, 7
lui     $t9, mmap@plt
jalr    $t9
nop
```

syscall wrapper

```
...
lw       $t0, 0xcafe
or       $a3, t0
li       $v0, 0x101D
syscall 0
nop
```

- Is the predecessor of $\texttt{ret}_{\texttt{sc}}$ really a syscall?
  - has the right syscall been invoked?
- Is the predecessor of $\texttt{ret}_{\texttt{lr}}$ really a control flow transfer?
  - does the target of the branch match the callee?
- Do the actual syscall arguments match the invariants?
  - does the syscall wrapper modify arguments?

Enforcing Symbol Integrity

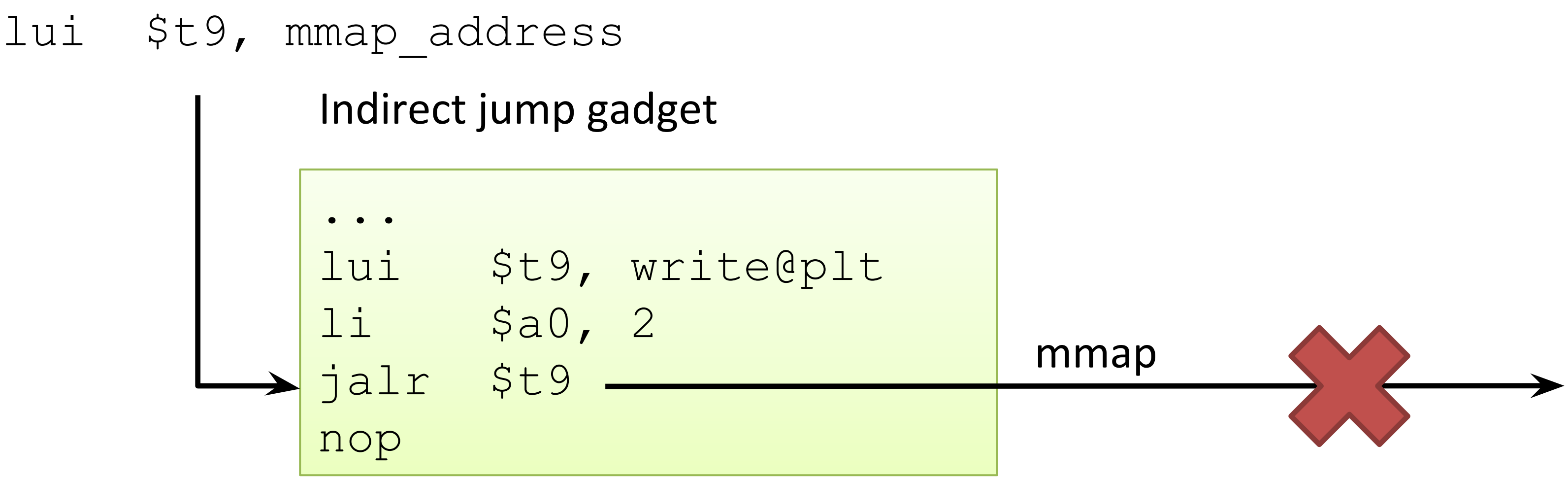


- Dynamic linking uses function symbols
- Symbol mmap has to be
  - exported by the library
  - imported by the program
- Match
  - symbol of function identified by return address
  - imports of binary identified by link address

Exploit Mitigation

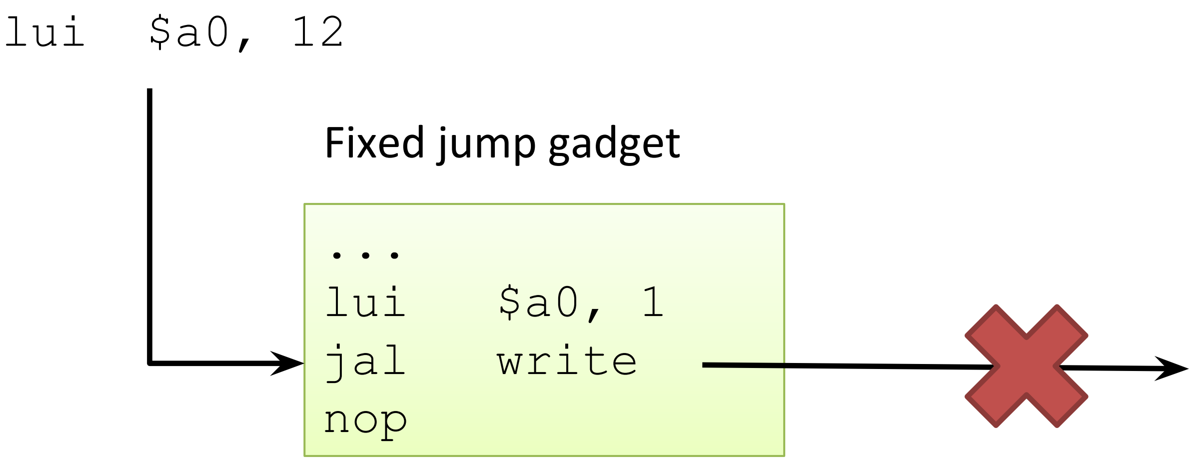
Attack class	Technique	Defense
Code injection	inject code in data segment	code provenance
	inject (and overwrite existing) code in text segment	code integrity (instruction mismatch)
Code reuse	use indirect jump gadget	code integrity (target of branch does not match)
		symbol integrity (function not imported)
	use gadget that calls library function	argument integrity (argument mismatch)

Exploit Mitigation: Code Reuse



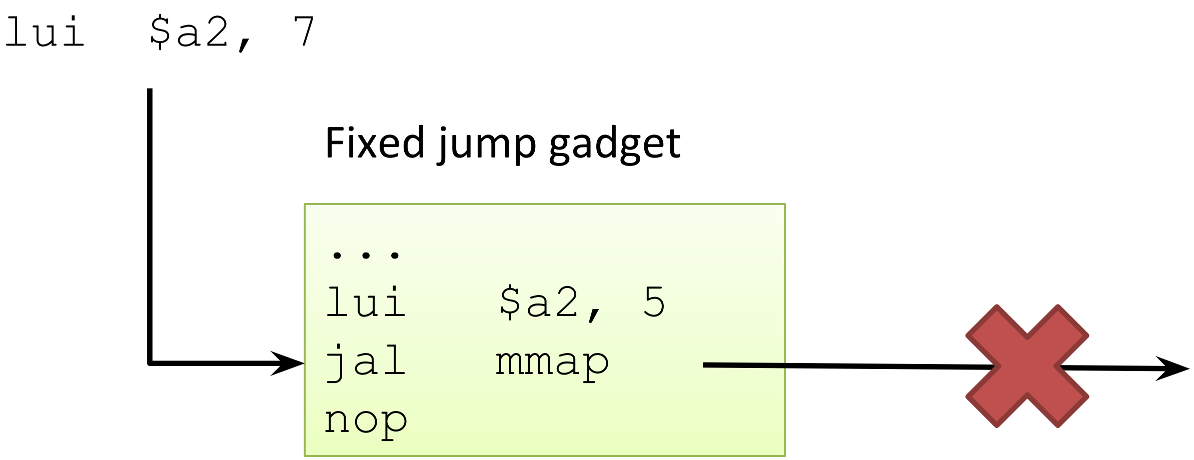
- Violates call chain integrity
  - register `$t9` does not match invariant

Exploit Mitigation: Code Reuse



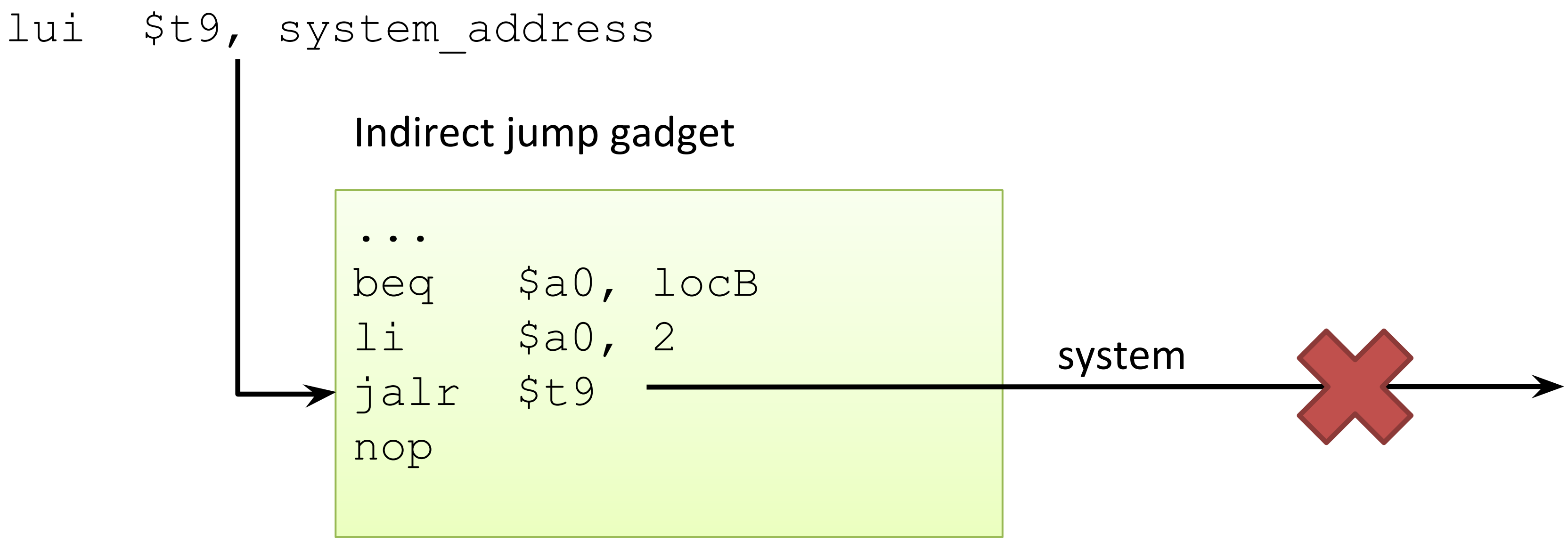
- Violates argument integrity
  - runtime state value for $a0 contradicts invariant
  - write can only access stdout

Exploit Mitigation: Code Reuse



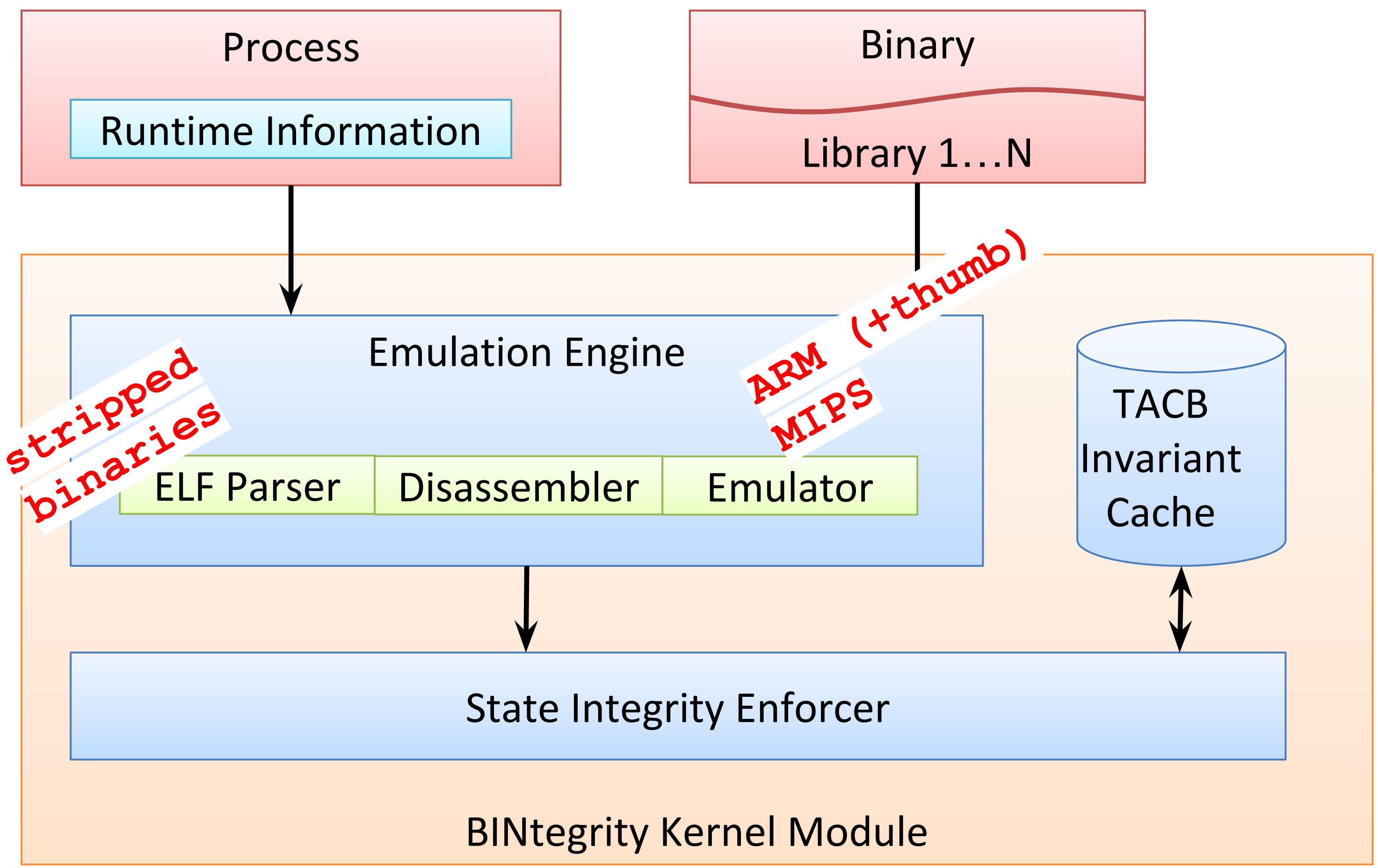
- Violates argument integrity
  - runtime state value for $a2 contradicts invariant: RWX (7) vs. RX (5)
  - mmap can only map read/write

Exploit Mitigation: Code Reuse



- Violates symbol integrity
  - `system` is not imported by the program

The BINtegrity System



Performance Evaluation

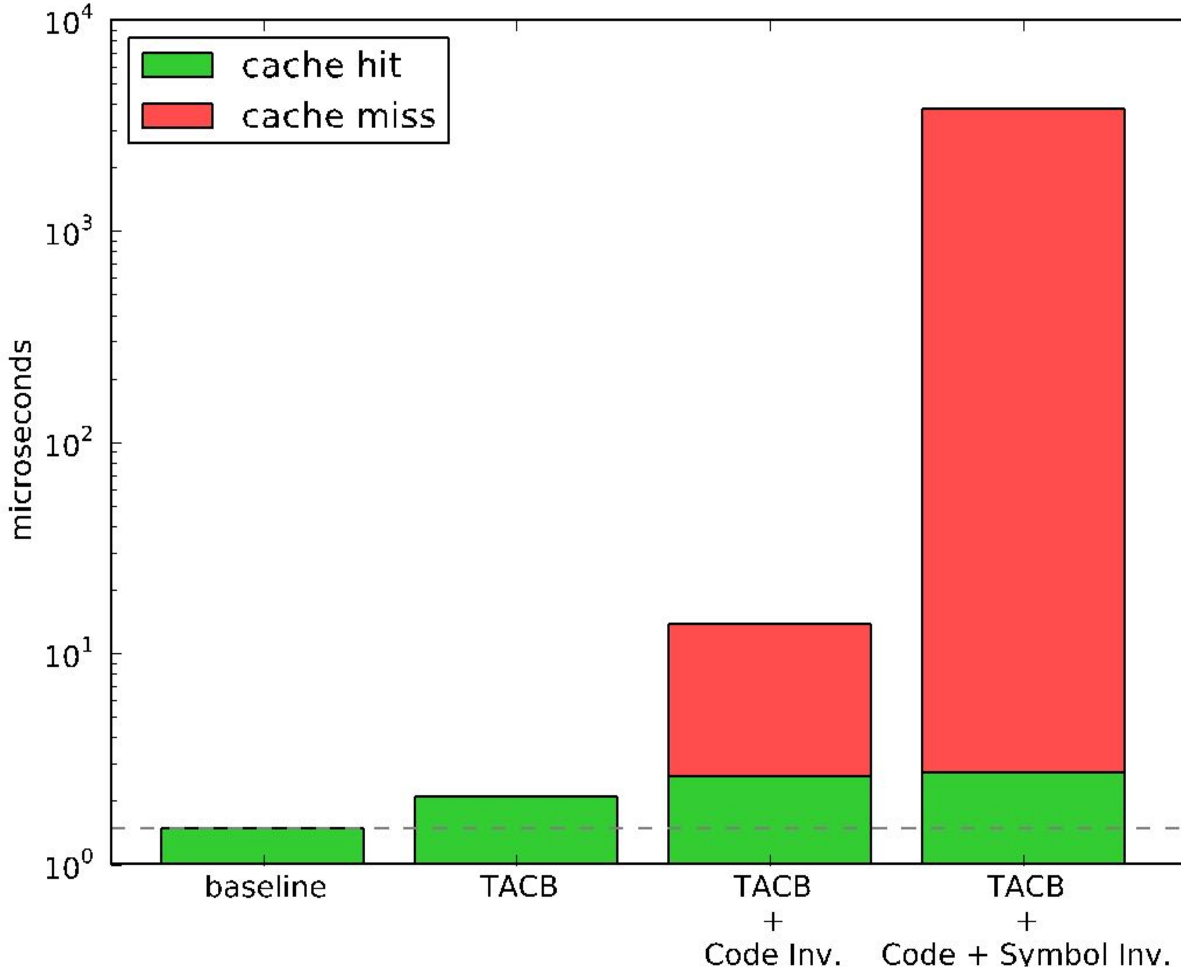
- Buffalo Router WZR-HP-G450H (MIPS)
  - Apache benchmark & nginx
  - <u>runtime overhead: 2.03%</u>

- Galaxy Nexus Phone (ARM)
  - AnTuTu benchmark
  - measures Android runtime & I/O subsystem
  - <u>runtime overhead: 1.2%</u>

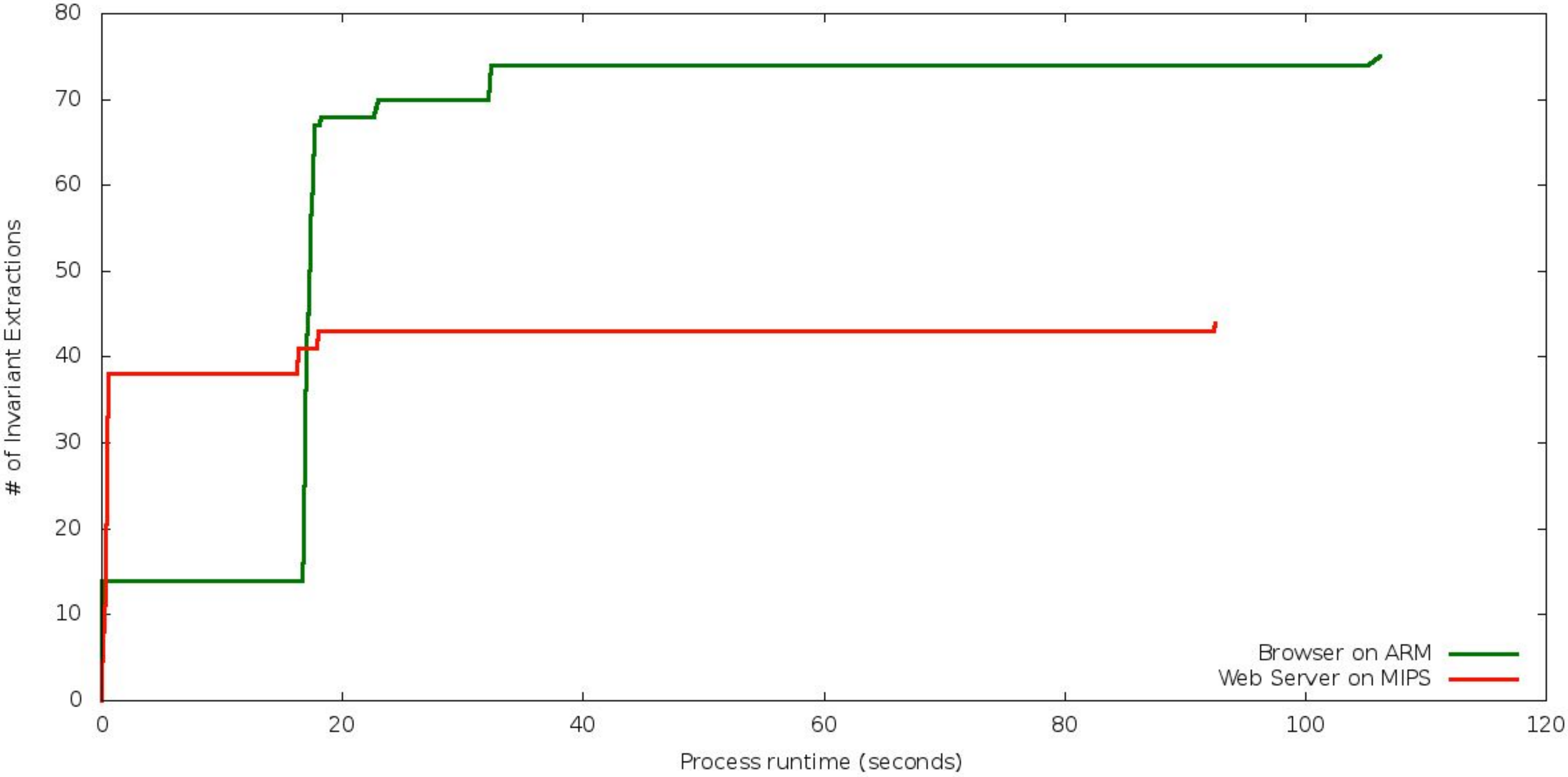
Internal Performance Evaluation

- Costly operations
  - reading and parsing files
  - instruction emulation
- Memory footprint
  - Kernel module code
  - Cache
    - cache invariants for < 257 code points
    - 16 bytes per code point
    - requires total of 12KB per process

Performance: Caching



Performance: Invariant Extractions



Conclusions

- Cover-all-bases mitigation approach
  - from payload injection, over hijacking control flow, to running the payload
- Practical
  - no rewriting, no instrumentation, no configuration
  - transparent to applications
- Efficient
  - only 2% overhead in application-level benchmarks
- Open source
  - download at http://www.bintegrity.org/

End