Experiences with the Carnegie Mellon Binary Analysis Platform (CMU BAP)

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Introduction - what is BAP?

Binary analysis framework:

- For program analysis
- For (aiding) reverse engineering (plugin for IDA similar to BinCAT[1])
- Written in OCaml (with bindings for C, Python and Rust)
- Support for many architectures (ARM, MIPS, PPC, x86/x86-64)

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[1] https://github.com/BinaryAnalysisPlatform/bap-ida-python

(Very brief) project history

Reengineering of Vine[1] from the BitBlaze project

…third binary analysis framework by same group: asm2c → Vine → BAP

Each iteration, different IR: C AST → VEX → BIR/BIL

BAP itself has been re-architectured during its development:

1. Library-based
2. Plugin-based + extension points

Used by CyLab spin-off startup ForAllSecure

…who produced MAYHEM (automated cyber reasoning system)

Use in research*

- Byteweight
  - Machine learning-based function start identification
- MAYHEM
  - Automated vulnerability discovery and exploit generation
- oo7 (Spectre checker)
  - Automated (binary-based) Spectre variant detection
- Stringer
  - Semi-automated backdoor & undocumented functionality detection
- HumIDIFy
  - Semi-automated backdoor detection (machine learning + static analysis)
- Saluki
  - Finding Taint-style Vulnerabilities with Static Property Checking (formal models of CWEs)
- Moflow framework
  - Automated vulnerability discovery and triage

* See bibliography at end of presentation for references/links

My experience with BAP

As part of PhD:

- BAP version 0.9.9
- Built two tools for (semi-)automated backdoor detection (using OCaml API):
  - Stringer (static analysis)
  - HumIDIFy (ML + static analysis)
- Used tools as part of workshop for [company] on backdoor detection

A tour of BAP*

*as of version 1.5.0

Architecture

- Core BAP library; features implemented with plugins
- By default provides:
  - LLVM based disassembler/loader backend
  - Hand-written lifters for ARM, MIPS, PPC, x86, x86-64
  - Function start/CFG recovery
- Represents a program in an IR (BIR); components represented by “Terms”
- Terms annotated with attributes (basic blocks -- BIL)

Extensible core components

- Loader (e.g., Mach-O, etc.)
- Target (e.g., RISC-V, etc.)
- Disassembler
- Attributes (given to terms)
- Symbolizer
- Rooter
- Brancher
- (CFG) Reconstructor
- Analysis (aka pass)

BAP Instruction Language (BIL)

- High-level IL
- ML-style constructs (e.g., let bindings)
- Models side-effects (e.g., modifications to `EFLAGS` via add, etc.)
- Simple and human-readable
- Formally defined (operational semantics[1], etc.)

```
0000023b: sub call_gmon_start()
00000212:
00000214: RSP := RSP - 8
0000021b: RAX := mem[0x600FE0, el]:u64
0000021c: v303 := RAX
00000222: ZF := 0 = v303
00000228: when ZF goto %00000223
00000227: goto %00000224
```

Side-effects on EFLAGS
& stack modelled
explicitly

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[1] https://github.com/BinaryAnalysisPlatform/bil/releases/download/v0.3/bil.pdf

Simple BIL example

```
void printme(const char *str) {
    puts(str);
}
```

disassembly

```
0x4006ed: push rbp
0x4006ee: mov  rbp, rsp
0x4006f1: mov  edi, 0x4008e0
0x4006f6: call 0x400510
0x4006fb: pop  rbp
0x4006fc: ret
```

lifting

```
000001b1: sub printme()
000001a2:
000001a3: v228 := RBP
000001a4: RSP := RSP - 8
000001a5: mem := mem with [RSP, el]:u64 <- v228
000001a6: RBP := RSP
000001a7: RDI := 0x4008E0
000001a8: RSP := RSP - 8
000001a9: mem := mem with [RSP, el]:u64 <- 0x4006FB
000001aa: call @puts with return %000001ab

000001ab:
000001ac: RBP := mem[RSP, el]:u64
000001ad: RSP := RSP + 8
000001ae: v246 := mem[RSP, el]:u64
000001af: RSP := RSP + 8
000001b0: return v246
```

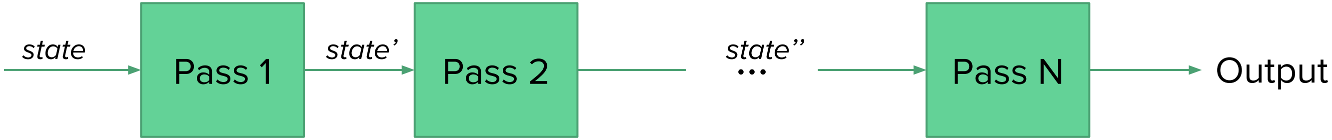
Same example in VEX (using angr)

```
IRSB {
   t0:Ity_I64 t1:Ity_I64 t2:Ity_I64 t3:Ity_I64 t4:Ity_I64 t5:Ity_I64 t6:Ity_I64
t7:Ity_I64 t8:Ity_I64 t9:Ity_I64 t10:Ity_I64 t11:Ity_I64

   00 | ------ IMark(0x4006ed, 1, 0) ------
   01 | t0 = GET:I64(rbp)
   02 | t5 = GET:I64(rsp)
   03 | t4 = Sub64(t5,0x0000000000000008)
   04 | PUT(rsp) = t4
   05 | STle(t4) = t0
   06 | ------ IMark(0x4006ee, 3, 0) ------
   07 | PUT(rbp) = t4
   08 | ------ IMark(0x4006f1, 5, 0) ------
   09 | PUT(rdi) = 0x00000000004008e0
   10 | PUT(rip) = 0x00000000004006f6
   11 | ------ IMark(0x4006f6, 5, 0) ------
   12 | t8 = Sub64(t4,0x0000000000000008)
   13 | PUT(rsp) = t8
   14 | STle(t8) = 0x00000000004006fb
   15 | t10 = Sub64(t8,0x0000000000000080)
   16 | ====== AbiHint(0xt10, 128, 0x0000000000400510) ======
   NEXT: PUT(rip) = 0x0000000000400510; Ijk_Call
}
```

```
IRSB {
   t0:Ity_I64 t1:Ity_I64 t2:Ity_I64 t3:Ity_I64
t4:Ity_I64 t5:Ity_I64 t6:Ity_I64 t7:Ity_I64

   00 | ------ IMark(0x4006fb, 1, 0) ------
   01 | t1 = GET:I64(rsp)
   02 | t0 = LDle:I64(t1)
   03 | t5 = Add64(t1,0x0000000000000008)
   04 | PUT(rsp) = t5
   05 | PUT(rbp) = t0
   06 | PUT(rip) = 0x00000000004006fc
   07 | ------ IMark(0x4006fc, 1, 0) ------
   08 | t3 = LDle:I64(t5)
   09 | t4 = Add64(t5,0x0000000000000008)
   10 | PUT(rsp) = t4
   11 | t6 = Sub64(t4,0x0000000000000080)
   12 | ====== AbiHint(0xt6, 128, t3) ======
   NEXT: PUT(rip) = t3; Ijk_Ret
}
```

Plugins

- Compositional in functional sense; two variants:
  - Extensions
  - Passes (special type of extension to implement analyses)



- State of framework passed between passes
- Composition of passes enables more complex analyses

Plugins (example analysis)

- Compute ratio of “jump” terms to other BIR terms

```
open Core_kernel.Std
open Bap.Std

let counter = object
  inherit [int * int] Term.visitor
  method! enter_term _ _ (jmps,total) = jmps,total+1
  method! enter_jmp _ (jmps,total) = jmps+1,total
end

let main proj =
  let jmps,total = counter#run (Project.program proj) (0,0) in
  printf "ratio = %d/%d = %g\n" jmps total (float jmps /. float total)

let () = Project.register_pass' main
```

Object to “visit” all IL terms

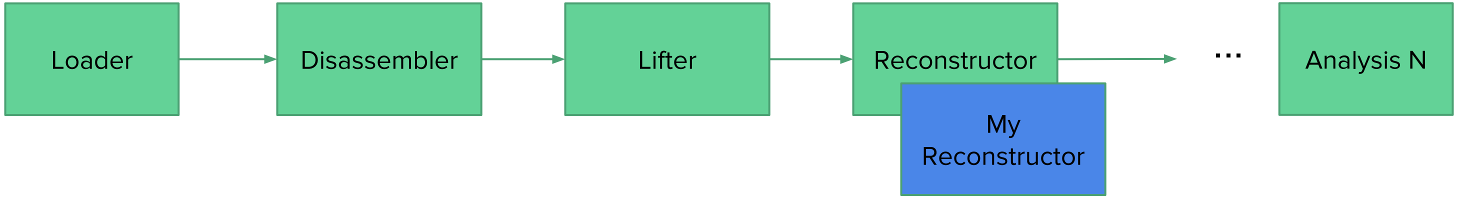
State is passed as “proj” or Project in BAP nomenclature

BAP from Python

```python
import bap
from bap.adt import Visitor

class Counter(Visitor) :
    def __init__(self):
        self.jmps = 0
        self.total = 0

    def enter_Jmp(self,jmp):
        self.jmps += 1

    def enter_Term(self,t):
        self.total += 1

proj = bap.run('/bin/true')
count = Counter()
count.run(proj.program)
print("ratio = {0}/{1} = {2}".format(count.jmps, count.total,
                                     count.jmps/float(count.total)))
```

Plugins - Extension points

- Extend core analysis components:
  - Handle new file formats
  - Implement new CFG recovery algorithm
  - …
- Provides a means of testing research on different aspects of binary analysis without having to focus on other aspects:



Byteweight

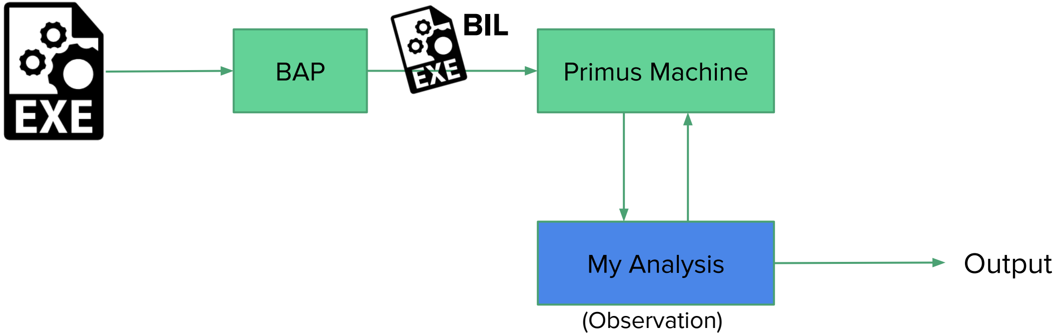
- Implemented as an extension to BAP as a “rooter”
- Provides ML-based function start identification for stripped binaries
- Reported improvements over state-of-the-art (IDA Pro)

Implementation of rooter and its registration as an extension to BAP’s analysis

```
let main path length threshold =
  let finder arch = create_finder path length threshold arch in
  let find finder mem =
    Memmap.to_sequence mem |>
    Seq.fold ~init:Addr.Set.empty ~f:(fun roots (mem,v) ->
        Set.union roots @@ Addr.Set.of_list (finder mem)) in
  let find_roots arch mem = match finder arch with
    | Error _ as err ->
      warning "unable to provide rooter service";
      err
    | Ok finder -> match find finder mem with
      | roots when Set.is_empty roots ->
        info "no roots was found";
        info "advice - check your compiler's signatures";
        Ok (Rooter.create Seq.empty)
      | roots -> Ok (roots |> Set.to_sequence |> Rooter.create)  in
  let rooter =
    let open Project.Info in
    Stream.Variadic.(apply (args arch $ code) ~f:find_roots) in
  Rooter.Factory.register name rooter
```

Primus

- Micro execution[1] framework (implemented as an “analysis”)
- Start execution from anywhere (without input or test driver)
- Scriptable (Primus Lisp)



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[1] P. Godefroid. "Micro execution." *Proceedings of the 36th International Conference on Software Engineering*, 2014

Taint

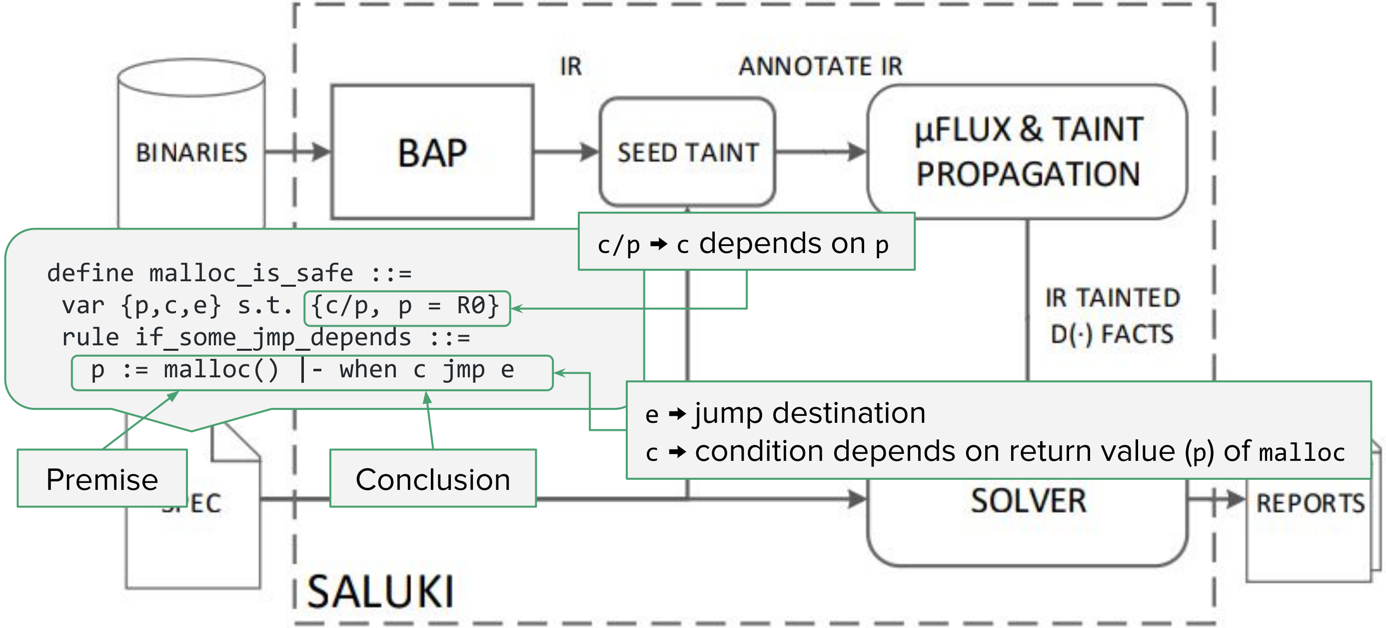
- Built as a Primus “observer”
- Abstract taint tracking engine
- Policy-based taint propagation
- Configuration via OCaml or Primus Lisp

```
bap ./test --taint-reg=malloc_result \
       --run \
       --run-entry-points=all-subroutines \
       --primus-limit-max-length=4096 \
       --primus-promiscuous-mode \
       --primus-greedy-scheduler \
       --primus-propagate-taint-from-attributes \
       --primus-propagate-taint-to-attributes \
       --print-bir-attr=tainted-{ptrs,regs} \
       --dump=bir:result.out \
       --report-progress
```

```
0000019d: call @malloc with return %0000019e
...
...
000001a7:
.tainted-regs {R0 => [0000019d]}
000003aa: memmove_result := R0
...
```

Taint tag

Saluki[1]



```
define malloc_is_safe ::=
 var {p,c,e} s.t. {c/p, p = R0}
 rule if_some_jmp_depends ::=
  p := malloc() |- when c jmp e
```

`c/p` → `c` depends on `p`

Premise

Conclusion

`e` → jump destination

`c` → condition depends on return value (`p`) of `malloc`

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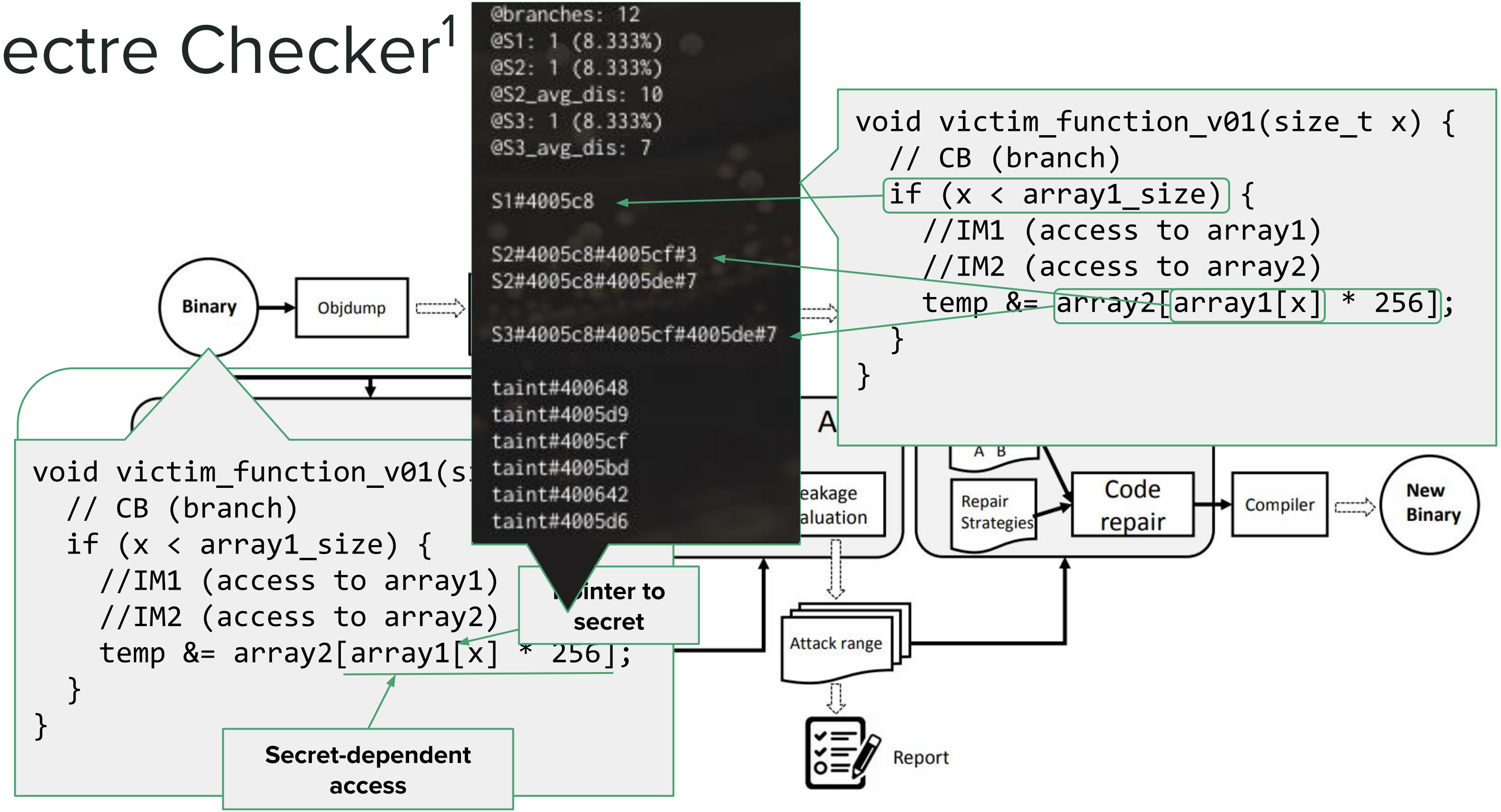
[1] I. Gotovchits, R. V. Tonder, D. Brumley. “Saluki: Finding Taint-style Vulnerabilities with Static Property Checking” (BAR Workshop @ NDSS), 2018 http://wp.internetsociety.org/ndss/wp-content/uploads/sites/25/2018/07/bar2018_19_Gotovchits_paper.pdf

Spectre Checker[1]



```
@branches: 12
@S1: 1 (8.333%)
@S2: 1 (8.333%)
@S2_avg_dis: 10
@S3: 1 (8.333%)
@S3_avg_dis: 7

S1#4005c8

S2#4005c8#4005cf#3
S2#4005c8#4005de#7

S3#4005c8#4005cf#4005de#7

taint#400648
taint#4005d9
taint#4005cf
taint#4005bd
taint#400642
taint#4005d6
```

```
void victim_function_v01(size_t x) {
  // CB (branch)
  if (x < array1_size) {
    //IM1 (access to array1)
    //IM2 (access to array2)
    temp &= array2[array1[x] * 256];
  }
}
```

```
void victim_function_v01(s
  // CB (branch)
  if (x < array1_size) {
    //IM1 (access to array1)
    //IM2 (access to array2)
    temp &= array2[array1[x] * 256];
  }
}
```

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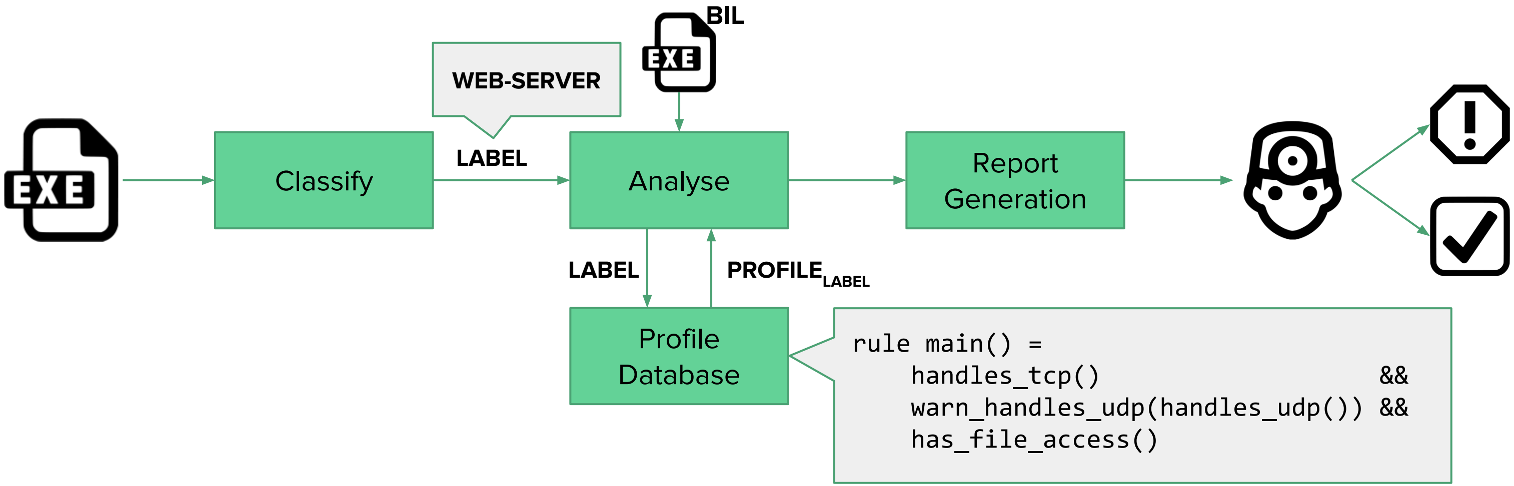
[1] G. Wang, S. Chattopadhyay, I. Gotovchits, T. Mitra, A. Roychoudhury. "oo7: Low-overhead Defense against Spectre Attacks via Binary Analysis" (preprint), 2018 https://arxiv.org/abs/1807.05843

First-hand experiences

HumIDIFy

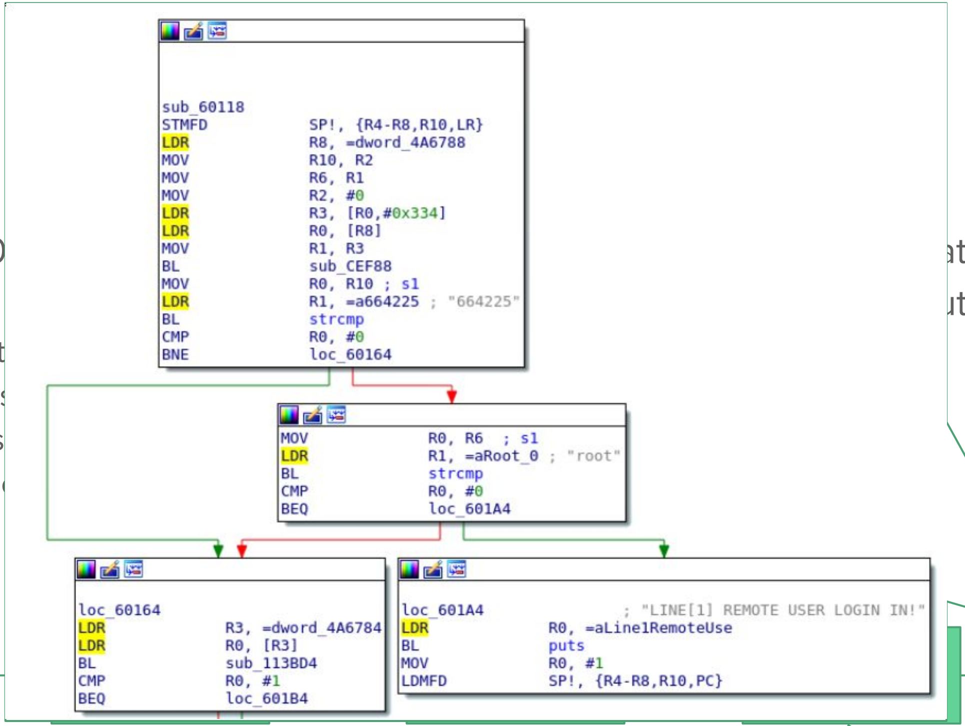
- SLOC: 3,510
- BAP used to implement static analyses:
    - Feature extraction for ML
    - To implement runtime for binary analysis DSL
- Good runtime perf: (1.31 + 0.291 + 1.53) ≈ 3.13s
- Detects numerous backdoors + anomalous functionality in Linux embedded binaries



```
rule main() =
    handles_tcp()                       &&
    warn_handles_udp(handles_udp()) &&
    has_file_access()
```

Stringer

- SLOC: ≈ 3,00 atically linked C++ binary ~16k
- BAP used to ute*
  - Automat functions
  - Locate s of uniqu

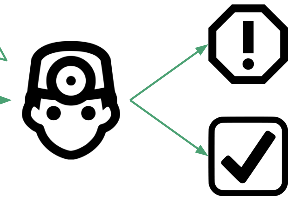


```
sub_60118
STMFD           SP!, {R4-R8,R10,LR}
LDR             R8, =dword_4A6788
MOV             R10, R2
MOV             R6, R1
MOV             R2, #0
LDR             R3, [R0,#0x334]
LDR             R0, [R8]
MOV             R1, R3
BL              sub_CEF88
MOV             R0, R10 ; s1
LDR             R1, =a664225 ; "664225"
BL              strcmp
CMP             R0, #0
BNE             loc_60164
```

```
MOV             R0, R6  ; s1
LDR             R1, =aRoot_0 ; "root"
BL              strcmp
CMP             R0, #0
BEQ             loc_601A4
```

```
loc_60164
LDR             R3, =dword_4A6784
LDR             R0, [R3]
BL              sub_113BD4
CMP             R0, #1
BEQ             loc_601B4
```

```
loc_601A4                ; "LINE[1] REMOTE USER LOGIN IN!"
LDR             R0, =aLine1RemoteUse
BL              puts
MOV             R0, #1
LDMFD           SP!, {R4-R8,R10,PC}
```



```
[f] 37.66: sub_60118
    34.89: 664225 (via: strcmp)
     2.77: root   (via: strcmp)
```

* Latest angr (using PyPy) takes > hour to just perform CFG recovery (CFGFast)

Using BAP for research

Pros:

- OCaml
- Documentation
- Support (active Gitter channel)
- Tutorials
- Fast (native code)
- Easy to test isolated research ideas/proof-of concepts

Cons:

- OCaml
- Steep learning curve
- Open-source examples
- Lack of visible community
- Fragmented contributions

Problems & Solutions

- Steep learning curve (even with substantial experience in OCaml)
- OCaml

- Byteweight for function start recovery (not perfect[1])
- Interworking with ARM/Thumb executables
- CFG recovery:
  - No direct support for indirect branches

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[1] D. Andriesse, A. Slowinska, and H. Bos. "Compiler-agnostic function detection in binaries." *(Euro S&P), 2017.*

Problems & Solutions

- Interface with IDA → current version supports this via plugin
  - Function identification
  - CFG recovery
  - Symbols
- Pass “T” flag per block from IDA to BAP to support ARM/Thumb interworking
- Recent plugin implementing VSA to aid in CFG recovery[1]

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[1] https://github.com/draperlaboratory/cbat_tools

Conclusions

Conclusions

- Highly suited for research
- Barrier for adoption largely due to language choice (also fast moving development)
- Extensible
- Fast

References

- R. Johnson. "Moflow framework", 2018 (https://github.com/moflow/moflow)
- T. Bao, J. Burket, M. Woo, R. Turner, D. Brumley. "Byteweight: Learning to recognize functions in binary code", USENIX Security, 2013
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- G. Wang, S. Chattopadhyay, I. Gotovchits, T. Mitra, A. Roychoudhury. "oo7: Low-overhead Defense against Spectre Attacks via Binary Analysis", (preprint) 2018
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- D. Andriesse, A. Slowinska, H. Bos. "Compiler-agnostic function detection in binaries", Euro S&P, 2017