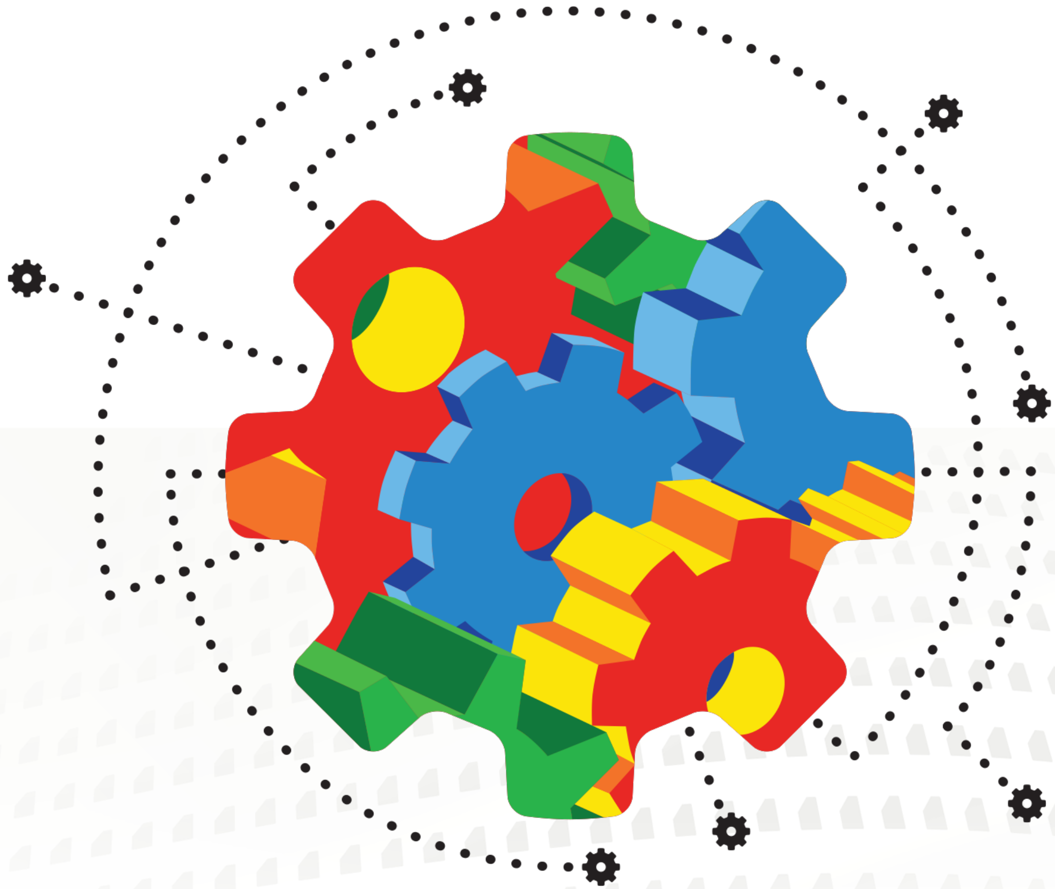
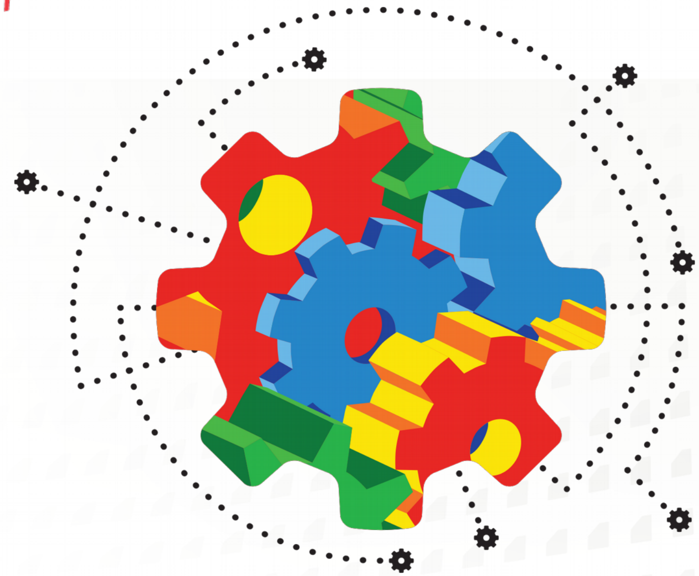


Fuzzing and Patch Analysis: SAGEly Advice

Sourcefire is now part of Cisco.



Introduction

Automated Test Generation

- Goal: Exercise target program to achieve full coverage of all possible states influenced by external input

- Code graph reachability exercise
- Input interaction with conditional logic in program code determines what states you can reach

Automated Testing Approaches

- Modern approaches fall into two buckets:
  - → Random Testing (Fuzzing)
    - Zero-knowledge mutation
    - Syntax model based grammar
    - Direct API interrogation
  - → Concolic Testing
    - Instrumented target program
    - Tracking of dataflow throughout execution
    - Observation of program branch logic & constraints
    - Symbolic reasoning about relationship between input and code logic

Advanced Fuzzing

- Advanced Fuzzers derive grammars from well formed data samples or are given a manually constructed syntax & interaction model that is expressed in a higher level grammar
- For automation, syntax is inferred using string grouping algorithms such as n-gram
- A good modern example is Radamsa
  - → Supply a corpus of well formed inputs
  - → Multiple grammar inference strategies
  - → Detection of repeated structures or identification of basic types is automatic

Limits to Fuzzing

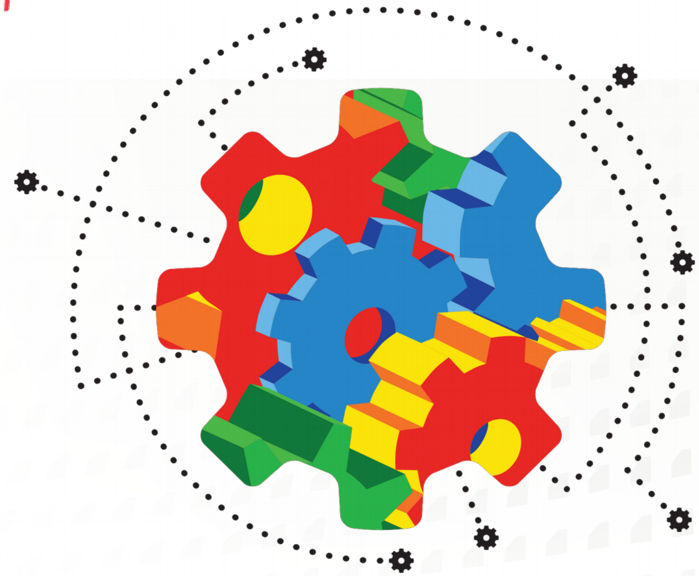
- Unfortunately even the most advanced fuzzers cannot cover all possible states because they are unaware of data constraints.
- The below example would require an upper bound of 2^32 or 4 billion attempts to meet the condition required to [illegible]

```
void test(char *buf)
{
    int n=0;
    if(buf[0] == 'b') n++;
    if(buf[1] == 'a') n++;
    if(buf[2] == 'd') n++;
    if(buf[3] == '!') n++;
    if(n==4) {
        crash();
    }
}
```

Concolic Testing

- For anything beyond string grouping algorithms, direct instrumentation of the code and observation of interaction between data and conditional logic is required

- Early academic work in this area:
  - → DART: Directed Automated Random Testing
    - 2005 - Patrice Godefroid, et al
  - → CUTE: a concolic unit testing engine for C
    - 2005 - Sen, Koushik
  - → EXE: Automatically Generating Inputs of Death
    - 2006 -Dawson Engler



Concolic Test Generation: Core Concepts

Code Coverage & Taint Analysis

- Code Coverage
  - → Analysis of program runtime to determine execution flow
  - → Collect the sequence of execution of basic blocks and branch edges

- Several approaches
  - → Native debugger API
  - → CPU Branch Interrupts
  - → Static binary rewriting
  - → Dynamic binary instrumentation

Code Coverage & Taint Analysis

- Taint Analysis
  - → Analysis of program runtime to determine data flow from external input throughout memory
  - → Monitor each instruction for propagation of user controlled input from source operands to destination operands
  - → Dependency tree is generated according to tainted data flows in memory or CPU registers
  - → Taint analysis is imperfect – propagation rules must dictate the level of inferred dataflow that is propagated

Dynamic Binary Instrumentation

- JIT modification of binary code
  - → As new code blocks are visited or modules are loaded, an analysis phase disassembles the binary to identify code structure
  - → Instructions may be inserted at arbitrary locations around or within the disassembled target binary
  - → Modified code is cached and referenced instead of original binary

- Skips some problems with static binary rewriting and maintains runtime state for conditional instrumentation

Symbolic Execution

- Symbolic execution involves computation of a mathematical expression that represents the logic within a program.
- It can be thought of as an algebra designed to express computation.

```
void test(char *buf)
{
    int n = 0;
    if(buf[0] == 'b') n+
+;
    if(buf[1] == 'a') n+
+;
    if(buf[2] == 'd') n+
+;
    if(buf[3] == '!') n+
+;
    if(n==4) {
        crash();
    }
}
```

```
(declare-const buf (Array Int Int))
(declare-fun test () Int)
(declare-const n Int)
(assert (= n 0))
(ite (= (select buf 0) 98) (+ n 1)
0)
(ite (= (select buf 1) 97) (+ n 1)
0)
(ite (= (select buf 2) 100) (+ n 1)
0)
(ite (= (select buf 3) 92) (+ n 1)
0)
(assert (= n 4))
(check-sat)
(get-model)
```

Symbolic Execution

- Symbolic execution involves computation of a mathematical expression that represents the logic within a program.
- It can be thought of as an algebra designed to express computation.

```
void condition(int x)
{
    int ret = 0;
    if (x > 50)
        ret = 1;
    else
        ret = 2;
    return ret
}
```

```
(declare-fun condition () Int)
(declare-const ret Int)
(declare-const x Int)
(assert (=> (>= x 50) (= ret 1)))
(assert (=> (< x 50) (= ret 2)))
(assert (= ret 1))
(check-sat)
(get-model)
---
sat
(model
    (define-fun x () Int 50)
    (define-fun ret () Int 1)
)
```

Symbolic Execution

- Last year we used Symbolic Execution to emulate forward from a crash to determine exploitability

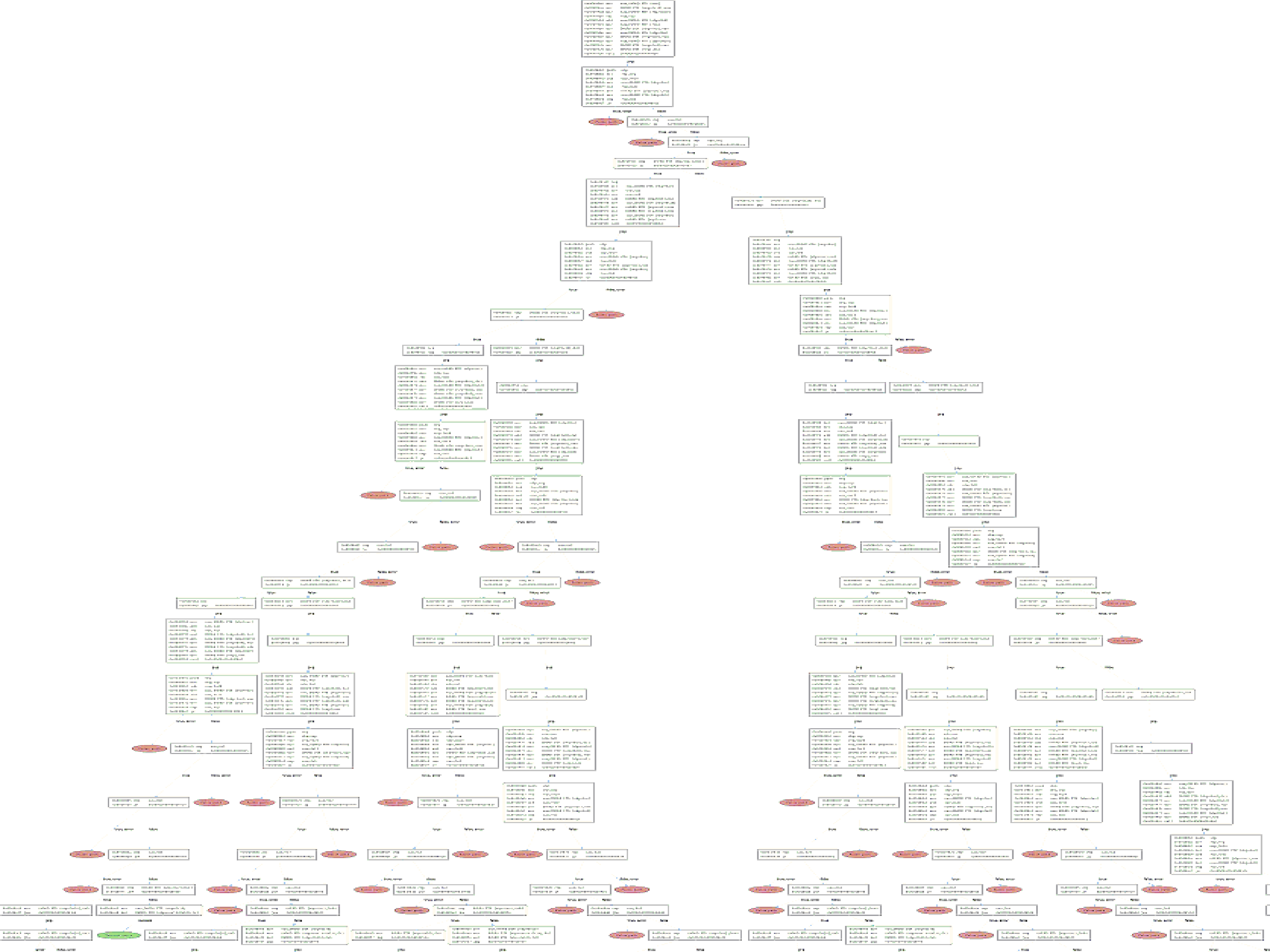
```
void test_motriage(unsigned int
*buf)
{
   unsigned int b,x,y;

   b = buf[0];
   x = buf[b+0x11223344];
   y = buf[x];
   exploit_me(1, x, y);
}
```

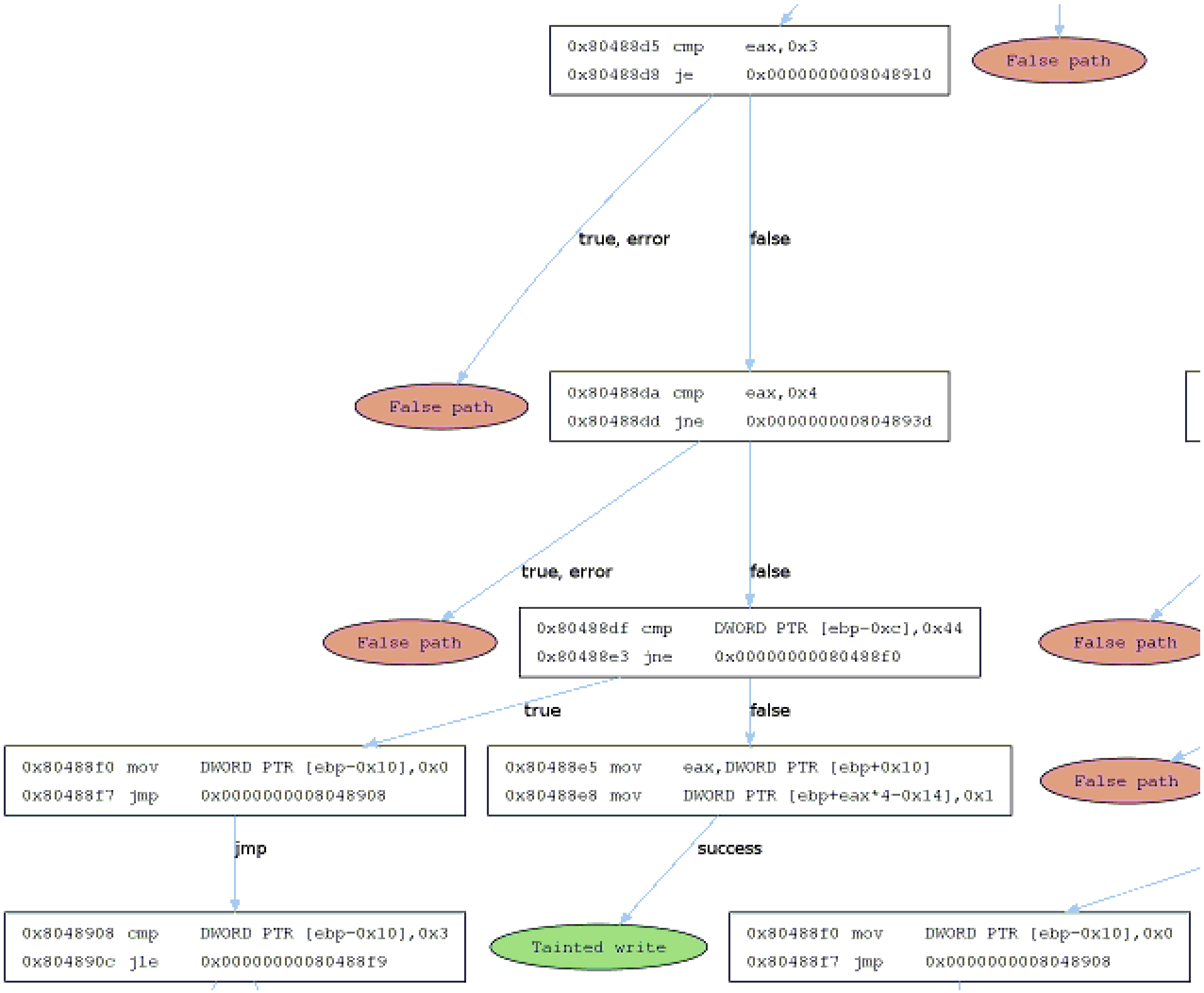
Symbolic Execution

- Last year we used Symbolic Execution to emulate forward from a crash to determine exploitability

```
void exploit_me
   (int depth,
   unsigned int x,
   unsigned int y)
{
   int stack[1];
   int b, i;
   b = x & 0xff;
   switch(depth) {
...
   }
   exploit_me(++depth, x>>8,
y);
}
```

```
case 4:
   if(b == 0x44)
      stack[y] = 1;
   return;
case 3:
   if(b != 0x33) y = 0;
   break;
case 2:
   if(b != 0x22) y = 0;
   break;
case 1:
   if(b != 0x11) y = 0;
   break;
default:
   assert(0);
```




0x80488d5 cmp eax,0x3
0x80488d8 je 0x0000000008048910
False path
true, error
false
False path
0x80488da cmp eax,0x4
0x80488dd jne 0x000000000804893d
true, error
false
False path
0x80488df cmp DWORD PTR [ebp-0xc],0x44
0x80488e3 jne 0x00000000080488f0
False path
true
false
0x80488f0 mov DWORD PTR [ebp-0x10],0x0
0x80488f7 jmp 0x0000000008048908
0x80488e5 mov eax,DWORD PTR [ebp+0x10]
0x80488e8 mov DWORD PTR [ebp+eax*4-0x14],0x1
False path
jmp
success
0x8048908 cmp DWORD PTR [ebp-0x10],0x3
0x804890c jle 0x00000000080488f9
Tainted write
0x80488f0 mov DWORD PTR [ebp-0x10],0x0
0x80488f7 jmp 0x0000000008048908

Constraint Generation

- Comparisons are done on values to determine which branch of code to take:

```
if (a > b):
    block1
else:
    block2
```

- We observe these constraints to determine what data value ranges allow execution in different paths
- A code path is determined by collecting a series of these constraints which determines the execution flow of the program

Constraint Generation

- Against binary targets we need to track flags and evaluate the dependent comparison before a jump

```
0x080483d4 <+0>:   push   %ebp
0x080483d5 <+1>:   mov    %esp,%ebp
0x080483d7 <+3>:   and    $0xfffffff0,%esp
0x080483da <+6>:   sub    $0x10,%esp
0x080483dd <+9>:   cmpl   $0x1,0x8(%ebp)
0x080483e1 <+13>:  jle    0x80483f1 <main+29>
0x080483e3 <+15>:  movl   $0x80484d0,(%esp)
0x080483ea <+22>:  call   0x80482f0 <puts@plt>
0x080483ef <+27>:  jmp    0x80483f2 <main+30>
0x080483f1 <+29>:  nop
0x080483f2 <+30>:  leave
0x080483f3 <+31>:  ret
```

- This may be done manually or through the use of an IR

Constraint Solving

- A formula representing the code path logic is generated in a format acceptable to a symbolic execution engine

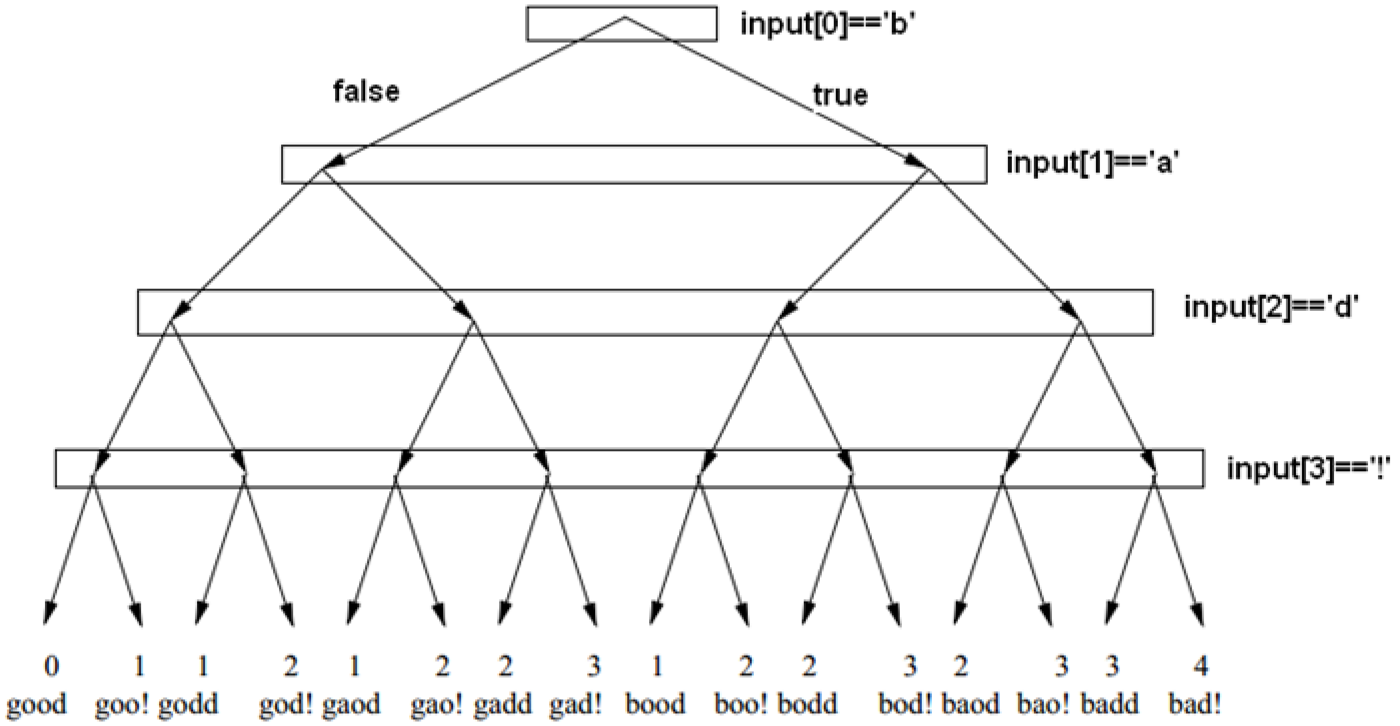
- To explore alternate paths, we invert the conditional logic of the last branch and allow the solver to generate an example that would match the inverted conditional logic

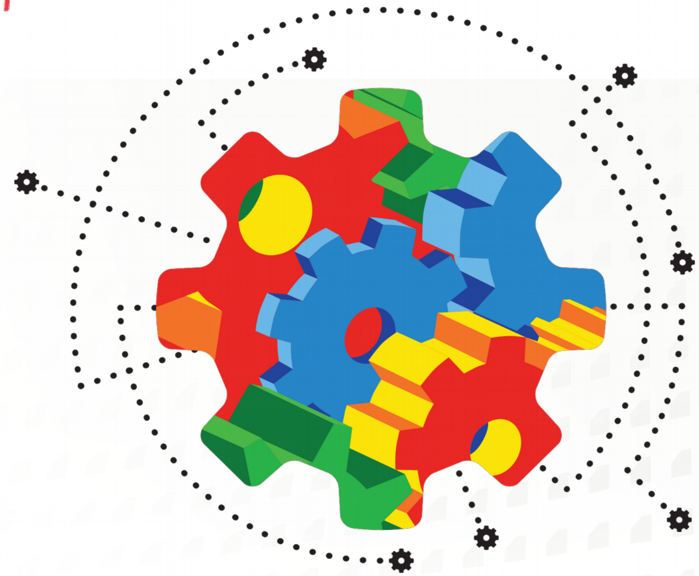
- Iterative use of this algorithm allows us to explore a complete program graph

Test Generation

- Input: ‘bad?’
- Formula generated by symbolic execution:
  - → $\Phi := (i_0=\text{‘b’})\ \&\&\ (i_1=\text{‘a’})\ \&\&\ (i_2=\text{‘d’})\ \&\&\ (i_3<>\text{‘!’})$
- New formulas:
  - → $\Phi_0 := (i_0=\text{‘b’})\ \&\&\ (i_1=\text{‘a’})\ \&\&\ (i_2=\text{‘d’})\ \&\&\ (i_3=\text{‘!’})$
  - → $\Phi_1 := (i_0=\text{‘b’})\ \&\&\ (i_1=\text{‘a’})\ \&\&\ (i_2<>\text{‘d’})\ \&\&\ (i_3<>\text{‘!’})$
  - → $\Phi_2 := (i_0=\text{‘b’})\ \&\&\ (i_1<>\text{‘a’})\ \&\&\ (i_2=\text{‘d’})\ \&\&\ (i_3<>\text{‘!’})$
  - → $\Phi_3 := (i_0<>\text{‘b’})\ \&\&\ (i_1=\text{‘a’})\ \&\&\ (i_2=\text{‘d’})\ \&\&\ (i_3<>\text{‘!’})$

Test Generation





Microsoft SAGE

Implementation

Optimizations

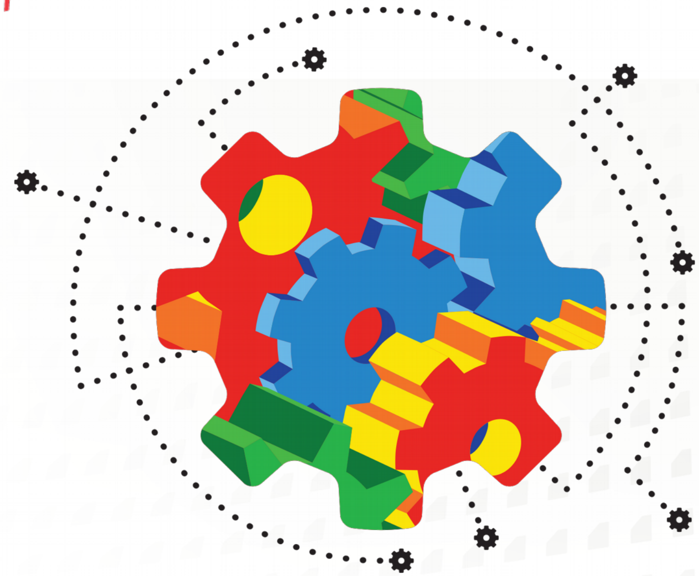
- Generational Search vs DFS
  - → DFS or BFS would negate only one of the branches
  - → Generational search negates each condition and solves for each, generating many new inputs per symbolic execution phase instead of just one

- Constraint Optimization
  - → Constraint Elimination - reduces the size of constraint solver queries by removing the constraints which do not share symbolic variables with the negated constraint
  - → Local constraint Caching - skips a constraint if it has already been added to the path constraint
  - → Flip count limit - establishes the maximum number of times a constraint generated from a particular program instruction can be flipped
  - → Constraint Subsumption - tracks constraints dominated by a specific branch, skips identical constraints generated from the same instruction location

Results

- Thousands of crashes found in the Windows 7 and Office products – 1/3 of all file fuzzing bugs since 2007

- Lessons Learned
  - → Vulnerabilities discovered are usually at shallow code depths
  - → Symbolic Execution state is limited so wrappers need to be developed for library code
  - → A small number of generations typically find the majority of vulnerabilities



Moflow::FuzzFlow

Sourcefire is now part of Cisco.

Implementation

Limitations

- Tracer
  - → Taint tracer from BAP is not optimized
  - → For this application, inputs over a few kB are problematic
  - → PIN is unable to flush single basic block hooks from code cache for code coverage hit trace
- Symbolic Execution
  - → Slow conversion from BIL to SMTLIB on big traces
- FuzzFlow
  - → Libraries need to be wrapped directly
  - → We lack most of the optimizations in SAGE such as constraint subsumption

Does It Blend?

```
int main(int argc, char *argv[])
{
  char buf[500];
  size_t count;
  fd = open(argv[1], O_RDONLY);
  if(fd == -1) {
    perror("open");
    exit(-1);
  }
  count = read(fd, buf, 500);
  if(count == -1) {
    perror("read");
    exit(-1);
  }
  close(fd);
  test(buf);
  return 0;

}
```

```
void crash(){
  int i;
  // Add some basic blocks
  for(i=0;i<10;i++){
    i += 1;
  }
  *(int*)NULL = 0;
}

void test(char * buf)
{
    int n=0;
    if(buf[0] == 'b') n++;
    if(buf[1] == 'a') n++;
    if(buf[2] == 'd') n++;
    if(buf[3] == '!') n++;
    if(n==4){
        crash();
    }
}
```

Does It Blend?

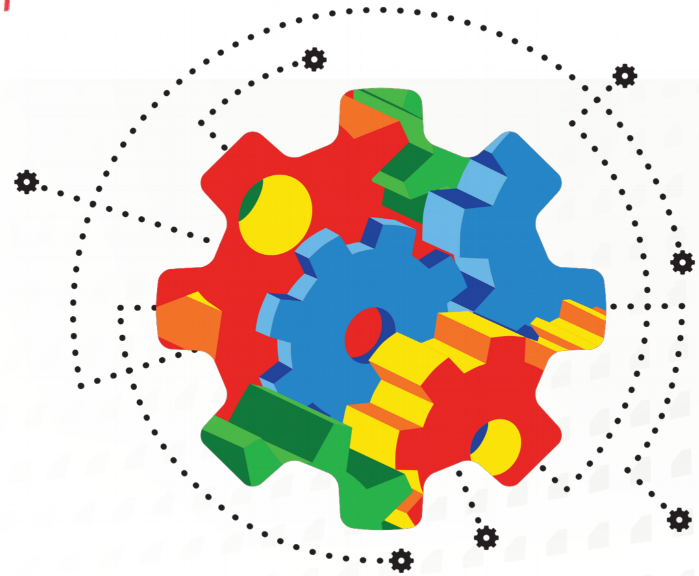
```
moflow@ubuntu:~/moflow-bap-0.7/custom_utils/egas$ ./egas -app test/bof1 -seed
test/input.txt
Starting program
Thread 0 starting
Opening tainted file: samples/13.sol
Tainting 5 bytes from read at bffafe30
buffer_size: 5, requested length: 5
Taint introduction #0. @bffafe30/5 bytes: file samples/13.sol
adding new mapping from file samples/13.sol to 0 on taint num 1
adding new mapping from file samples/13.sol to 1 on taint num 2
adding new mapping from file samples/13.sol to 2 on taint num 3
adding new mapping from file samples/13.sol to 3 on taint num 4
adding new mapping from file samples/13.sol to 4 on taint num 5
Activating taint analysis
CRASH! Sample: samples/13.sol saved as crashes/2014-06-20_22:40:10_13.crash
----------STATS----------
%    total     count     desc
68%  13s  9    taint tracing the target (produces .bpt)
16%  3s   14   gathering coverage info
5%   1s   9    symbolic execution
0%   0s   0    .bpt concretization
0%   0s   13   solver interaction
11%  2s   1    unaccounted
-------------------------
elapsed: 19.000000
```

Real World Vulnerability Discovery

```
moflow@ubuntu:~/moflow-bap-0.7/custom_utils/egas$ ./egas -app /home/moflow/graphite2-1.2.3/tests/comparerenderer/comparerenderer -seed /home/moflow/graphite2-1.2.3/tests/fonts/tiny.ttf -fmt "-t /home/moflow/graphite2-1.2.3/tests/texts/udhr_nep.txt -s 12 -f %s -n“



Breakpoint 1, _IO_fread (buf=0x0, size=1, count=3758096384, fp=0x8053230) at iofread.c:37
37	in iofread.c
(gdb) bt
#0  _IO_fread (buf=0x0, size=1, count=3758096384, fp=0x8053230) at iofread.c:37
#1  0x4003a8ca in graphite2::FileFace::get_table_fn(void const*, unsigned int, unsigned int*) ()
   from /home/moflow/graphite2-1.2.3/src/libgraphite2.so.3
#2  0x4002e8e5 in graphite2::Face::Table::Table(graphite2::Face const&, graphite2::TtfUtil::Tag) ()
   from /home/moflow/graphite2-1.2.3/src/libgraphite2.so.3
#3  0x4002858a in (anonymous namespace)::load_face(graphite2::Face&, unsigned int) ()
   from /home/moflow/graphite2-1.2.3/src/libgraphite2.so.3
#4  0x40028695 in gr_make_face_with_ops () from /home/moflow/graphite2-1.2.3/src/libgraphite2.so.3
#5  0x40028aac in gr_make_file_face () from /home/moflow/graphite2-1.2.3/src/libgraphite2.so.3
#6  0x0804d56d in Gr2Face::Gr2Face(char const*, int, std::string const&, bool) ()
#7  0x0804b664 in main ()
```

Real World Vulnerability Discovery

```
const void *FileFace::get_table_fn(const void* appFaceHandle, unsigned int name, size_t
*len)
{
    if (appFaceHandle == 0) return 0;
    const FileFace & file_face = *static_cast<const FileFace *>(appFaceHandle);
    void *tbl;
    size_t tbl_offset, tbl_len;
    if (!TtfUtil::GetTableInfo(name, file_face._header_tbl,
                               file_face._table_dir, tbl_offset, tbl_len))
        return 0;

    if (tbl_offset + tbl_len > file_face._file_len
            || fseek(file_face._file, tbl_offset, SEEK_SET) != 0)
        return 0;

    tbl = malloc(tbl_len);
    if (fread(tbl, 1, tbl_len, file_face._file) != tbl_len)
    {
        free(tbl);
        return 0;
    }

    if (len) *len = tbl_len;
    return tbl;
}
```



Binary Differencing

The Good Old Days

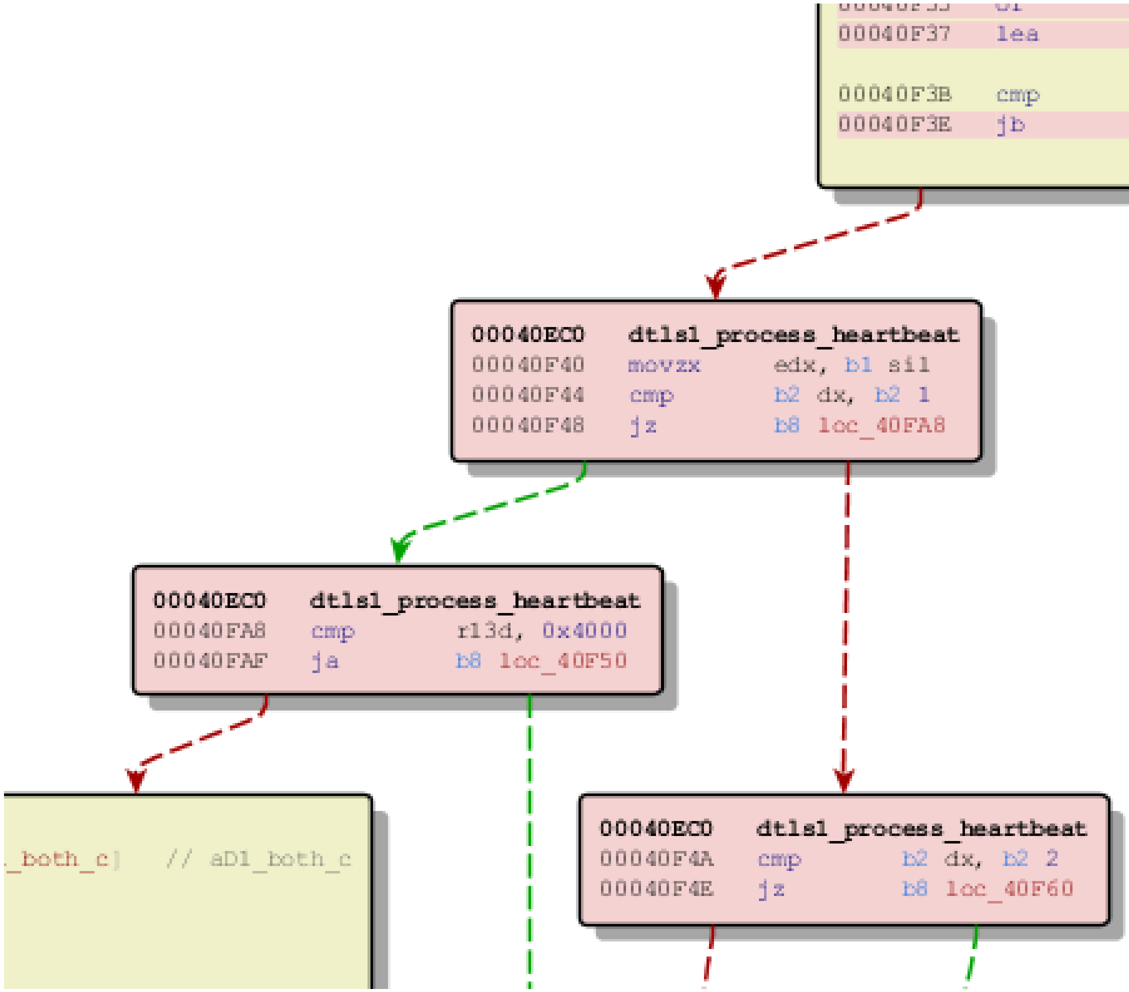
- In 2004, Halvar was the first to apply isomorphic graph comparison to the problem of binary program differencing
- The primary class of vulnerabilities at the time were Integer Overflows
  - → "Integer overflows are heavily represented in OS vendor advisories, rising to number 2 in 2006" http://cwe.mitre.org/documents/vuln-trends/index.html
  - → Integer Overflows are localized vulnerabilities that result in array indexing or heap allocation size miscalculations
- Many vulnerabilities were targeting file formats such a Microsoft Office

BinDiff in 2014

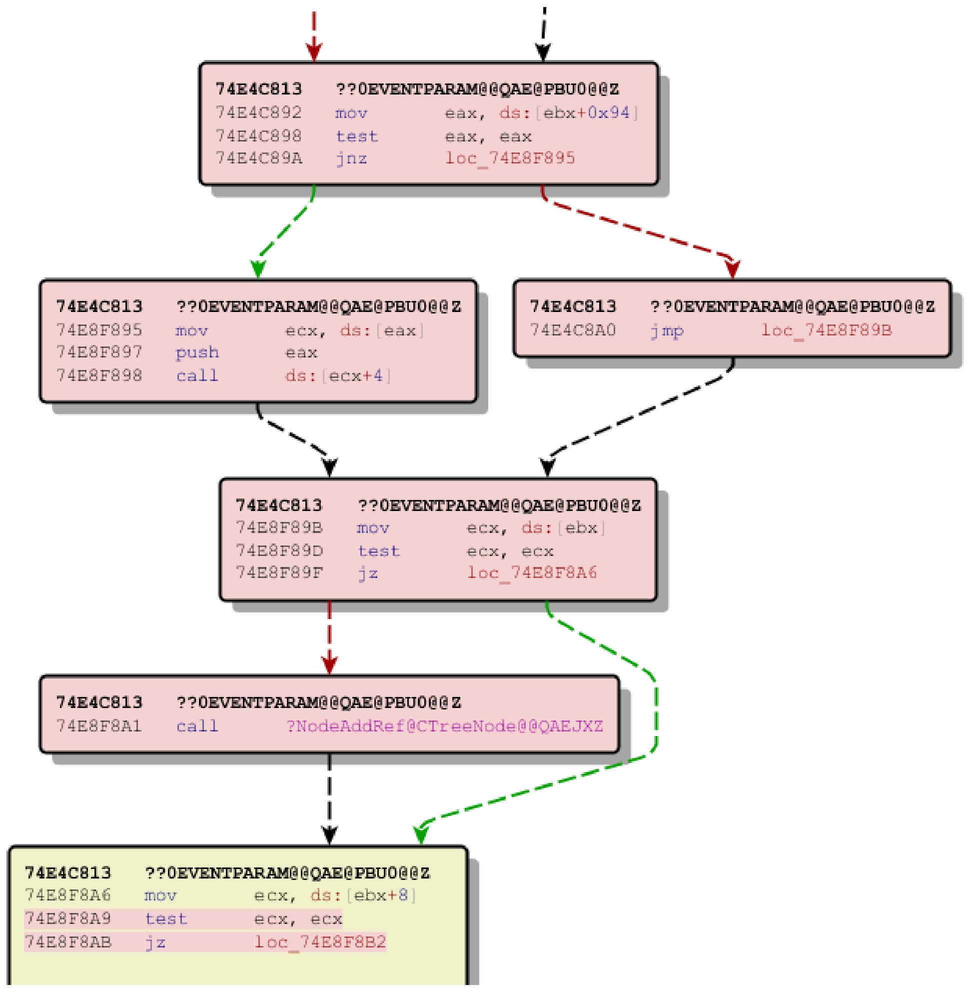
- Last update for the only commercialized BinDiff tool (Zynamics BinDiff) was in 2011

- The majority of vulnerabilities being patched by Microsoft are use-after-free bugs in Internet Explorer which has a high degree of separation between the root cause that gets patched and the actual code path that can trigger the bug leading to an exploitable condition
  - → First added to CWE in 2008, now dominates as a vulnerability class in web-browsers and document parsers

Inline Bounds Checking



Use-After-Free



Function Matching

- Hash Matching (bytes/names)
- MD index matching (flowgraph/callgraph, up/down)
- Instruction count
- Address sequence
- String references
- Loop count
- Call sequence

Basic Block Matching

- Edges Prime Product
- Hash/Prime
- MD index (flowgraph/callgraph, up/down)
- Loop entry
- Entry/Exit point
- Jump sequence

Practical Problems

- Mismatched functions
  - → Some functions are identical in both binaries, but mismatched by the differ
- Assembly refactoring
  - → Some functions are semantically identical in both binaries, but some assembly instructions have changed/moved
- Little to no context
  - → Functions are given a similarity rating, but no potential indicators of security-related additions

Practical Problems

- Compiler optimizations are not handled
- Chunked functions are not handled
- BinDiff heuristics are not tunable / configurable
- IDA misidentifies data as code

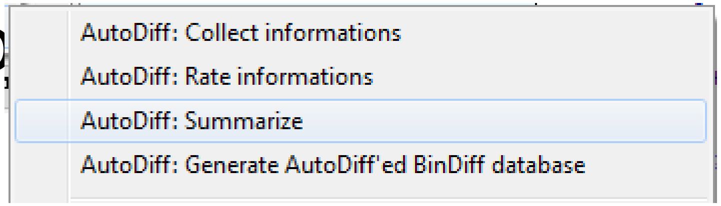
- UAF vulnerabilities are hard to reverse engineer
  - → The DOM is massive and interactions between objects are not defined
  - → The patches are typically simple reference counting patches (add missing calls to AddRef)

Mismatched Functions

matched basicb	basicblocks prir	basicblocks secor	matched instructior	instructions primary	instructions seconda	matched edges	edges primary	edges seco
1	1	1	7	7	14	0	0	0
1	1	1	7	8	14	0	0	0
1	1	1	11	14	21	0	0	0
13	28	14	64	288	109	8	45	22
13	14	28	64	109	288	8	22	45
8	9	12	37	126	138	6	12	19
2	4	8	7	36	68	0	4	11
3	3	16	16	19	184	1	3	22
8	16	9	58	184	126	6	22	12
3	3	35	4	14	243	1	3	49
4	8	7	9	68	69	2	11	8
1	1	3	4	14	19	0	0	3
1	1	3	1	6	14	0	0	3
15	25	52	35	169	413	6	39	80
1	4	1	1	18	6	0	4	0
1	1	4	5	34	36	0	0	4
15	52	25	35	413	169	6	80	39
1	8	1	6	39	7	0	12	0
1	1	9	6	28	54	0	0	12
1	9	1	9	88	28	0	12	0
1	1	9	7	14	88	0	0	12
1	9	1	5	54	34	0	12	0
4	35	4	4	243	18	3	49	4
1	12	1	6	138	8	0	19	0
1	18	1	9	278	13	0	25	0
6	6	57	16	34	373	4	6	83
6	57	6	16	373	34	4	83	6
2	4	3	13	81	19	0	4	3
3	3	18	10	19	278	1	3	25
4	7	4	13	69	81	3	8	4

AutoDiff

- Our solution is to post-process the database generated from BinDiff
- We augment the existing database by performing further analysis with IDApython scripts
- New tables are added to supplement the existing informatio



AutoDiff

- Features
  - → Instruction counting (including chunked function)
  - → Instructions added/removed from each function
  - → IntSafe library awareness
  - → Filtering of innocuous / superfluous changes
  - → Filtering of changes without a security impact
    - Example: new 'ret' instructions generated by compiler
  - → Mnemonic list comparison
    - To determine when register substitution is the only change

Results

- MS13-097 – ieinstal.dll: 19% reduction

```
=======================================================
=                AutoDiff / Statistics                =
=======================================================
Number of changed functions declared by BinDiff : 179
Number of functions filtered out by Sanitizer   : 26
Number of functions contain "IntSafe patch"     : 1
Number of functions ReMatched                   : 7
Number of functions still left to analysis      : 145
```

Results

- MS14-017 – wordcnv.dll: 76% reduction

```
=======================================================
=                 AutoDiff / Statistics               =
=======================================================
Number of changed functions declared by BinDiff : 55
Number of functions filtered out by Sanitizer   : 0
Number of functions contain "IntSafe patch"     : 0
Number of functions ReMatched                   : 42
Number of functions still left to analysis      : 13
```

Results

- MS14-035 – urlmon.dll: 29% reduction

```
=======================================================
=                AutoDiff / Statistics                =
=======================================================
Number of changed functions declared by BinDiff : 31
Number of functions filtered out by Sanitizer   : 9
Number of functions contain "IntSafe patch"     : 0
Number of functions ReMatched                   : 0
Number of functions still left to analysis      : 22
```

Results

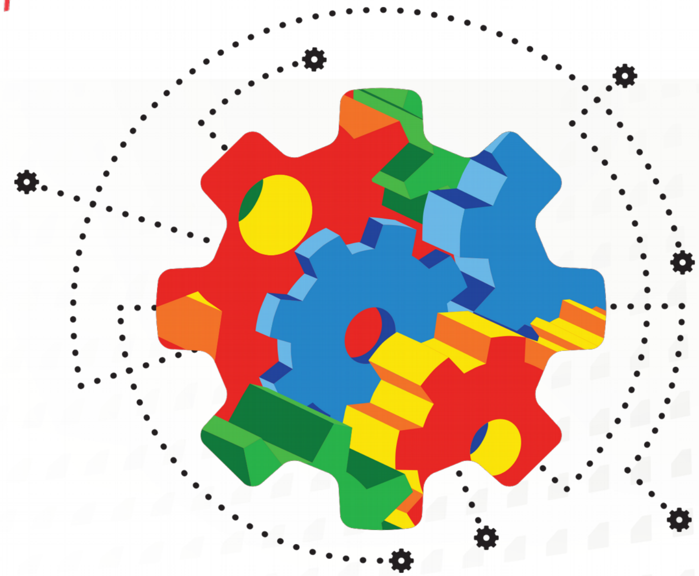
- MS14-035 – mshtml.dll: 21% reduction

```
=======================================================
=                AutoDiff / Statistics                =
=======================================================
Number of changed functions declared by BinDiff : 543
Number of functions filtered out by Sanitizer   : 56
Number of functions contain "IntSafe patch"     : 0
Number of functions ReMatched                   : 61
Number of functions still left to analysis      : 426
```

Results

- Adobe CVE-2014-0497: 87% reduction

```
=======================================================
=                AutoDiff / Statistics                =
=======================================================
Number of changed functions declared by BinDiff : 1118
Number of functions filtered out by Sanitizer   : 975
Number of functions contain "IntSafe patch"     : 0
Number of functions ReMatched                   : 0
Number of functions still left to analysis      : 143
```



Semantic Difference Engine

BinDiff Problem Areas

- Reassignment of registers while maintaining the same semantics
- Inversion of branch logic
  - → such as `jge -> jl`
- Using more optimized assembler instructions that are semantically equivalent

The Idea

- We've shown success using symbolic execution to analyze code paths to generate inputs
- We should be able to ask a solver to tell us if two sets of code are equivalent
- In last year's presentation we showed an example of exactly thi
  - → Is "add eax, ebx" equivalent to this code

```
add eax, ebx
xor ebx, ebx
sub ecx, 0x123
setz bl
add eax, ebx
```

The Idea

```
add eax, ebx
xor ebx, ebx
sub ecx, 0x123

setz bl
add eax, ebx
```

```
ASSERT( 0bin1 = (LET initial_EBX_77_0 = R_EBX_6 IN
(LET initial_EAX_78_1 = R_EAX_5 IN
(LET R_EAX_80_2 = BVPLUS(32, R_EAX_5,R_EBX_6) IN
(LET R_ECX_117_3 = BVSUB(32, R_ECX_7,0hex00000123)
IN
(LET R_ZF_144_4 = IF (0hex00000000=R_ECX_117_3)
THEN 0bin1 ELSE 0bin0 ENDIF IN
(LET R_EAX_149_5 = BVPLUS(32, R_EAX_80_2,
(0bin0000000000000000000000000000000 @
R_ZF_144_4)) IN
(LET final_EAX_180_6 = R_EAX_149_5 IN
IF (NOT(final_EAX_180_6=BVPLUS(32,
initial_EAX_78_1,initial_EBX_77_0))) THEN
);
QUERY(FALSE);
COUNTEREXAMPLE;
```

```
Model:
R_ECX_7 -> 0x123
Solve result: Invalid
```

The Idea

- Strategy would be to mark function parameters as symbolic and discover each path constraint to solve for inputs that would reach all paths
- At termination of each path the resulting CPU state and variable values should be identical
- Unfortunately this led to a false impression of the feasibility of this approach

The Reality

- Low level IR is tied to a memory and register model
- This level of abstraction does not sufficiently alias references to the same memory
- At minimum private symbol information would be needed to abstract beyond the memory addresses so we could manually match the values
- Decompilation would be a better first step towards this strategy, but symbol names

A Practical Approach

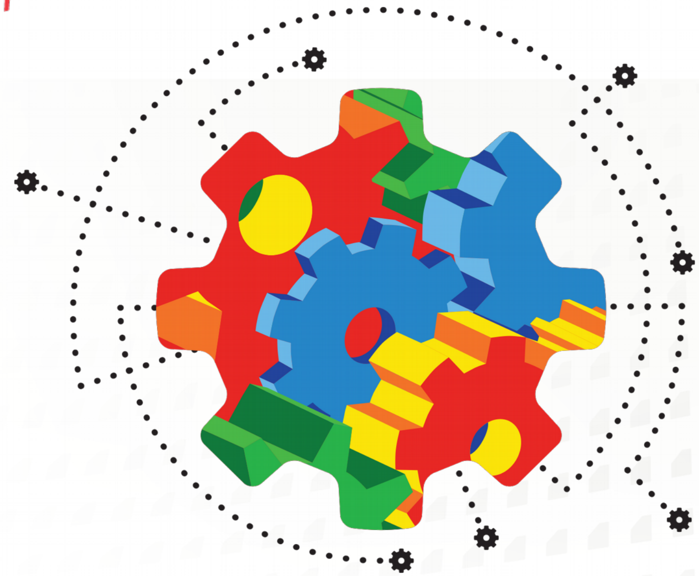
- David Ramos and Dawson Engler published "Practical, low-effort equivalence verification of real code" which shows a technique for performing a semantic equivalence test against source code using a modified version of KLEE
- Original application was for program verification of new implementations vs reference implementations, our problem is a subset of this
- Turns out the approach is nearly identical but works on a higher level of abstraction

A Practical Approach

- Code is compiled with symbol information using KLEE/LLVM
- A test harness is linked against each of the two functions to be compared
- The harness marks each parameter of the two functions as symbolic
- If input parameters are dereferenced as pointers, memory is lazily allocated as symbolic values
- Symbolically executes each function for each discovered constraint
- At the end of execution, KLEE traverses each memory location and solves for equivalent values at each location
- On failure of this check, a concrete input is generated that can prove the functions are different, else they've been proven equal

Where to Next

- The ability to alias memory references through the use of symbol information is the crucial missing piece of the puzzle for our approach
- There are additional difficulties with reference tracking, object comparison for passed parameters or return values, as well as overlapping memory references
- They explicitly specify that inline assembler is not handled due to their reliance on symbol information



Conclusions

Thank You!

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  - → Marcin Noga
  - → Yves Younan
  - → Pawel Janic (emeritus)

  - → Code release will be announced on
    - http://vrt-blog.snort.org/