Micro Execution

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What is Micro Execution?

```
void test-driver() {
  char* buffer = malloc(10);
  memcpy(buffer, "hello");
  foo(buffer);
}
```

allocate memory

input data

known I/O signature

```
void foo(char *p) {  // p is a 1-byte input
  char v = *p;       // *p is a 1-byte input
  return;
}
```

Micro Execution is the ability to run any code fragment without a user-provided test driver or input data

What is Micro Execution?

can execute any code

intercepts all memory operations

allocates memory

provides input values

VM for test isolation and generation

```
void foo(char *p) {  // p is a 4-byte input
  char v = *p;       // *p is a 1-byte input
  return;
}
```

Micro Execution is the ability to run any code fragment without a user-provided test driver or input data

What is Micro Execution?

Micro Execution is the ability to run any code fragment without a user-provided test driver or input data

- The user selects any function or code location in any dll/exe
- A runtime VM starts executing the code at that location, catches all memory operations before they occur, and provides input values according to a customizable *memory policy*

  Ex: "an input is any value read from an uninitialized function argument, plus any dereference to a previous input (recursive definition)"

Start here

```
void foo(char *p) {  // p is a 4-byte input
  char v = *p;       // *p is a 1-byte input
  return;
}
```

Note: under this policy, uninitialized global-var reads are *not* inputs (other memory policies can be defined)

MicroX

- MicroX is a first prototype VM allowing micro execution of x86 binary code
  - Implemented as an extension of Nirvana (processor emulator)
  - Execute any x86 code in any (user-mode) Windows dll or exe
  - No source code, no pdb required
  - The user defines the starting point
  - Use a default memory policy, or define a new one…
  - Input values can be generated randomly, be zero, read from a file, read from a process dump, or be generated by SAGE
    - SAGE = tool for dynamic test generation with SMT constraint solving, widely used at Microsoft for security testing (see [ICSE'2013])
  - Stops when crash, max instr count reached, exec leaves the dll,…
  - No test driver required:
    - Inputs/Outputs are discovered dynamically by MicroX

Example

Start here

```
void foo(char *p) {  // p is a 4-byte input
  char v = *p;       // *p is a 1-byte input
  return;
}
```

is compiled into (x86)

```
 [...]
      push  ebp            ; foo starts here
      mov   ebp, esp
      push  ecx
      mov   eax, DWORD PTR [ebp+8] ; p
      mov   cl, BYTE PTR [eax]     ; *p
      mov   BYTE PTR [ebp-1], cl   ; v
      mov   esp, ebp
      pop   ebp
      ret   0
      [...]
```

micro executed

```
initEIP is 72B51005
initEBP is 001EF988

Read Mem Access at address 001EF990 of 4 bytes
   Initializing 4 input bytes:
     [0]=78 [1]=14 [2]=20 [3]=00
   Adding 00201478 to list of known addresses
 SetGuestEffectiveAddress returned 00201440

Read Mem Access at address 00201478 of 1 bytes
   Initializing 1 input bytes: [0]=29
 SetGuestEffectiveAddress returned 0020C490

Write Mem Access at address 001EF987 of 1 bytes
 SetGuestEffectiveAddress returned 001EF987

END: ExitProcess is called

***** External Memory Stats: *****
Number of Mem Accesses: 2 (2 Reads, 0 Writes)
Number of Addresses: 2 (total 5 bytes)
Number of Inputs: 2 (total 5 bytes)

***** Native Memory Stats: *****
Number of Module Accesses: 0 (0 Reads, 0 Writes)
Number of Other Accesses: 1 (0 Reads, 1 Writes)

***** General Stats: *****
Number of Unique Instructions After Start: 9
Number of Warnings: 0
Number of Errors: 0
```

How is MicroX implemented?

- Program instrumentation: using micro-operations (not new)

mov eax, [ecx] $\xrightarrow{\text{micro-operations}}$

```
...
GenerateEffectiveAddress
...
PREMemoryAccessCallBack
...
mov eax, [EffectiveAddress]
...
```

New: EffectiveAddress can be hijacked here

- External memory manager
  - Maps program-visible addrs to invisible ExternalMemory addrs
  - Maintains R/W consistency, consistent addressing (ptr arith,…)
  - 100% dynamic, see paper for details

- Input value generation
  - Random, zero, native, file, process-dump modes
  - Next iterations can be generated with SAGE

Limitations of Micro Execution

- False Positives (spurious bugs)
  - Micro execution makes sense mostly if all inputs are unconstrained
  - Otherwise, crashes may be unrealistic, and guidance is needed to specify realistic input constraints, either by the user or by a whole program analysis tool (SAGE…)
- False Negatives (missed bugs)
  - May miss bugs if input set is too small (e.g., ignore a global variable) → adjust memory policy
  - Poor test coverage? Use dynamic test generation (SAGE), …
- Can only find bugs that are local to the code under test

The next applications largely avoid those limitations

- Work in progress

Application 1: API Fuzzing

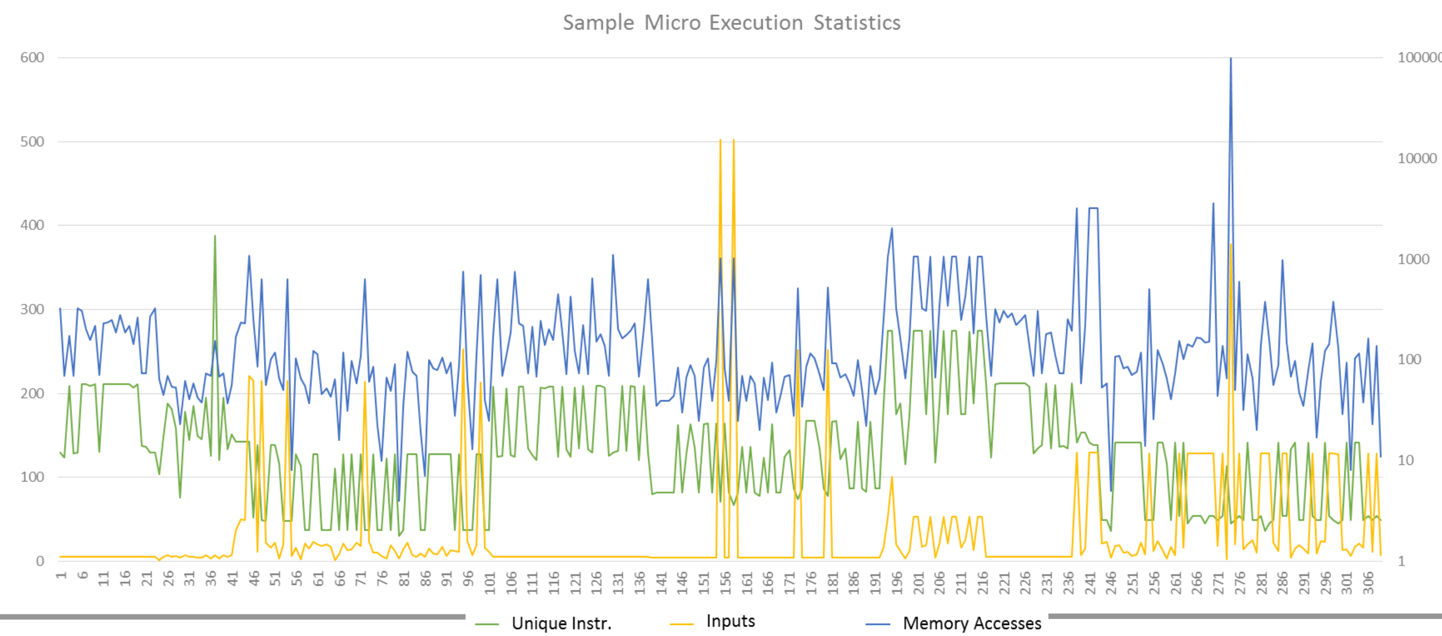
- New API fuzzer packaging MicroX+SAGE:
  - Specify a dll name and a list of dll-exported functions
    - No need for number of args, types, test driver!
  - Automatically run MicroX+SAGE on each function for 1min

Function Name	Unique Instructions (avg [min-max])	Inputs (avg [min-max])	Memory Accesses (avg [min-max])	Tests	Crashes
_i64toa_s	179 [124-211]	5 [5-5]	202 [69-323]	23	0
_snwscanf_s	164 [76-388]	5 [1-7]	60 [23-155]	18	0
_splitpath_s	142 [142-142]	89 [37-221]	431 [170-1090]	4	0
_strnset_s	82 [48-139]	74 [3-215]	201 [8-636]	10	0
_strset_s	81 [30-128]	27 [1-253]	105 [4-754]	56	0
_ui64toa_s	165 [121-208]	5 [5-5]	242 [68-753]	19	0
_ui64tow_s	169 [121-209]	5 [5-5]	258 [68-1105]	18	0
_ultoa_s	107 [67-164]	36 [4-502]	121 [20-1026]	31	2
_ultow_s	119 [74-167]	25 [4-252]	107 [22-529]	23	2
_vsnprintf_s	222 [116-275]	34 [3-101]	660 [66-2030]	24	0
_i64tow_s	181 [124-212]	5 [5-5]	199 [69-319]	21	0
_vsnwprintf_s	144 [139-153]	90 [7-130]	2172 [59-3189]	6	6
_wcsnset_s	79 [36-141]	57 [2-378]	1691 [5-100000]	66	4

Table 1: Sample experimental results with 13 exported functions part of ntdll.dll.

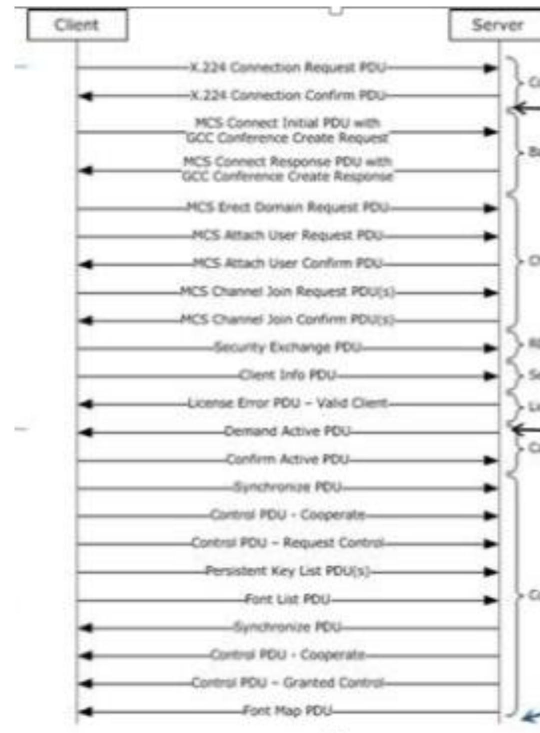
Application 1: API Fuzzing & Diffing

- Repeat on another dll version and diff the results
  - ~1,800 dlls in c:\windows\system32 alone
- Remarks: Micro execution is…
  - Fast and automatic, zero-cost test-setup
  - Good code coverage (thanks to SAGE)
  - Generates tons of data… (ex: useful for API diffing)



Application 2: Parser Isolation & Fuzzing

- Identify parsing code buried anywhere
  - Ex: packet parsers
- Start micro executing that code
  - MicroX discovers automatically its I/O
  - Input values are initialized from a dump
  - Packet values are fuzzed with SAGE
- Note: MicroX + dump = "micro-fork"
  - State is recreated partially (no bottom stack) and lazily (on-demand)



Application 3: Targeted Fuzzing

- Fast precise analysis of components of large parsers
  - Ex: with SAGE
    - a single symbolic execution of MS Excel takes ~1 hour
      - 47Kbytes input file, ~1.5 billion x86 instructions, ~25,000 constraints
    - a single symbolic execution of one function buried in Excel, running with MicroX, may take only ~1 second !
- Automatic program decomposition
  - Identify sub-parser and fuzz them in isolation
- Compositional testing
  - Memorize the sub-parser results with symbolic test summaries

Application 4: Unit/Program Verification

- The ANI Windows parser

  350+ fcts in 5 DLLs, parsing in ~110 fcts in 2 DLLs, core = 47 fcts in user32.dll →

- Is "attacker memory safe"

  = no attacker-controllable buffer overflow

- How? Compositional exhaustive testing
  - "perfect" symbolic execution in SAGE (max precision, no divergences, no x86 incompleteness, no Z3 timeouts, etc.),
  - *manual* bounding of input-dependent loops (only ~10 input bytes + file size), and
  - 5 *user-guided* simple summaries

- And modulo fixing a few bugs… ☺

- 100% dynamic (=zero static analysis)

- 1st Windows image parser proved attacker memory safe

- See "Proving Memory Safety of the ANI Windows Image Parser using Compositional Exhaustive Testing", MSR-TR-2013-120, with intern Maria Christakis

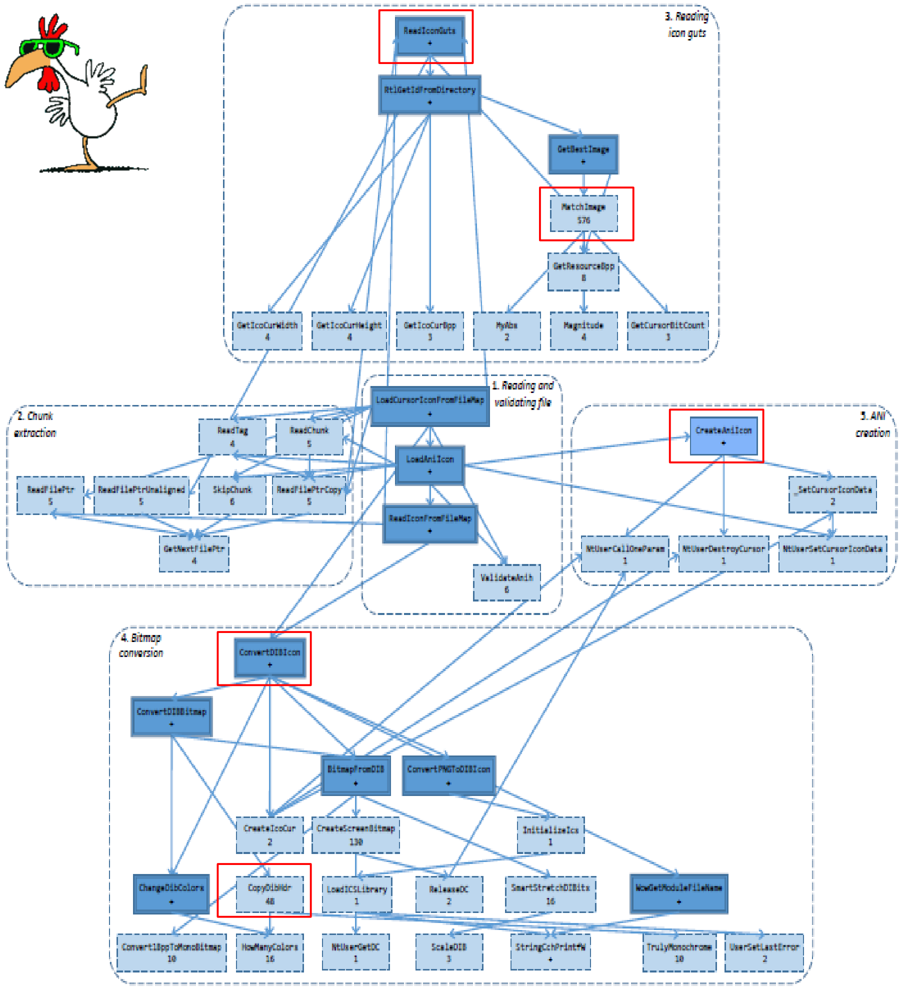


Figure 3. The callgraph of the 47 user32.dll functions implementing the ANI parser core. Functions are grouped based on the architectural component of Fig. 2 to which they belong. The different shades and lines of the boxes denote the verification strategy we used to prove memory safety of each function. Functions are annotated with the number of their execution paths. A + indicates that a function contains too many execution paths to be exhaustively enumerated within 12 hours without using additional techniques for controlling path explosion.

Application 5: Malware Detection

- Think of MicroX as an "eval(x86-code)" function
  - Can run any code to see if it uncloaks itself and then does something malicious

- Note: work in progress, see paper for more

Related Work

- Static program analysis
  - Simulates the execution of program paths
  - Uses abstraction:
    - often "over-approximate" abstractions
    - Hence imprecision triggers false alarms!

- Micro execution: locality but with precision
  - Concrete execution: testing
  - No false alarms due to abstraction (since NO abstraction)
  - Only cause of false alarms: lack of environment assumptions
    - Micro execution may start in an unrealistic initial state

Other Related Work

- Automatic test-driver generation ("closing" open systems)
  - Through static program transformations (PLDI'98, etc.)
  - Automatic static input-interface discovery and test gen (DART,...)
- Automatic dynamic test generation
  - SAGE, Pex, KLEE, S2E, etc.
  - API specific or need test driver with "symbolic" inputs ("param. unit tests")
- Automatic sub-component mock/stub/shim creation
  - Still requires a run-time environment
  - Orthogonal and complementary to micro execution
- How to specify input preconditions and output postconditions
  - Test driver, Code Contracts,...
  - Memory policy = "abstract" test driver - how to edit & refine mem. policies?
- Etc. (see paper)

Conclusion

Micro Execution is the ability to run any code fragment without a user-provided test driver or input data

- Key: a runtime environment which can intercept and redirect input/output memory operations before they occur, and can provide input values according to general rules
- MicroX = 1st VM for test isolation and generation
- Can start/stop executions anywhere and enables local, fast, precise, dynamic analysis of small code fragments & executions
- Lowers the cost of test setup (no test driver)
- How to get the best of static and dynamic program analysis
  - Speed/locality of static analysis with precision of dynamic analysis
  - Enables automatic program decomposition, compositional testing,…
- Many potential applications – but what is the "killer app"?