The Avatar project:
Improving embedded security with S²E, KLEE and Qemu

http://www.s3.eurecom.fr/tools/avatar/

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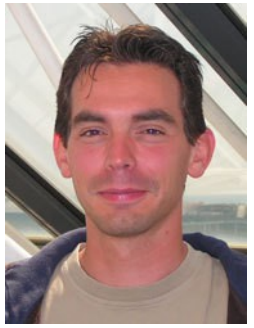
About us

- Eurecom, a consortium of European universities in French riviera
- Security research group
  - 9 people
- Applied system security
  - Embedded systems
  - Networking devices
  - Critical infrastructures





Outline

- Embedded security
- Avatar overview
- Framework components
- Field testing
- Conclusions

Software everywhere

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

Reasons for embedded security

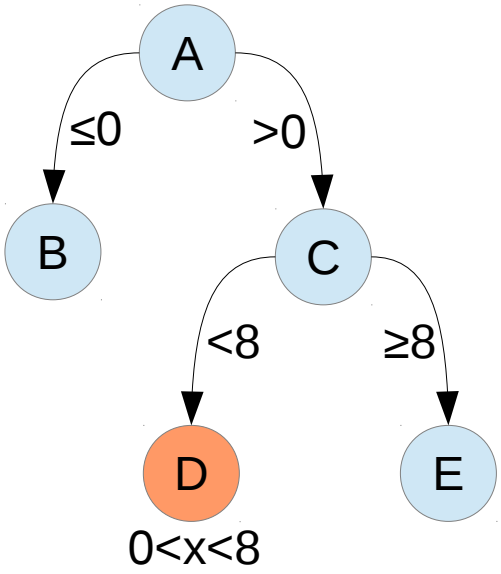
- Embedded devices are ubiquitous
  - Even if not visible, your lives depend on them
- Can operate for many years
  - Legacy systems, no (security) updates
- Have large attack surfaces
  - Networking, forgotten debug interfaces, etc.
- Sometime too easy to take-over/backdoor

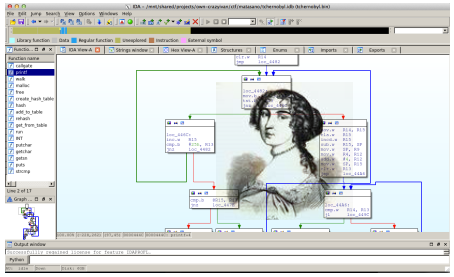
Challenges in embedded security

- No source code available
  - Often monolithic binary-only firmwares
- No toolchain available
- No documentation available
- Unique tools (to flash and debug) for each manufacturer

Wishlist for security evaluation

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





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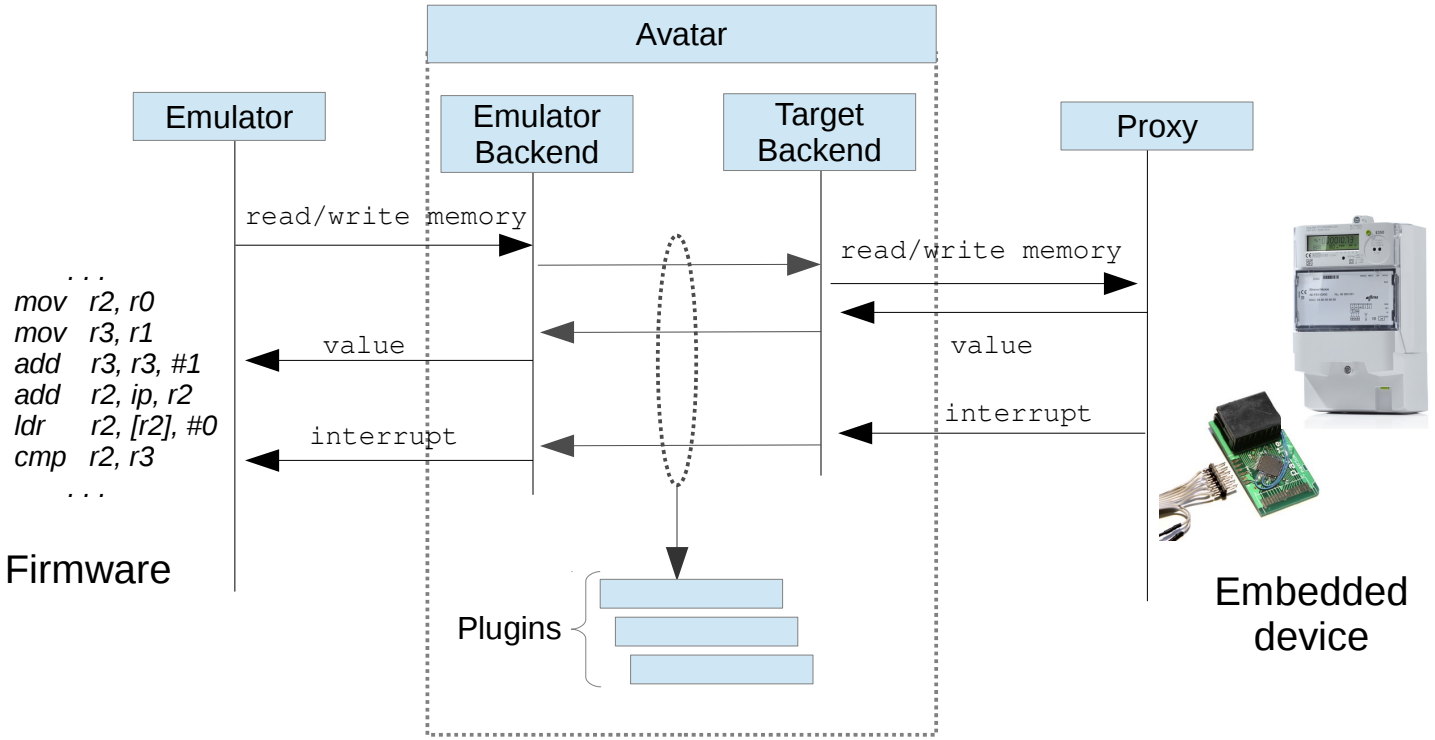
Why Avatar

- Provide a framework for
  - In-vivo analysis of any kind of device
  - Advanced debugging
  - Easy prototyping
- Integrated workbench
  - To use all techniques together on a live system
- Not only focused on security
  - Debugging/profiling/tracing is hard in embedded environments

Avatar: basics

- Emulate embedded devices' firmwares
- Forward peripheral accesses to the device under analysis
- Do **NOT** attempt to emulate peripherals
  - No documentation
  - Reverse engineering is difficult

Avatar overview



Avoid NIH syndrome

- S²E (Qemu+Klee)
  - for emulation and symbolic execution
- GDB and OpenOCD
  - to attach components and devices
- Your own tools for analysis
  - IDA Pro, Capstone, Netzob…

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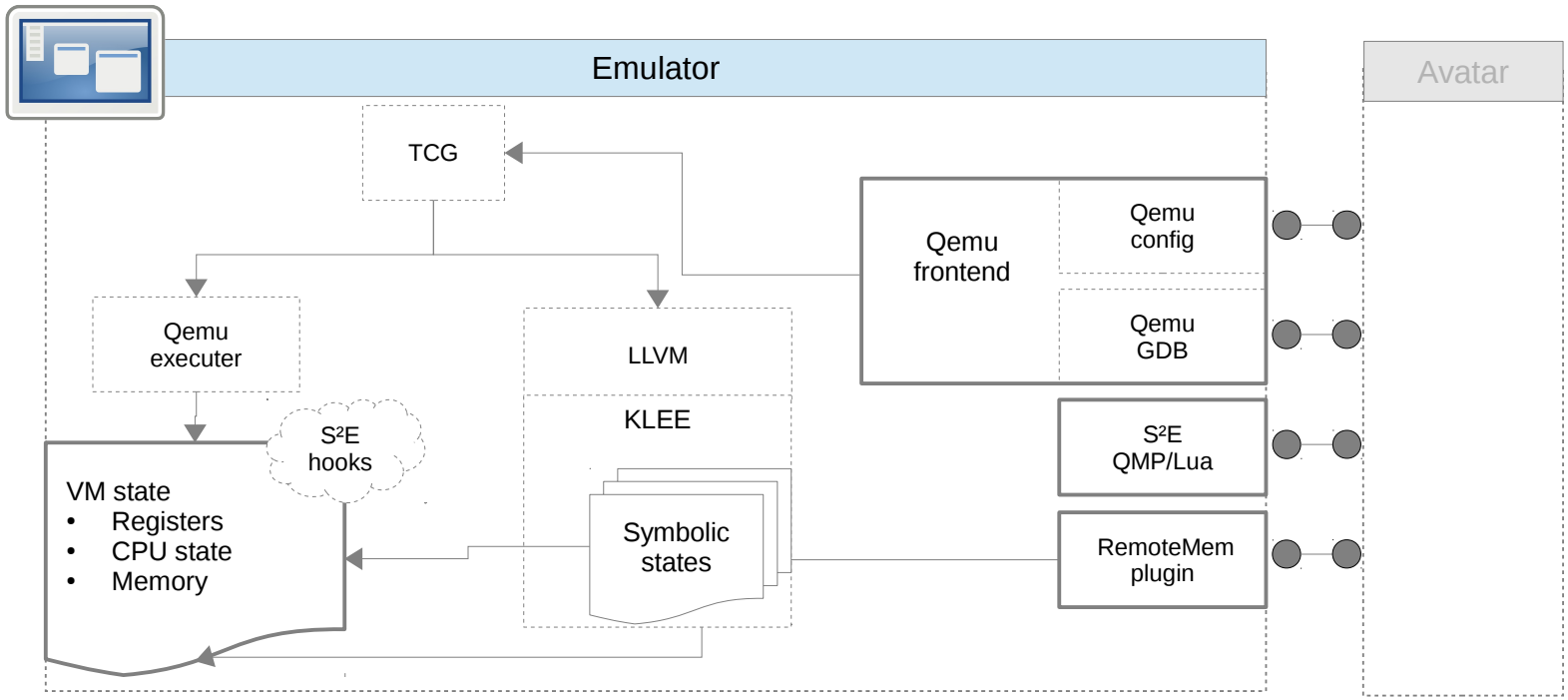
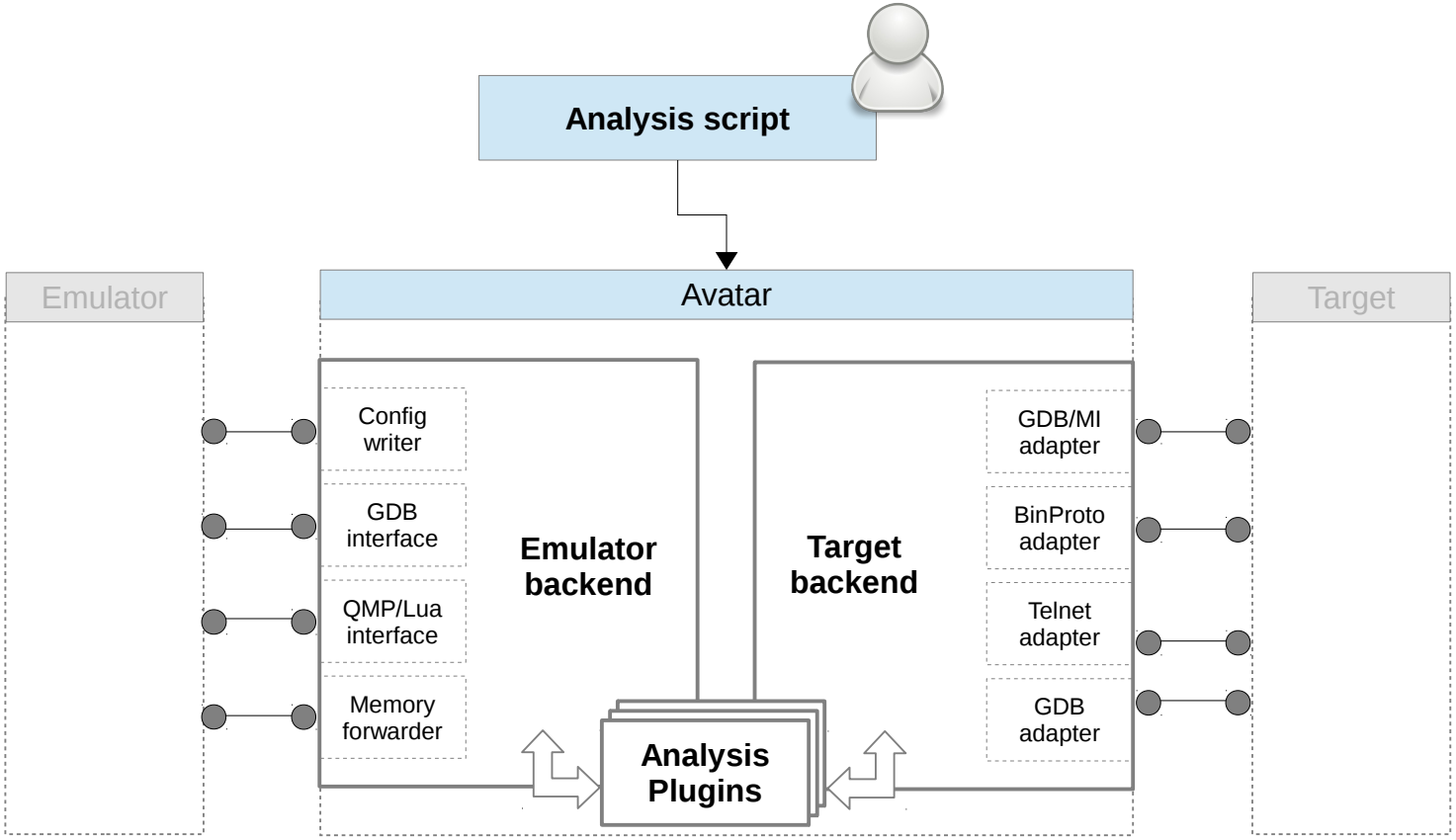
LLVM under the hood

- S²E combines existing tools to achieve symbolic execution of x86/ARM binary code
  - Qemu translates binary code to an intermediate representation (TCG)
  - QEMU-LLVM translates TCG to LLVM bytecode
  - KLEE executes LLVM bytecode symbolically

S²E in a nutshell



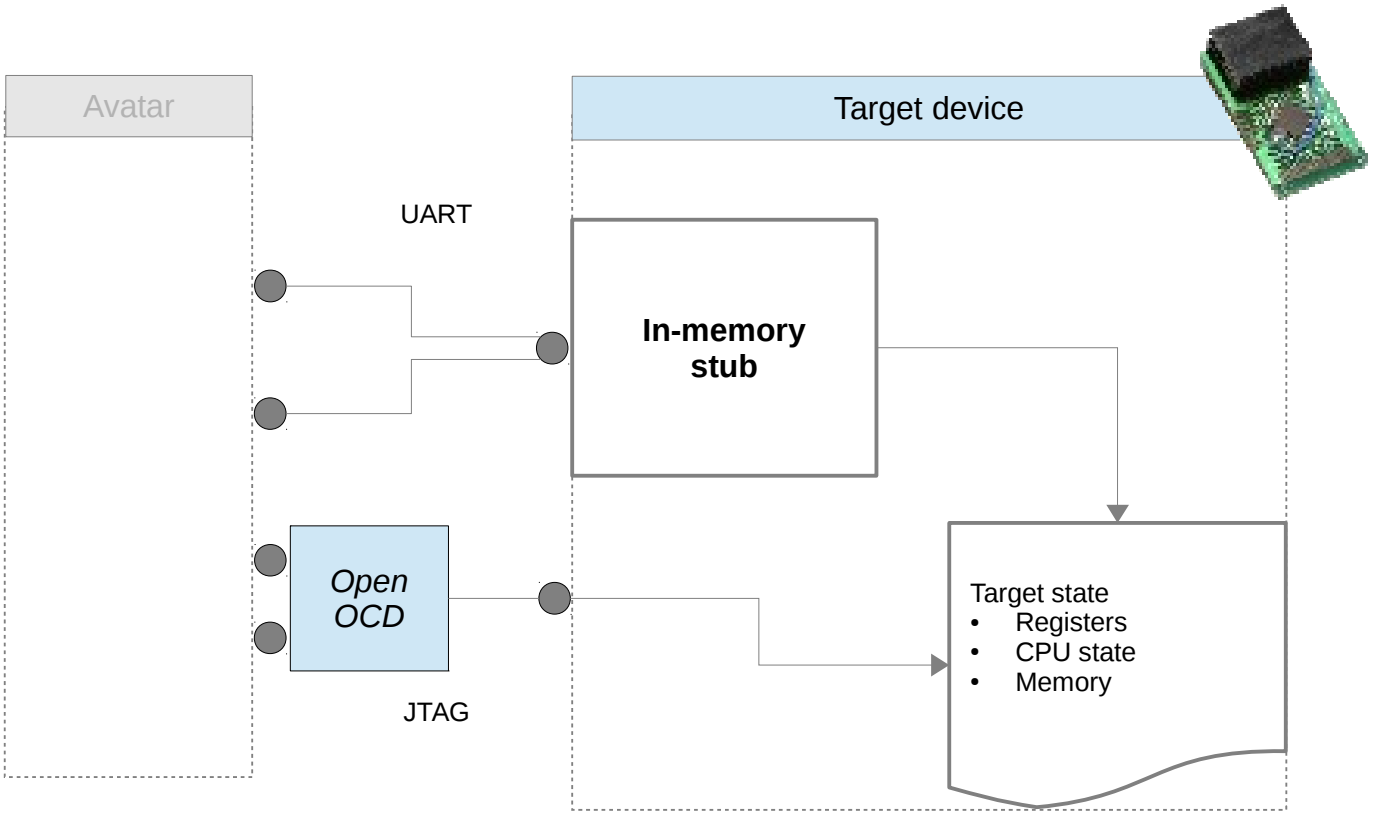
Python3 framework



Analysis platform

- Avatar provides analysis glue
  - Orchestrate execution
  - Bridge between emulator ⟷ device
  - Intercept/manipulate memory accesses
  - External integration, exposing GDB or JSON interfaces

Embedded target



Target communication

- Either a debugging interface
  - JTAG
  - Debug Serial Interface

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

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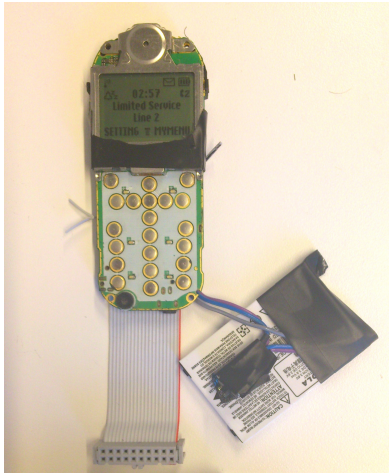
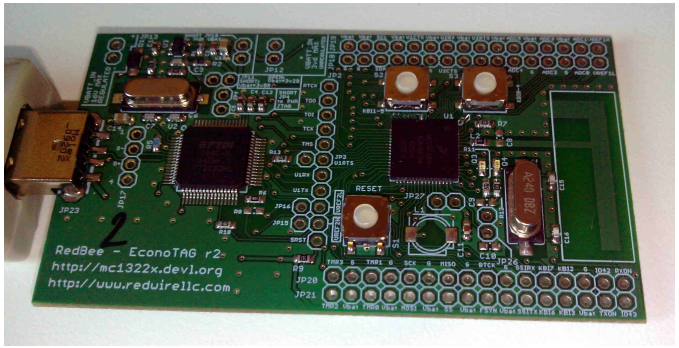
Usecases

- Check for hidden backdoors in HDD firmware
- Fuzzing/symbolic execution of SMS decoding on feature phone
- Vulnerabilities check on programmable wireless sensors





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 instr./sec.
- Interrupts are tricky, can overwhelm emulation

Improving performance

- Point of Interest is often far down in the firmware
  - Trap execution on device and transfer state to the emulator
- A large part of forwarded accesses are to non-IO memory
  - Detect and drop forwarding for non-IO memory regions (stack, heap and code in the emulator)
- High-periodicity interrupts can be synthesized to avoid saturation

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Limitations

- State consistency
  - DMA memory changes not tracked
- Timing consistency
  - Emulated execution time much slower than real execution time
- Symbolic execution
  - Coherency between HW and SW
- Bug-finding strategies to be improved

Recap

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

Questions?

Thank you for listening!

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

References

- AVATAR web page: http://www.s3.eurecom.fr/tools/avatar/
- AVATAR: A Framework to Support Dynamic Security Analysis of Embedded Systems' Firmwares, Jonas Zaddach, Luca Bruno, Aurelien Francillon, Davide Balzarotti
- Howard: a dynamic excavator for reverse engineering data structures, Asia Slowinska, Traian Stancescu, Herbert Bos
- 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, Vitaly 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

Extra: GDB stub

- GDB can connect to targets using a serial interface and a simple protocol
- There is a stub implementation in the source code tree, but not for ARM and it's bloated (for our purposes)
- 6 primitives are enough to give debugging support with software breakpoints:

Read bytes, write bytes, read registers, write registers, continue and get signal