AVATAR: A Framework for Dynamic Security Analysis of Embedded Systems' Firmwares

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Outline

- Introduction
- AVATAR overview
- Framework components
- Use cases
- Conclusion

Software is everywhere

- Embedded devices are diverse – but all of them run software

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Reasons for embedded security

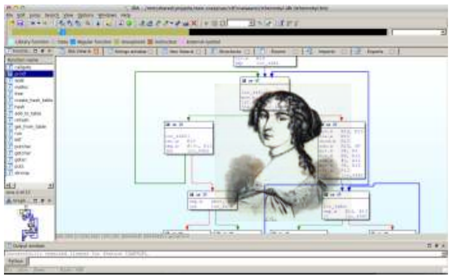
- Embedded devices are ubiquitous
  - Even if invisible, they are essential to your life
- Can operate for many years
  - Legacy systems, no (security) updates
- Have a large attack surface
  - Networking, forgotten debug interfaces, etc

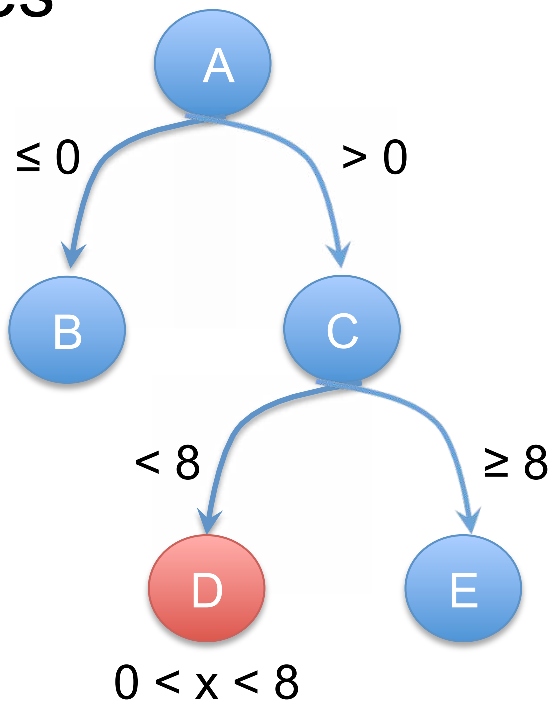
Third party security evaluation

- No source code available
- No toolchain available
- No documentation available
- Distinct tools (to flash and debug) for each manufacturer

Wishlist for security evaluation

- Typical PC security toolbox
  - Advanced debugging techniques
    - Tracing
    - Fuzzing
    - Tainting
    - Symbolic Execution
  - Integrated tools
    - IDA Pro
    - GDB





Challenges

- Advanced dynamic analysis needs emulation
- Full emulation
  - Unknown peripherals
  - Firmware fails if peripherals are missing
- Integration
  - Support multiple vendors and platforms

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AVATAR

- Orchestrate execution between emulator and device
- Forward peripheral accesses to the device under analysis
- Do **not** attempt to emulate peripherals
  - No documentation
  - Reverse engineering is difficult

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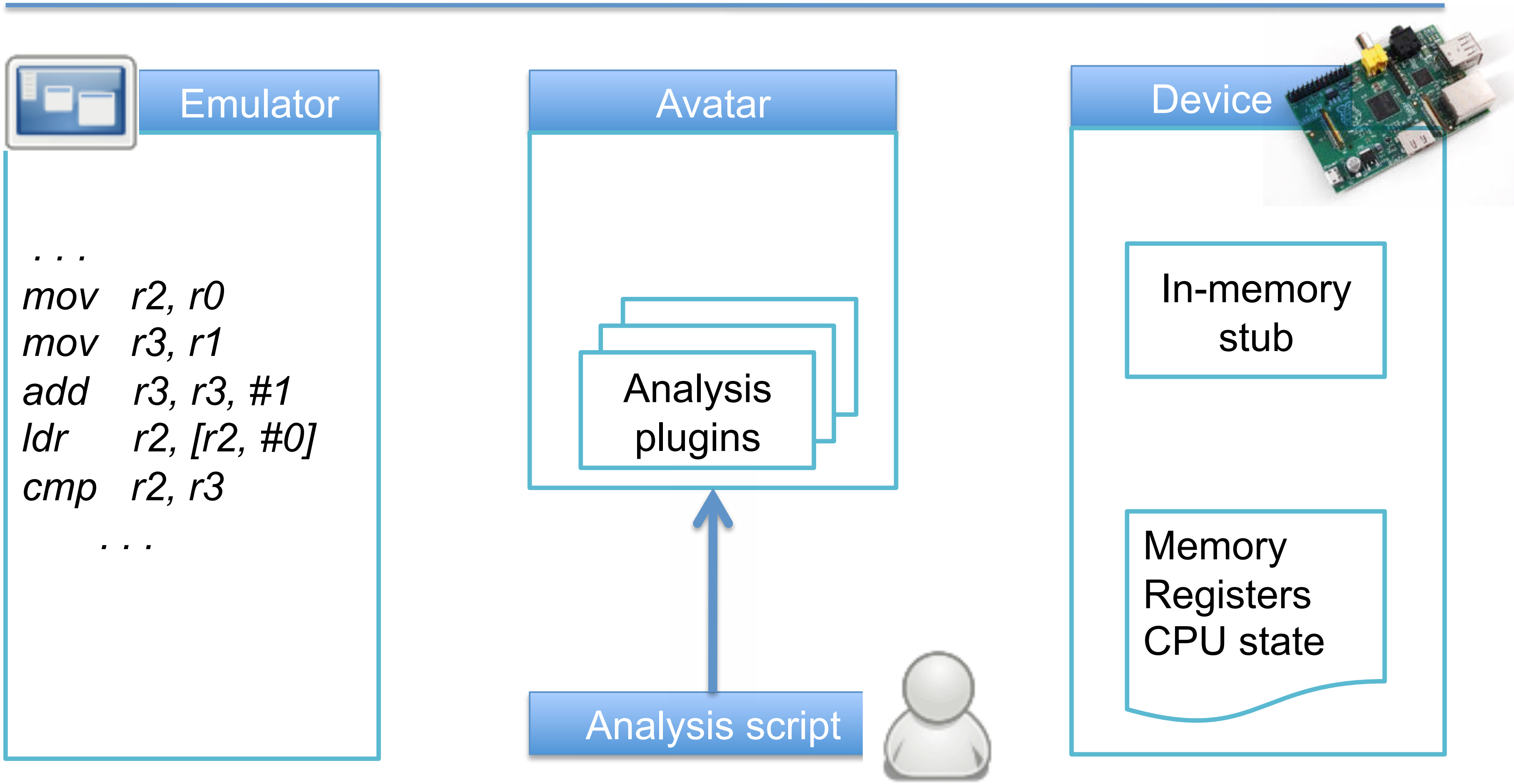
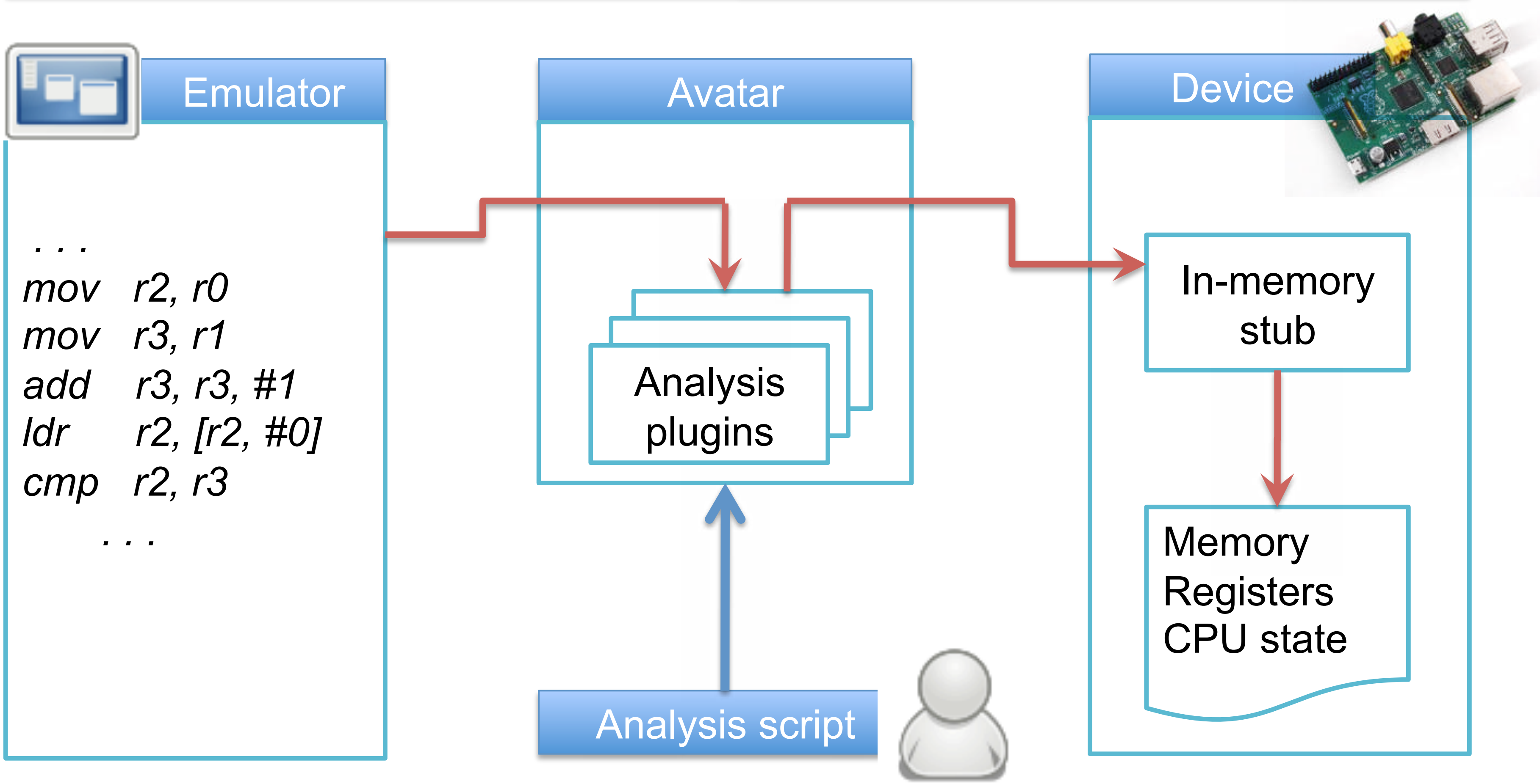
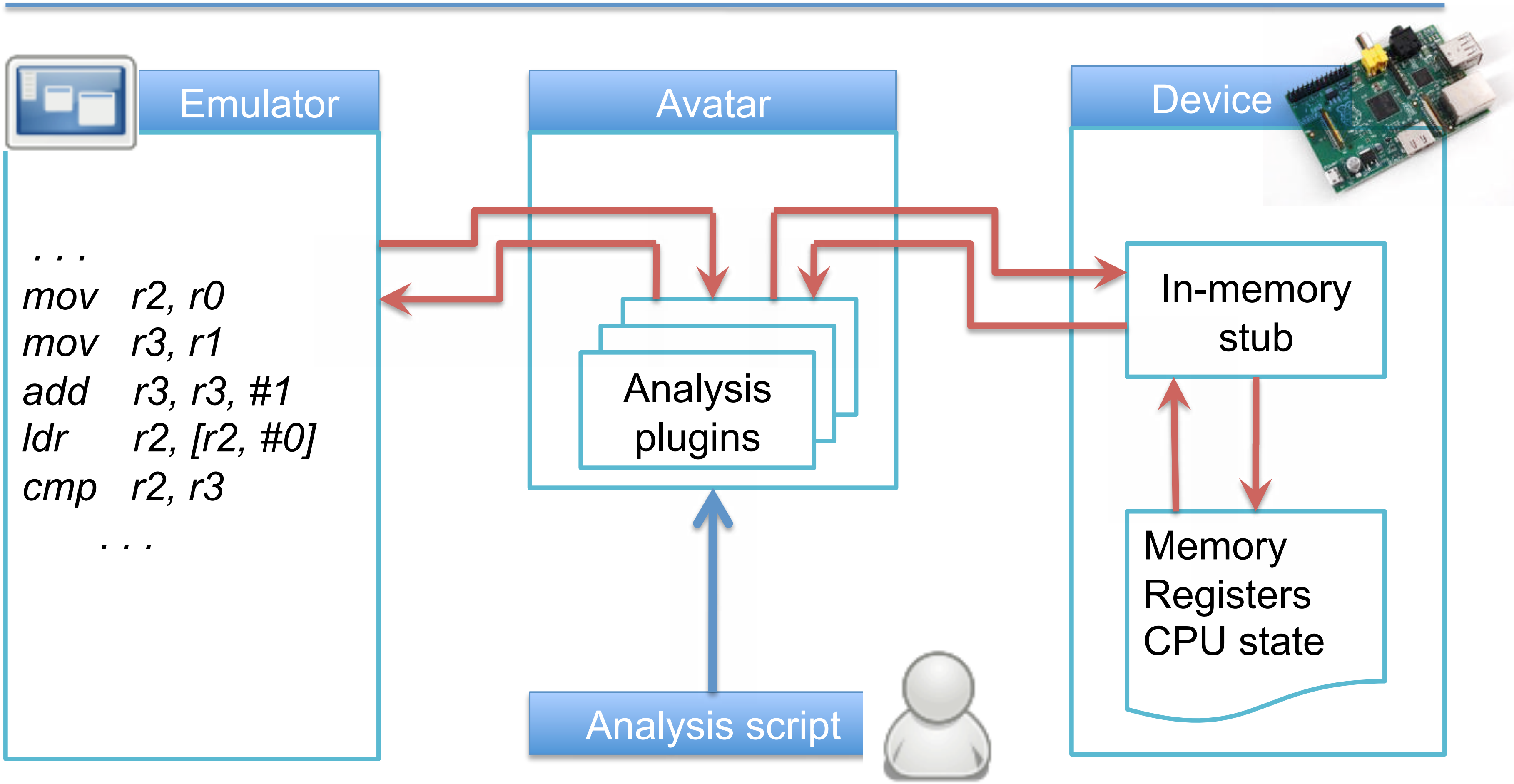
Avatar overview



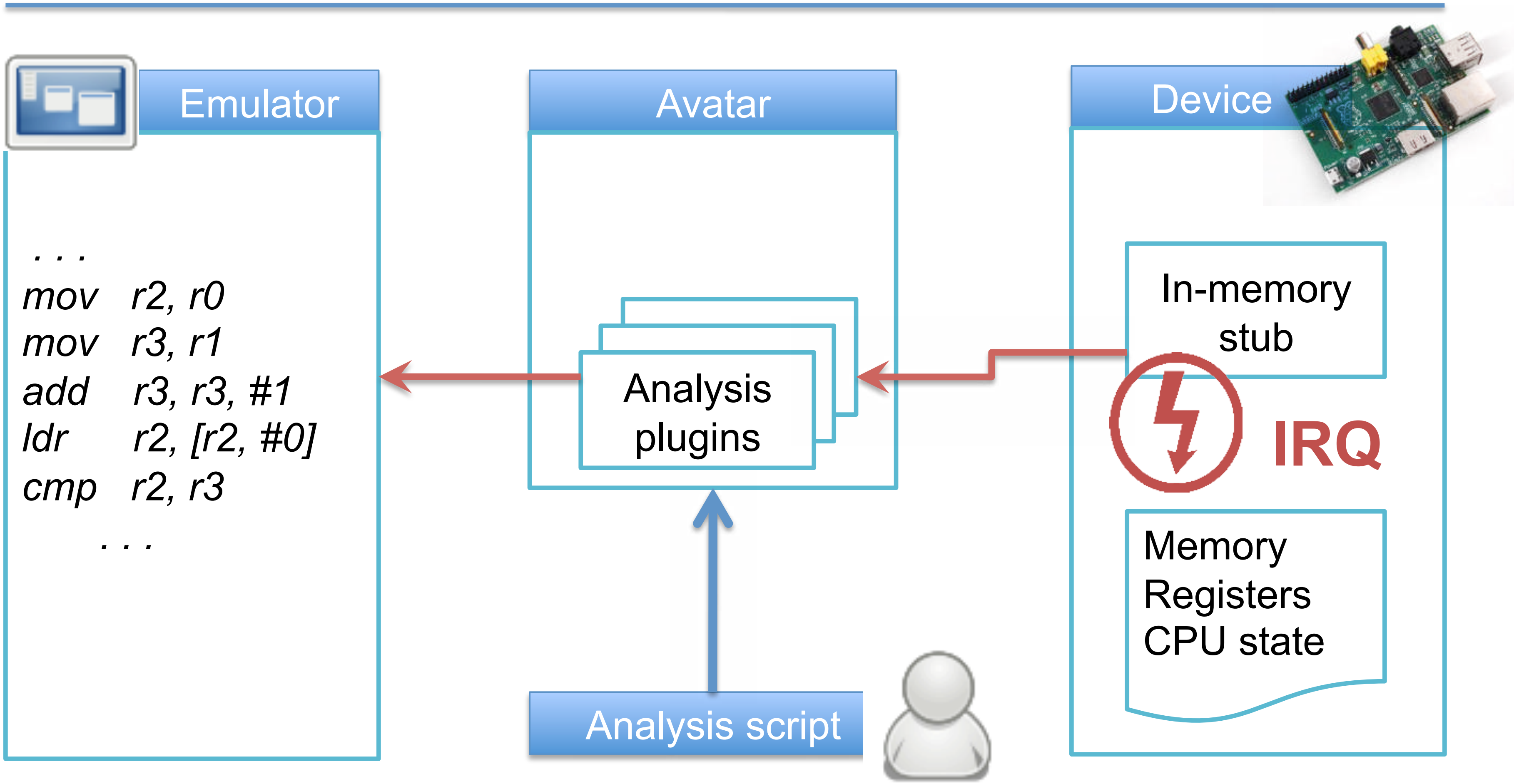
Avatar overview



Avatar overview



Avatar overview



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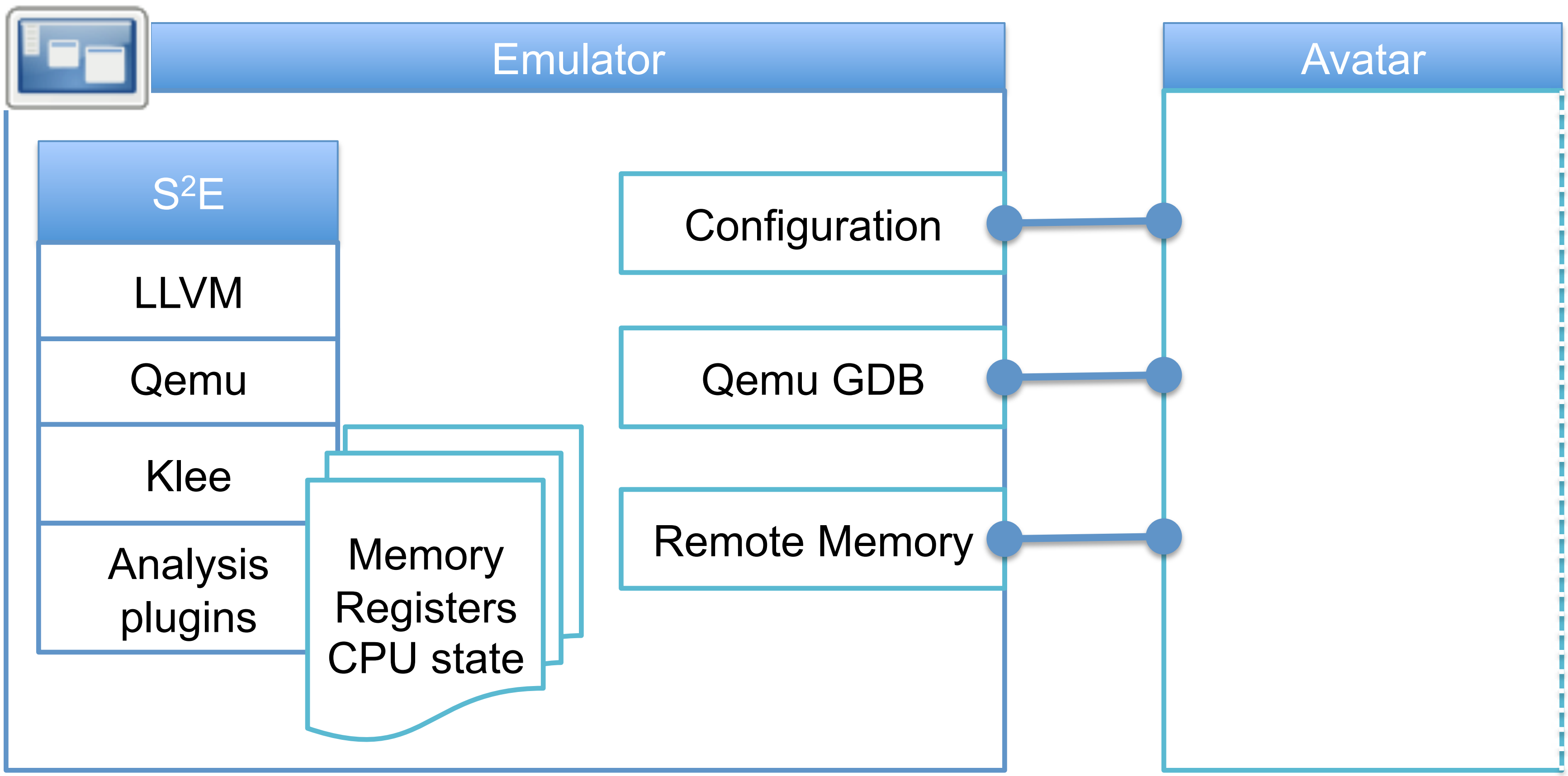
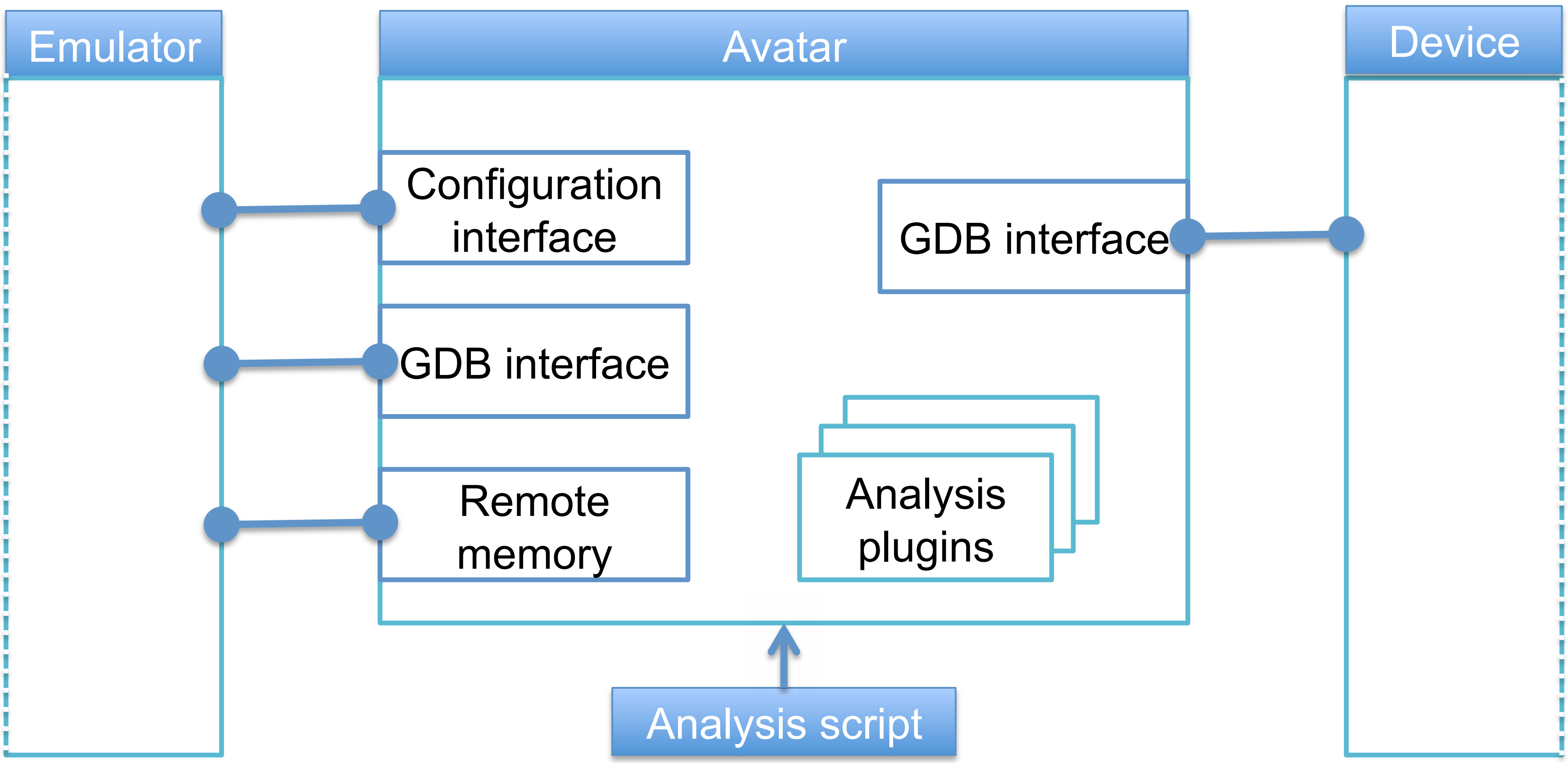
Emulator

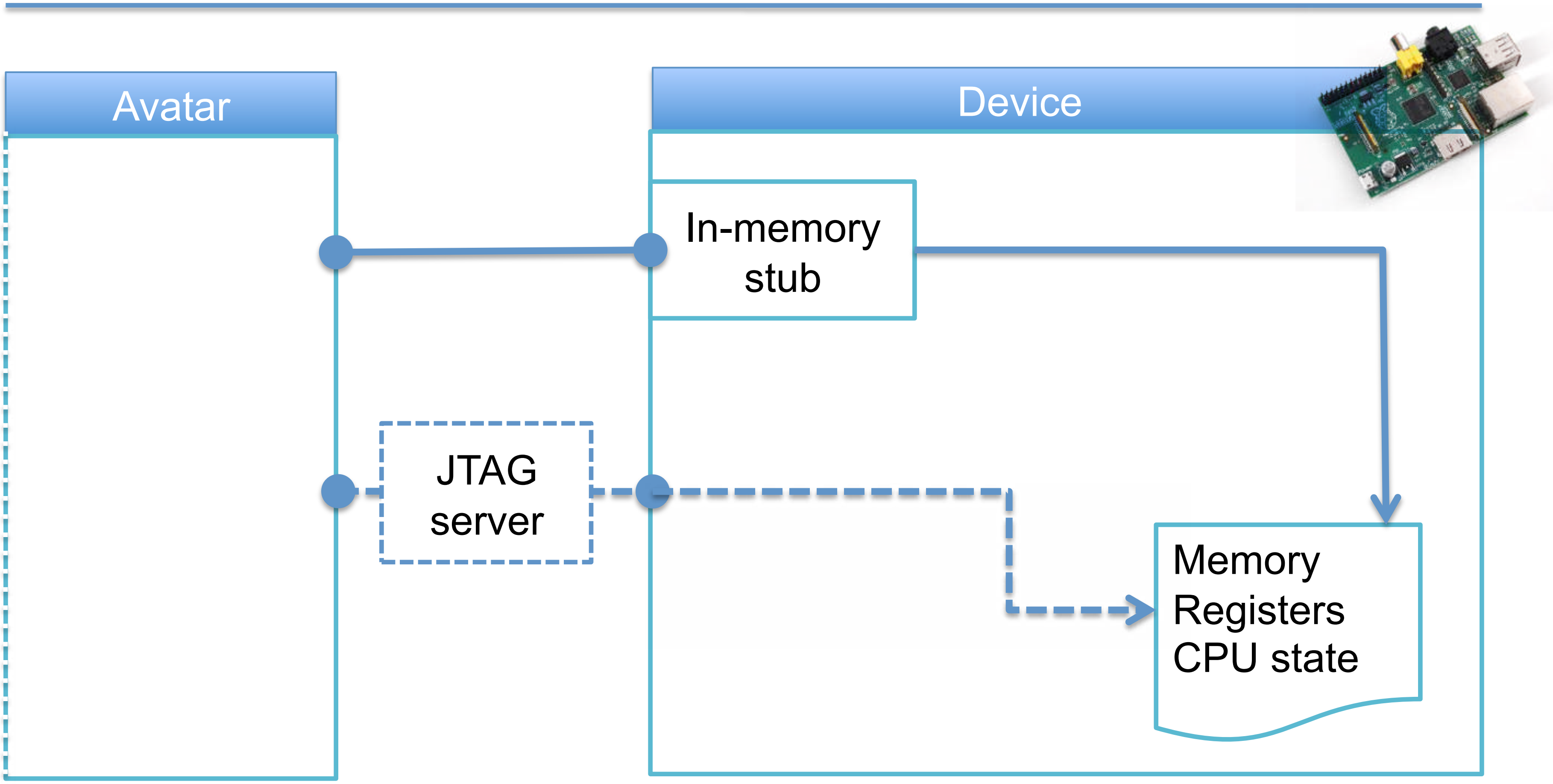


Emulator
Avatar
S²E
LLVM
Qemu
Klee
Analysis plugins
Memory
Registers
CPU state
Configuration
Qemu GDB
Remote Memory

Avatar core


Emulator
Avatar
Device
Configuration interface
GDB interface
GDB interface
Remote memory
Analysis plugins
Analysis script

Embedded target



Target communication

- Either a debugging interface
  - JTAG
  - Debug Serial Interface

- Or code injection and a communication channel
  - Custom GDB Stub + Serial Port

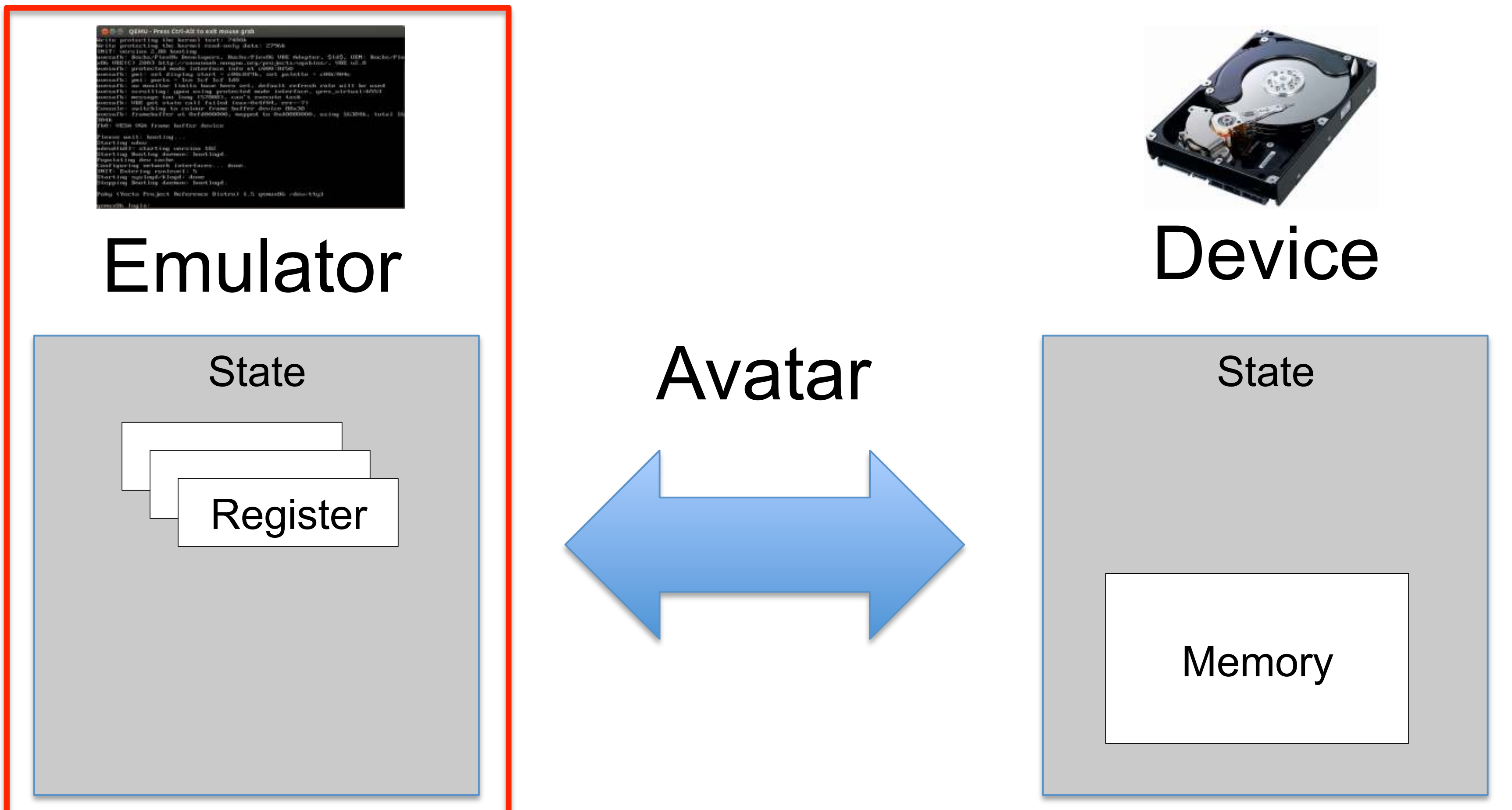
Bottlenecks

- Emulated execution is much slower than execution on the real device
  - Memory access forwarding through low-bandwidth channel is the bottleneck
  - In one case down to ~10 memory accesses/sec.
- Interrupts can saturate debug connection

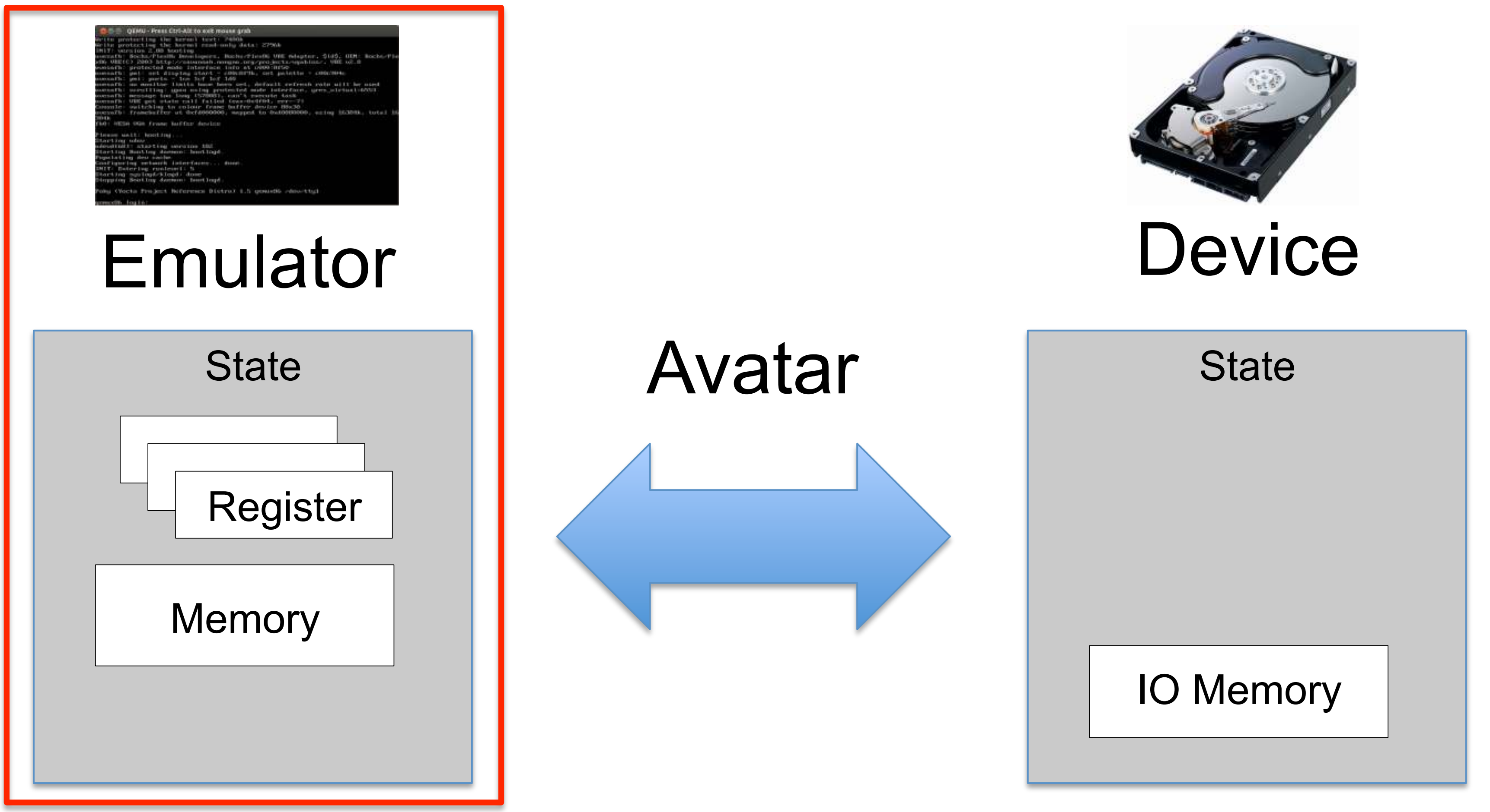
Improving performance

- Transfer execution/state
  - From the device to the emulator
  - From the emulator to the device
- Migrate memory and code snippets
  - Keep memory regions in the emulator
  - Execute IO-intensive pieces of code on the device

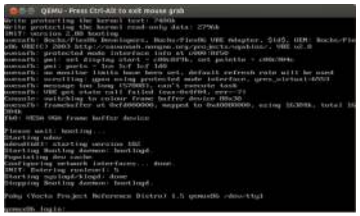
Full separation mode



Memory access optimization



Execute code snippets on the device



Emulator

State

Code

Avatar

Device

State

Execute code snippets on the device

Emulator

Device

State

Code

State

Code

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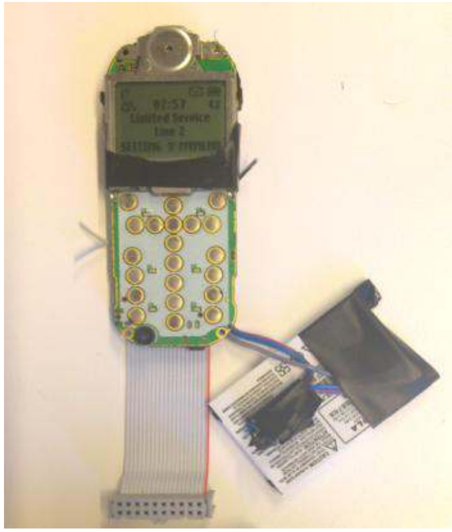
Use case: Hard Disk

- Recover bootloader protocol with symbolic execution
  - Inject GDB stub
  - Instrument flash loading
  - Inject symbolic values for data read from serial port
  - Keep track of which input leads into which code flow

http://www.s3.eurecom.fr/docs/ndss14_zaddach.pdf

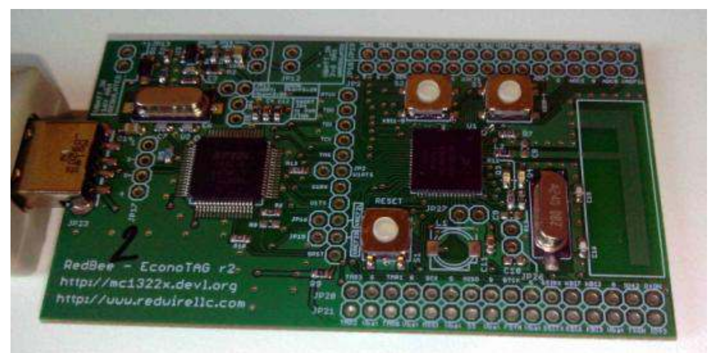
Use case: GSM Phone

- Search vulnerabilities in SMS decoding routine
  - Connect through JTAG
  - Execute on device until SMS decoding
  - Replace SMS payload with symbolic values
  - Check for symbolic values in
    - program counter
    - load/store address

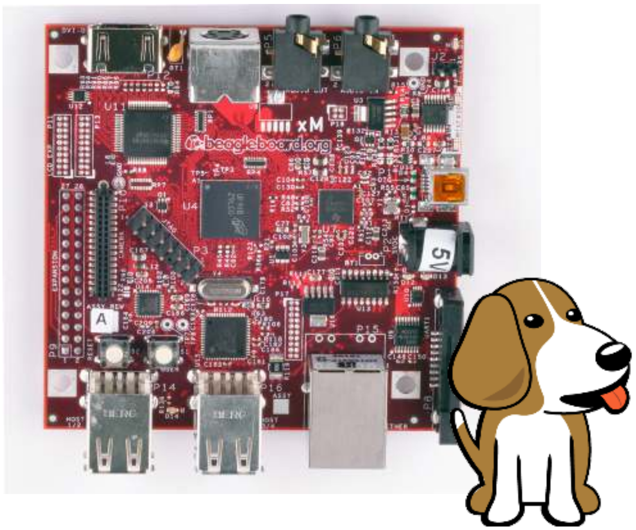


Use case: Econotag

- Find proof-of-concept bug in user application
  - Connect through JTAG
  - Execute on device until Zigbee packet arrives
  - Replace payload with symbolic values
  - Check for symbolic values in
    - program counter
    - load/store address



We are adding more devices



QEMU
open source processor emulator

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Future work

- Enhance state consistency
  - DMA memory changes not tracked
- Automatically emulate peripherals
- Improve symbolic execution
  - Coherency between HW and SW
  - Improve bug-finding strategies

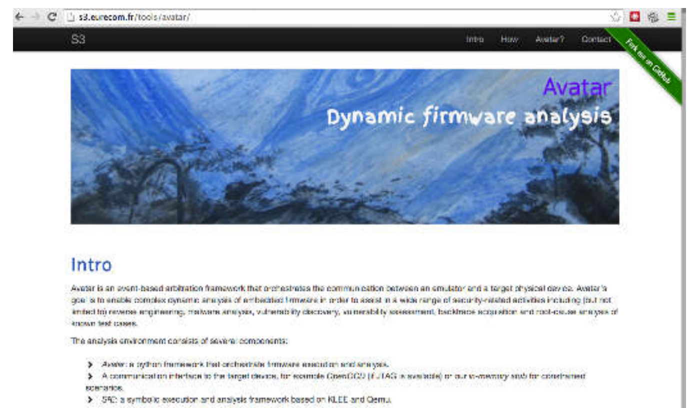
Conclusion

- AVATAR is a modular open-source tool to
  - Enable dynamic analysis
  - And perform symbolic execution
  - On embedded devices
  - Where only binary code is available

→A first step towards better analysis tools for embedded systems!

Questions?

- Thank you for listening!
- Open source on github:
  https://github.com/eurecom-s3/avatar-python
- Project page:
  http://s3.eurecom.fr/tools/avatar/



Thanks to Pascal Sachs and Luka Malisa who built an earlier prototype of the system, and Lucian Cojocar for applying and extending AVATAR

References

- AVATAR web page: http://www.s3.eurecom.fr/tools/avatar/
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- KLEE webpage: http://ccadar.github.io/klee/
- S2E webpage: https://s2e.epfl.ch/
- S2E: A Platform for In-Vivo Multi-Path Analysis of Software Systems, italy Chipounov, Volodymyr Kuznetsov, George Candea
- The S2E Platform: Design, Implementation, and Applications, Vitaly Chipounov, Volodymyr Kuznetsov, George Candea
- QEMU webpage: http://qemu.org
- Dowsing for Overflows: A Guided Fuzzer to Find Buffer Boundary Violations, Istvan Haller, Asia Slowinska, Matthias Neugschwandtner, Herbert Bos

Injecting a debugger

- Requires writing and executing memory
  - Debug menus allow this sometimes
  - A code execution vulnerability can be used
- Requires a communication channel
  - Serial port, GPIO, Power consumption, …
  - GPIO
- Requires an unused memory location in the firmware
  - Stub is about 3k of code

Full separation mode

Emulator

State

Register

Avatar

Device

State

Memory

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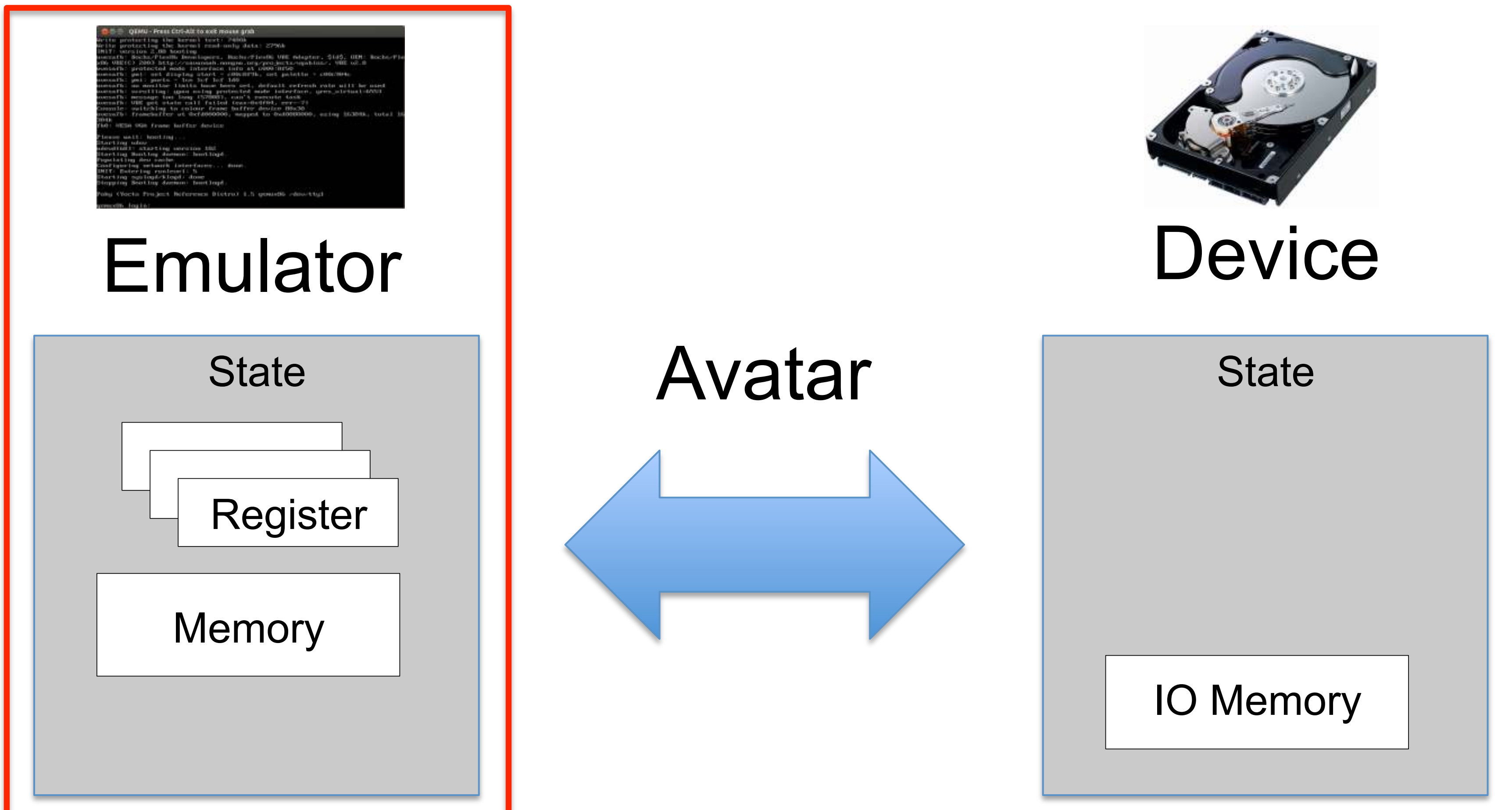
Memory access optimization



Transfer execution from emulator to device

Emulator

State

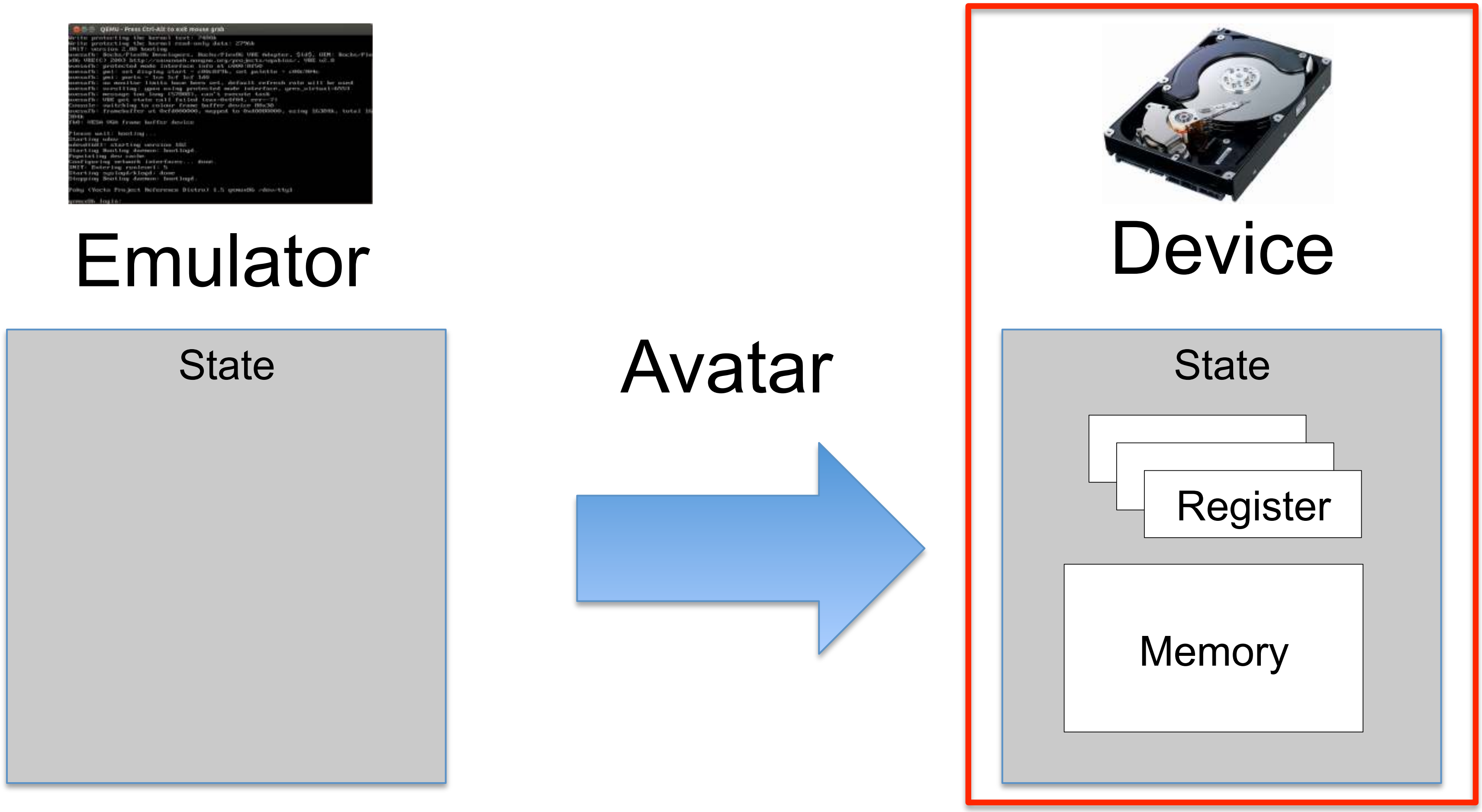
Register

Memory

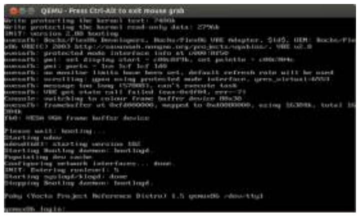
Device

State

Transfer execution from emulator to device



Transfer execution from device to emulator



Emulator

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Memory

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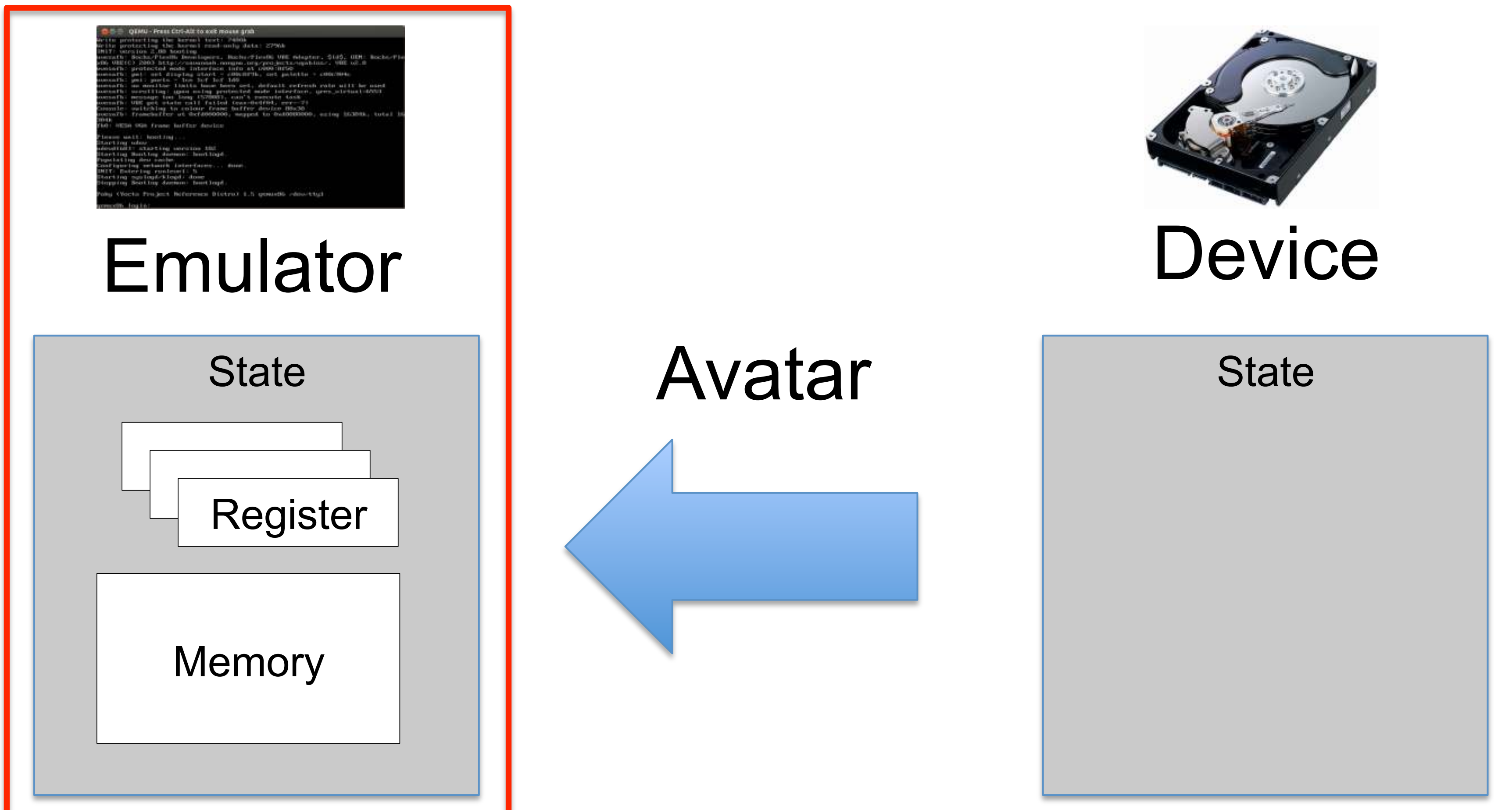

Software interrupts

- Software Interrupts
  - Are issued by an interrupt instruction in the code
- Can be entirely emulated
  - Qemu manages calling of software interrupt handlers

http://home.netcom.com/~swansont/interrupt.jpg

Task completion interrupts

- Triggered by application requests
  - Responses aligned with firmware execution speed
  - E.g., signal that a requested DMA transfer has finished
- Can be forwarded from the device to the emulator
  - A stub on the device traps interrupts and forwards them

External event interrupts

- Signals an external event
  - Events aligned to wall-clock instead of execution time
  - E.g., that a time span has elapsed
- Solution depends
  - Controllable interrupts can be forwarded
  - Uncontrollable interrupts need to be synthesized
    - Original interrupts are suppressed
    - Emulated interrupts are inserted according to emulated execution speed