GRAMMATECH

Capabilities Labeling

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Defining the Problem

Have you ever needed to understand someone else's code?

```
/* Calculate a checksum. I don't know the name
of the one we're using but this seems to work. */
uint16_t crc16(const uint8_t* buffer, size_t size) {
  uint16_t tmp, crc = 0xffff;

  for (size_t i=0; i < size; i++) {
    tmp = (crc >> 8) ^ buffer[i];
    crc = (crc << 8) ^ crc_table[tmp];
  }

  return crc;
}
```

Defining the Problem

What if you didn’t even have source code?

```
00000000 <proc_800213c>:
   0:   e52db004        push    {fp}            ; (str fp, [sp, #-4]!)
   4:   e28db000        add     fp, sp, #0
   8:   e24dd01c        sub     sp, sp, #28
   c:   e50b0018        str     r0, [fp, #-24]  ; 0xffffffe8
  10:   e50b101c        str     r1, [fp, #-28]  ; 0xffffffe4
  14:   e3e03000        mvn     r3, #0
  18:   e14b30b6        strh    r3, [fp, #-6]
  1c:   e3a03000        mov     r3, #0
  20:   e50b300c        str     r3, [fp, #-12]
  24:   ea00001d        b       a0 <proc_800213c+0xa0>
  28:   e15b30b6        ldrh    r3, [fp, #-6]
  2c:   e1a03423        lsr     r3, r3, #8
  30:   e1a03803        lsl     r3, r3, #16
  34:   e1a02823        lsr     r2, r3, #16
  38:   e51b300c        ldr     r3, [fp, #-12]
  3c:   e51b1018        ldr     r1, [fp, #-24]  ; 0xffffffe8
  40:   e0813003        add     r3, r1, r3
  44:   e5d33000        ldrb    r3, [r3]
  48:   e1a03803        lsl     r3, r3, #16
  4c:   e1a03823        lsr     r3, r3, #16
  50:   e0233002        eor     r3, r3, r2
  54:   e14b30be        strh    r3, [fp, #-14]
  58:   e15b30b6        ldrh    r3, [fp, #-6]
  5c:   e1a03403        lsl     r3, r3, #8
  60:   e1a03803        lsl     r3, r3, #16
  64:   e1a02843        asr     r2, r3, #16
  68:   e15b30be        ldrh    r3, [fp, #-14]
  6c:   e59f1050        ldr     r1, [pc, #80]   ; c4 <proc_800213c+0xc4>
  70:   e1a03083        lsl     r3, r3, #1
  74:   e0813003        add     r3, r1, r3
  78:   e1d330b0        ldrh    r3, [r3]
  7c:   e1a03803        lsl     r3, r3, #16
  80:   e1a03843        asr     r3, r3, #16
  84:   e0233002        eor     r3, r3, r2
  88:   e1a03803        lsl     r3, r3, #16
  8c:   e1a03843        asr     r3, r3, #16
  90:   e14b30b6        strh    r3, [fp, #-6]
  94:   e51b300c        ldr     r3, [fp, #-12]
  98:   e2833001        add     r3, r3, #1
  9c:   e50b300c        str     r3, [fp, #-12]
  a0:   e51b200c        ldr     r2, [fp, #-12]
  a4:   e51b301c        ldr     r3, [fp, #-28]  ; 0xffffffe4
  a8:   e1520003        cmp     r2, r3
  ac:   bafffffd        blt     28 <proc_800213c+0x28>
  b0:   e15b30b6        ldrh    r3, [fp, #-6]
  b4:   e1a00003        mov     r0, r3
  b8:   e28bd000        add     sp, fp, #0
  bc:   e49db004        pop     {fp}            ; (ldr fp, [sp], #4)
  c0:   e12fff1e        bx      lr
```

Defining the Problem

Maybe a decompiler will help? Maybe not a lot…


```
ushort proc_800213c(int param_1,int param_2)
{
  int local_10;
  ushort local_a;

  local_a = 0xffff;
  for (local_10 = 0; local_10 < param_2; local_10 =
local_10 + 1) {
    local_a = *(ushort *)
              (&table +
              (uint)(ushort)((ushort)*(byte
*)(param_1 + local_10) ^ local_a >> 8) * 2) ^
             (ushort)(((uint)local_a << 0x18) >>
0x10);
  }
  return local_a;
}
```

Towards a Solution…

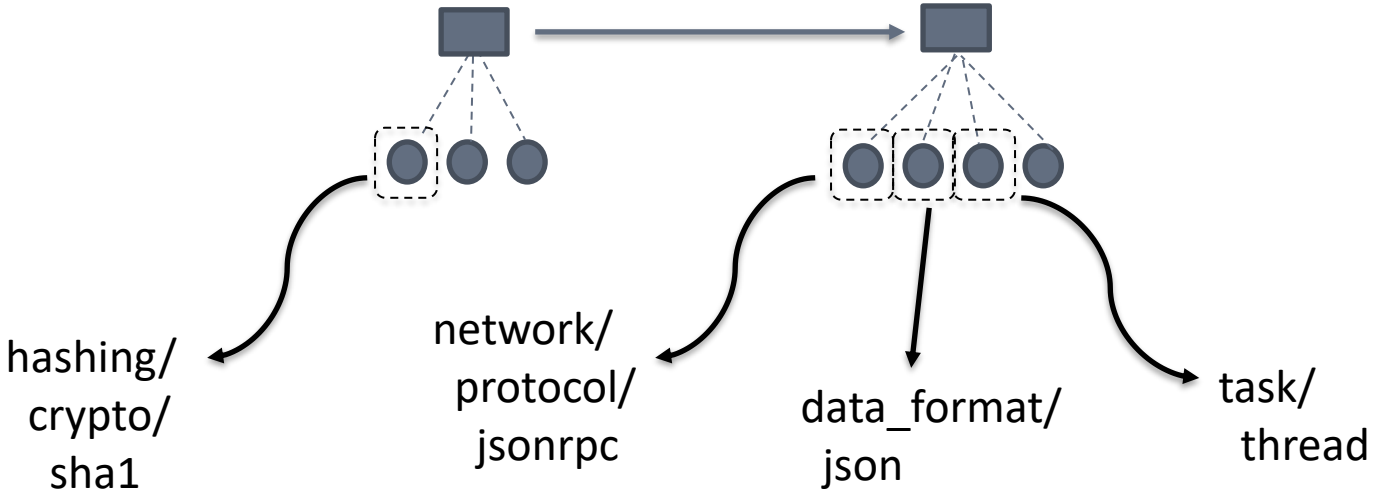
What if you had a tool that helped you understand what code does?

Capabilities Labeling

- Static analysis technique
- For binaries – no source code needed
- Works for “bare” binaries – no symbols
- Helps understand the purpose of code:
  - What code is part of the embedded web server?
  - Which functions access the encryption hardware?
  - Where can I inject simulated serial-port data?

What are Capability Labels?

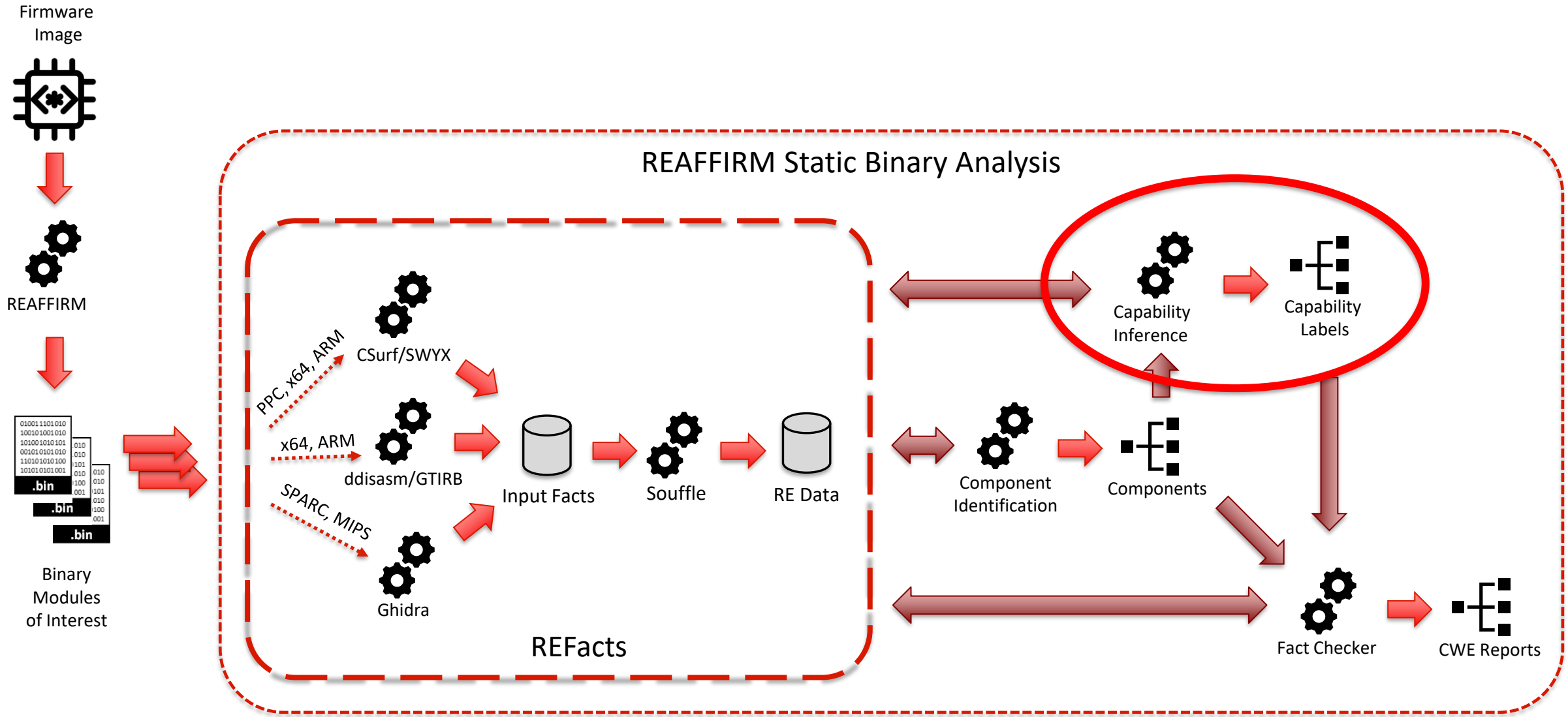
- Annotations that describe “purpose” of functions
  - Pre-defined collection of human-readable labels
  - Hierarchically organized (specific types within categories)
- May be combined with binary component analysis (e.g., compilation units)
  - Labels can then be aggregated over collections of related functions *(not shown below)*



REAFFIRM Intro

- REAFFIRM: Reverse Engineer, Analyze, and Fuzz FIRMware
  - Unpacks wide variety of firmware formats
  - Extracts, rehosts, and harnesses firmware functionality
  - Supports testing / fuzzing of firmware on commodity hardware
  - Also works on “easier” desktop/server binaries
- REAFFIRM is a toolbox
- Capabilities Labeling is one recently-added tool

REAFFIRM Toolchain Overview



Capabilities Hierarchy

- Represented as forest; most specific at the leaves
- Currently 187 types in 37 categories
- Examples:

```
audio/format:                Encodes or decodes audio formats
authentication/credentials:  Manages credentials for authentication
buffer/copy:                 Copies data between buffers/arrays
buffer/transform/base64:     Encodes/decodes data as base64
bus/serial:                  Generic serial data interface, e.g. UART
data_format/json:            Parses or emits data in JSON format
data_structure/ring_buffer:  Uses a ring buffer (circular queue)
encryption/aes:              Encrypts or decrypts data via the AES cipher
file/system/directory:       Accesses directories on the filesystem
hashing/checksum/adler32:    Computes Adler32 checksums
image/png:                   Encodes or decodes PNG images
network/protocol/http:       Communicates over HTTP
task/process/create:         Creates processes
```

Capability Labeling on ArduCopter

- For our examples, we are using “ArduCopter”
- Drone autopilot, open-source, C and C++
- Monolithic, typical of baremetal or real-time OS firmware
- Binary size: 3.6MB, 10760 functions
- 36 capability types in 16 categories identified in 14.8m
  - Static analysis: 9.0m (serves all later analyses)
  - Capabilities: 0.5m
  - Other analyses ~5.3m

Applications for Capabilities

- Helps focus analysis effort where it counts
  - Manual analysis:
    - *Highlight most relevant code*
  - Automated analysis
    - *Detect some weaknesses automatically*
    - *Improve scalability*

Capabilities Focus in Manual Analysis

- Expected functionality helps find targets for deeper dive
  - Locate buffer overrun risks
    - CWE-120 “buffer copy without checking size of input” (**`buffer/copy`**)
    - CWE-242 “inherently dangerous function” (**`bad_func`**)
  - Analyze code in a downed UAV
    - Check for GPS time spoofing weaknesses (**`time/lowlevel`**)
- Unexpected functionality may also warrant investigation
  - Understand why there is undocumented GPIO access (**`bus/gpio`**) inside the SD-Card driver code

Capabilities Focus in Automated Analysis

- Automatically identify weaknesses
  - E.g., CWE-327 “broken or risky cryptographic algorithm”
- Direct analysis to key security-related areas
  - Identify the (215) functions that relate to Arducopter’s “lua” parser
  - Fuzz to see if parsing failures can crash SW/device
- Level of effort can be scaled relative to importance
  - Allocate fuzzing resources (# of cores, # of days)
  - Safety critical systems ≫ user features
  - Exposed interfaces ≫ protected interfaces

Capabilities Heuristics

- How do we find capabilities?
- How much does this depend on symbols?
  - A little bit, but not as much as you might think
- Does this work on any processor type?
  - Very little that is ISA-dependent
  - Multiple frontends (including Ghidra) for flexibility

Multiple Sources of Signal for Labeling

- Library specifications (needs symbols)
  - Use of a library implies capability
    - e.g., libxml2 --> **`data_format/xml`**
  - Use of an API implies capability
    - e.g., execv() --> **`task/process/create`**

- Mathematical constants/tables (works on bare binaries)
  - Many cryptographic and checksum algorithms
  - Can usually distinguish between variants (**`encryption/des3`** vs **`encryption/aes`**)

- Hardware accesses (bare OK)
  - Map hardware addresses to capabilities
  - E.g., 0x40013800 is STM32F family UART status register (**`bus/serial`**)

Multiple Sources of Signal for Labeling

- Semantic patterns in instructions (bare OK)
  - Heuristics based on semantics or control/data flow
  - E.g., **`hashy`** functions have high percentage of XOR and shifts in loop(s)

- String literals/tokens (bare OK)
  - Look for file format or protocol specific strings/terms
  - Based on data mining from GitHub source code – machine learning

- Message matching (bare OK)
  - User and log messages *retained in binary* and contain valuable information
  - Based on human expertise – “expert system” like capability
  - E.g., "cannot open file '%s' (%s)“ -> **`file/system, error/file`**

Accuracy Assessment

- Validation by comparison to expert human analyst
  - But: analyst worked from *source code*; tool worked from *binary*
  - And: tool has improved since analyst did this work
- Human analyst reviewed 1046 functions:
    - 649 functions for which (older) tool identified at least one capability
    - 397 functions tool did not identify (random sample)
    - Represents only ~10% of functions in binary
  - Human review time: 985 min (pos), 865 min (neg) = 30.8h
- Automated analysis >1200x faster (on per-function basis)
- Analyst used more labels (76 vs 36), but less consistently

Accuracy Assessment

Statistic	Analyst Result	REAFFIRM Result
Functions analyzed	1046	10760
Processing time (minutes)	1850	14.8
Speed (functions/minute)	0.57	728
Functions initially labelled	518	649 (initial), 906 (latest)
Functions analyst could not find	125	n/a
# Unique capabilities	78	36
Most common labels	error, parsing, task, bus	error, parsing, time, processor

Accuracy Assessment

- Comparison of labels identified 67 human errors and omissions – cases where analyst initially failed
  - Some source code compile-time generated
  - Some functions too complex to readily understand
  - Compile-time optimizations couldn't be guessed
  - Or, "mental fatigue": analyst simply missed the obvious

Accuracy Assessment

- After analyst corrections:
  - Where both analyst and REAFFIRM applied a label, 71.6% category match
  - Approaches typical human-to-human inter-rater reliability of 75-80%
  - Where REAFFIRM applied labels and analyst did not, only 5 labels (<0.05%) marked “wrong” by analyst

Concluding Thoughts on Accuracy

- Difficult to establish absolute “ground truth”
  - Humans make mistakes and disagree on classifications
- Significant errors (false positives) from tool are rare and obscure
  - For example, 32-bit value 2.0f == 0x40000000; this happens to correspond to a target processor MMIO address for a hardware counter/timer.
- False negatives are more frequent, but less problematic
  - They won’t lead you astray; they will just fail to offer guidance
  - REAFFIRM is cautious, but FN rate (~22%) is being improved

Future Directions

- Several new areas of ongoing research
  - Structural information (wrappers, thunks)
  - Different ways to aggregate information above the function (“is-a” versus “has-a”)
  - Bounded symbolic execution for identification
    - Already demonstrated on math primitives: REMath
    - Could identify core library functions, e.g., strcpy

Questions