500 Machine-Years of Software Model Checking and SMT Solving

Patrice Godefroid

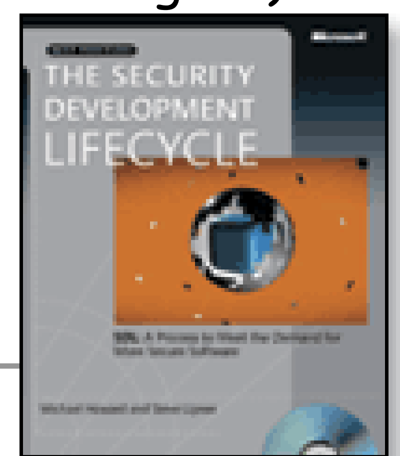
Microsoft Research

Security is Critical (to Microsoft)

- Software security bugs can be very expensive:
  - Cost of each Microsoft Security Bulletin: $Millions
  - Cost due to worms (Slammer, CodeRed, Blaster, etc.): $Billions
- Many security exploits are initiated via files or packets
  - Ex: MS Windows includes parsers for hundreds of file formats
- Security testing: "hunting for million-dollar bugs"
  - Write A/V (always exploitable), Read A/V (sometimes exploitable), NULL-pointer dereference, division-by-zero (harder to exploit but still DOS attacks), etc.

Hunting for Security Bugs

- Main techniques used by "black hats":
  - Code inspection (of binaries) and
  - Blackbox fuzz testing
- Blackbox fuzz testing:
  - A form of blackbox random testing [Miller+90]
  - Randomly fuzz (=modify) a well-formed input
  - Grammar-based fuzzing: rules that encode "well-formed"ness + heuristics about how to fuzz (e.g., using probabilistic weights)
- **Heavily** used in security testing
  - Simple yet effective: many bugs found this way…
  - At Microsoft, fuzzing is mandated by the SDL →



Introducing Whitebox Fuzzing

- Idea: mix fuzz testing with dynamic test generation
  - Symbolic execution
  - Collect constraints on inputs
  - Negate those, solve with constraint solver, generate new inputs
  - → do "systematic dynamic test generation" (=DART)
- Whitebox Fuzzing = "DART meets Fuzz"

  Two Parts:

  1. Foundation: DART (Directed Automated Random Testing)
  2. Key extensions ("Whitebox Fuzzing"), implemented in SAGE

Automatic Code-Driven Test Generation

Problem:

Given a sequential program with a set of input parameters, generate a set of inputs that maximizes code coverage

= "automate test generation using program analysis"

This is not "model-based testing"
(= generate tests from an FSM spec)

How? (1) Static Test Generation

- Static analysis to partition the program's input space [King76,…]
- Ineffective whenever symbolic reasoning is not possible
  - which is frequent in practice… (pointer manipulations, complex arithmetic, calls to complex OS or library functions, etc.)

Example:

```
int obscure(int x, int y) {
  if (x==hash(y)) error();
  return 0;
}
```

Can't statically generate values for x and y that satisfy "x==hash(y)" !

How? (2) Dynamic Test Generation

- Run the program (starting with some random inputs), gather constraints on inputs at conditional statements, use a constraint solver to generate new test inputs
- Repeat until a specific program statement is reached [Korel90,…]
- Or repeat to try to cover ALL feasible program paths: DART = Directed Automated Random Testing = systematic dynamic test generation [PLDI'05,…]
  - detect crashes, assertion violations, use runtime checkers (Purify, Valgrind, AppVerifier,…)

DART = Directed Automated Random Testing

Example:

```
int obscure(int x, int y) {
  if (x==hash(y)) error();
  return 0;
}
```

Run 1 : - start with (random) x=33, y=42
- execute concretely and symbolically:
  if (33 != 567) | if $\boxed{\text{(x != hash(y))}}$
  constraint too complex
  → simplify it: x != 567
- solve: x==567 → solution: x=567
- new test input: x=567, y=42

Run 2 : the other branch is executed
All program paths are now covered !

- Observations:
  - Dynamic test generation extends static test generation with additional runtime information: it is more powerful
    - see [DART in PLDI'05], [PLDI'11]
  - The number of program paths can be infinite: may not terminate!
  - Still, DART works well for small programs (1,000s LOC)
  - Significantly improves code coverage vs. random testing

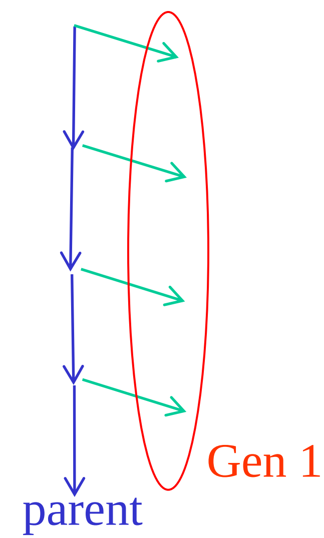
DART Implementations

- Defined by symbolic execution, constraint generation and solving
  - Languages: C, Java, x86, .NET,…
  - Theories: linear arith., bit-vectors, arrays, uninterpreted functions,…
  - Solvers: lp_solve, CVCLite, STP, Disolver, Z3,…
- Examples of tools/systems implementing DART:
  - EXE/EGT (Stanford): independent ['05-'06] closely related work
  - CUTE = same as first DART implementation done at Bell Labs
  - SAGE (CSE/MSR) for x86 binaries and merges it with "fuzz" testing for finding security bugs (more later)
  - PEX (MSR) for .NET binaries in conjunction with "parameterized-unit tests" for unit testing of .NET programs
  - YOGI (MSR) for checking the feasibility of program paths generated statically using a SLAM-like tool
  - Vigilante (MSR) for generating worm filters
  - BitScope (CMU/Berkeley) for malware analysis
  - CatchConv (Berkeley) focus on integer overflows
  - Splat (UCLA) focus on fast detection of buffer overflows
  - Apollo (MIT/IBM) for testing web applications

…and more!

Whitebox Fuzzing [NDSS'08]

- Whitebox Fuzzing = "DART meets Fuzz"
- Apply DART to large applications (not unit)
- Start with a well-formed input (not random)
- Combine with a generational search (not DFS)
  - Negate 1-by-1 each constraint in a path constraint
  - Generate many children for each parent run
  - Challenge all the layers of the application sooner
  - Leverage expensive symbolic execution



- Search spaces are huge, the search is partial… yet effective at finding bugs !

Example

```
void top(char input[4])
{
    int cnt = 0;
    if (input[0] == 'b') cnt++;
    if (input[1] == 'a') cnt++;
    if (input[2] == 'd') cnt++;
    if (input[3] == '!') cnt++;
    if (cnt >= 4) crash();
}
```

input = "good"

Path constraint:

I_0!='b'	→	I_0='b'	bood
I_1!='a'	→	I_1='a'	gaod
I_2!='d'	→	I_2='d'	godd
I_3!='!'	→	I_3='!'	goo!

SMT solver

good

→ SAT

Gen 1

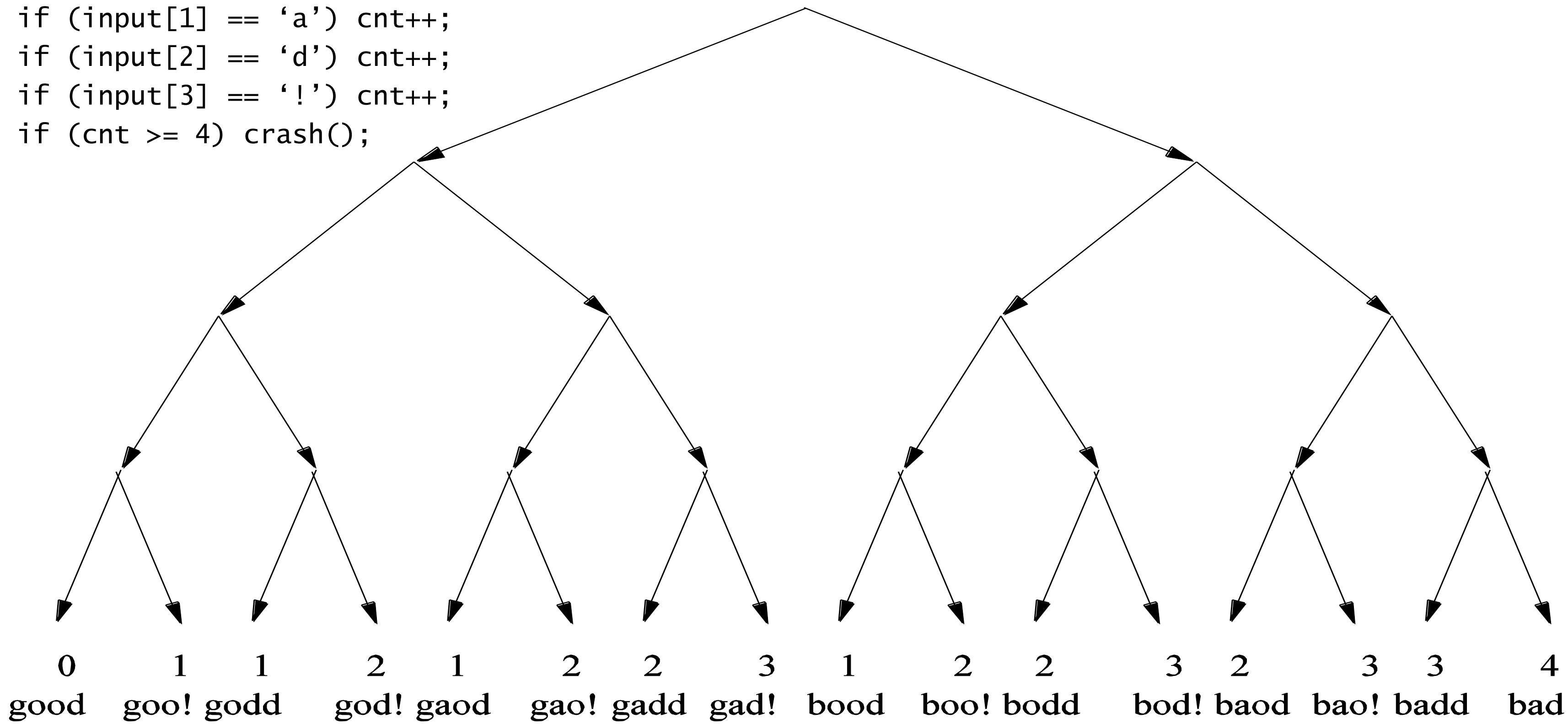
Negate each constraint in path constraint

Solve new constraint → new input

The Search Space

```
void top(char input[4])
{
   int cnt = 0;
   if (input[0] == 'b') cnt++;
   if (input[1] == 'a') cnt++;
   if (input[2] == 'd') cnt++;
   if (input[3] == '!') cnt++;
   if (cnt >= 4) crash();
}
```

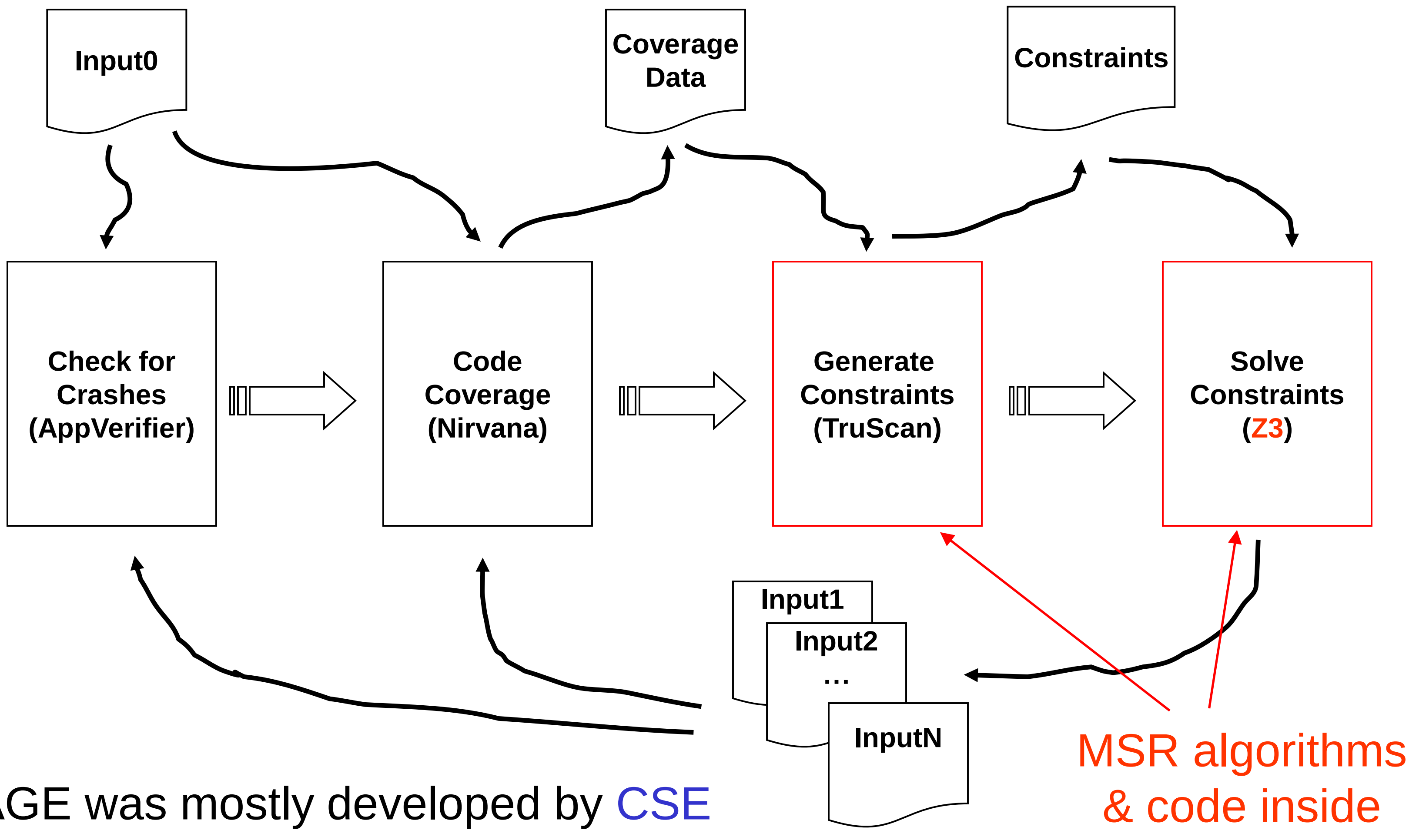
If symbolic execution is perfect and search space is small, this is verification !



SAGE (Scalable Automated Guided Execution)

- Generational search introduced in SAGE
- Performs symbolic execution of x86 execution traces
  - Builds on Nirvana, iDNA and TruScan for x86 analysis
  - Don't care about language or build process
  - Easy to test new applications, no interference possible
- Can analyse any file-reading Windows applications
- Several optimizations to handle huge execution traces
  - Constraint caching and common subexpression elimination
  - Unrelated constraint optimization
  - Constraint subsumption for constraints from input-bound loops
  - "Flip-count" limit (to prevent endless loop expansions)

SAGE Architecture



SAGE was mostly developed by CSE (2006-2008)

MSR algorithms & code inside (2006-2014)

Some Experiments

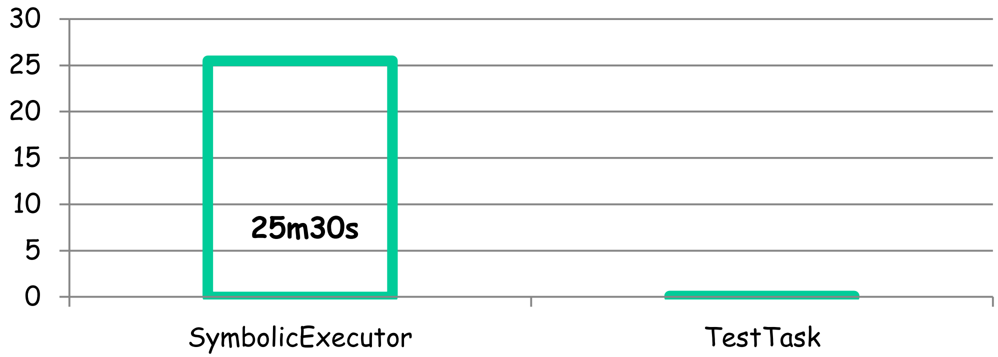
Most much (100x) bigger than ever tried before!

- Seven applications – 10 hours search each

App Tested	#Tests	Mean Depth	Mean #Instr.	Mean Input Size
ANI	11468	178	2,066,087	5,400
Media1	6890	73	3,409,376	65,536
Media2	1045	1100	271,432,489	27,335
Media3	2266	608	54,644,652	30,833
Media4	909	883	133,685,240	22,209
Compressed File Format	1527	65	480,435	634
OfficeApp	3008	6502	923,731,248	45,064

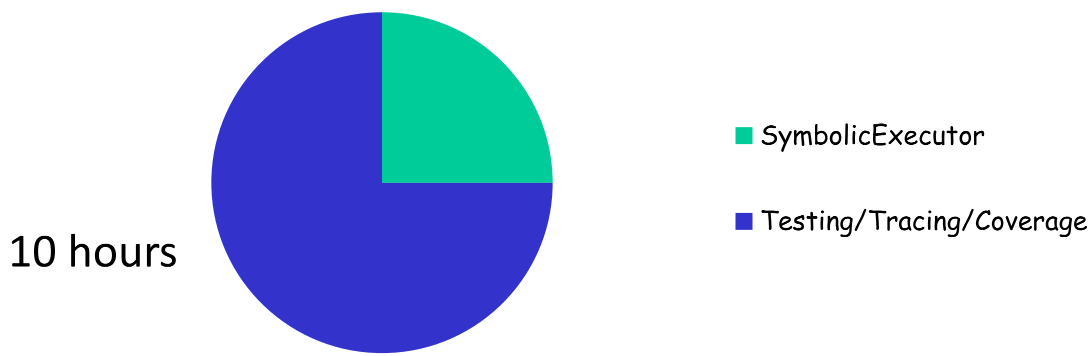
Generational Search Leverages Symbolic Execution

- Each symbolic execution is expensive



X1,000

- Yet, symbolic execution does not dominate search time



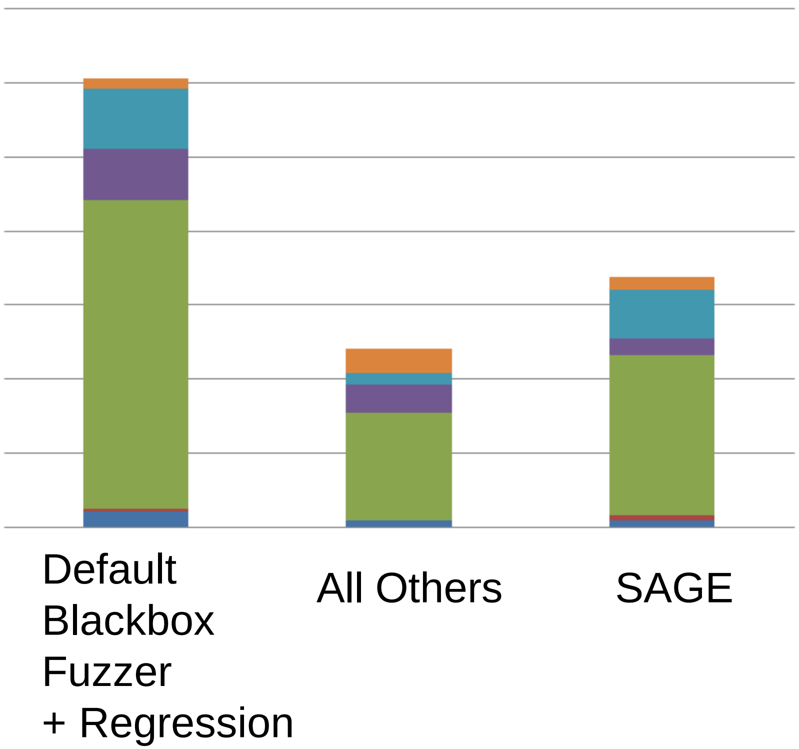
SAGE Results

Since April'07 1st release: many new security bugs found
(missed by blackbox fuzzers, static analysis)

- Apps: image processors, media players, file decoders,…
- Bugs: Write A/Vs, Read A/Vs, Crashes,…
- Many triaged as "security critical, severity 1, priority 1" (would trigger Microsoft security bulletin if known outside MS)
- Example: WEX Security team for Win7
  - Dedicated fuzzing lab with 100s machines →
  - 100s apps (deployed on 1billion+ computers)
  - ~1/3 of all fuzzing bugs found by SAGE !
- SAGE = gold medal at Fuzzing Olympics organized by SWI at BlueHat'08 (Oct'08)
- Credit due to entire SAGE team + users !

WEX Fuzzing Lab Bug Yield for Win7

How fuzzing bugs found (2006-2009) :



SAGE is running 24/7 on 100s machines:
"the largest usage ever of any SMT solver"
N. Bjorner + L. de Moura (MSR, Z3 authors)

- 100s of apps, total number of fuzzing bugs is confidential
- But SAGE didn't exist in 2006
- Since 2007 (SAGE 1st release), ~1/3 bugs found by SAGE
- But SAGE currently deployed on only ~2/3 of those apps
- Normalizing the data by 2/3, SAGE found ~1/2 bugs
- SAGE was run last in the lab, so all SAGE bugs were missed by everything else!

SAGE Summary

- SAGE is so effective at finding bugs that, for the first time, we face "bug triage" issues with dynamic test generation
- What makes it so effective?
  - Works on large applications (not unit test, like DART, EXE, etc.)
  - Can detect bugs due to problems across components
  - Fully automated (focus on file fuzzing)
  - Easy to deploy (x86 analysis – any language or build process !)
    - 1st tool for whole-program dynamic symbolic execution at x86 level
  - Now, used daily in various groups at Microsoft

More On the Research Behind SAGE

- How to recover from imprecision in symbolic exec.? PLDI'05, PLDI'11
  - Must under-approximations
- How to scale symbolic exec. to billions of instructions? NDSS'08
  - Techniques to deal with large path constraints
- How to check efficiently many properties together? EMSOFT'08
  - Active property checking
- How to leverage grammars for complex input formats? PLDI'08
  - Lift input constraints to the level of symbolic terminals in an input grammar
- How to deal with path explosion ? POPL'07, TACAS'08, POPL'10, SAS'11
  - Symbolic test summaries (more later)
- How to reason precisely about pointers? ISSTA'09
  - New memory models leveraging concrete memory addresses and regions
- How to deal with floating-point instructions? ISSTA'10
  - Prove "non-interference" with memory accesses
- How to deal with input-dependent loops? ISSTA'11
  - Automatic dynamic loop-invariant generation and summarization

\+ research on constraint solvers

"Practical Verification"

- Since 2009: 500+ machine-years of running SAGE
- Practical goals:
  - Eradicate all remaining buffer overflows in all Windows parsers
    - Ex: <5 security bulletins in all the SAGE-cleaned Win7 parsers, 0 over the last 3 years
  - Reduce costs & risks for Microsoft, increase those for Black Hats!
    - Many have probably moved to greener pastures already… (Ex: Adobe, Java, Browsers,…)
- If nobody can find bugs in P, P is observationally equivalent to "verified"!
- This is "practical verification" or "security bug eradication" !

What Next? Towards "Verification"

- When can we safely stop testing?
  - When we know that there are no more bugs ! = "Verification"
  - "Testing can only prove the existence of bugs, not their absence." [Dijkstra]
  - Unless it is exhaustive! This is the "model checking thesis"
  - "Model Checking" = exhaustive testing (state-space exploration)
  - Two main approaches to software model checking:

Modeling languages —state-space exploration→ Model checking

abstraction ↑ (SLAM, Bandera, FeaVer, BLAST,…)

adaptation ↓

Programming languages —state-space exploration→ Systematic testing

Concurrency: **VeriSoft, JPF, CMC, Bogor, CHESS,…**

Data inputs: **DART, EXE, SAGE,…**

Exhaustive Testing ?

- Model checking is always "up to some bound"
  - Limited (often finite) input domain, for specific properties, under some environment assumptions
    - Ex: exhaustive testing of Win JPEG parser up to 1,000 input bytes
      - 8000 bits → 2^8000 possibilities → if 1 test per sec, 2^8000 secs
      - FYI, 15 billion years = 473040000000000000 secs = 2^60 secs!

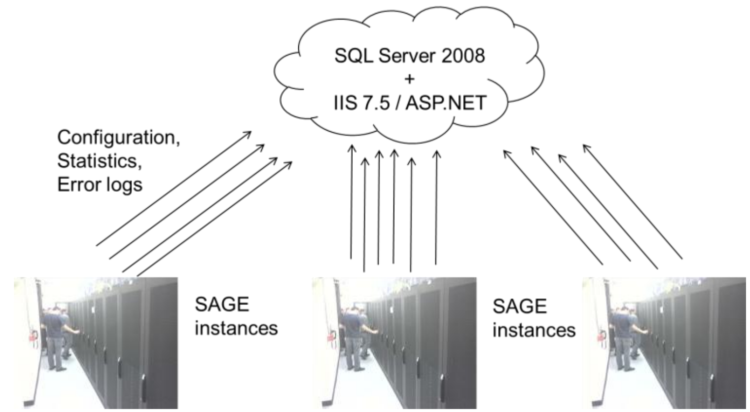
      → MUST be "symbolic" ! ☺ How far can we go?

- This is "formal verification" (model checking)

How Far from "Formal Verification"?

Two main problems:

1. Identify and patch holes in symbolic execution + constraint solving
   - Log unhandled input-tainted x86 instructions: Sagan



   - Extend symbolic execution engine manually
   - Or semi-automatically: see "Automated Synthesis of Symbolic Instruction Encodings from I/O Samples" [PLDI'12]

2. Tackle "path explosion"

From Program to Logic, Today

- VC-gen/BMC: one formula for the entire program
  - Tracks all (data+control) dependencies in one formula
  - Great when it works! (constraint solver faster than prg testing)
  - But does not scale to large programs!
- DART: one formula per program path
  - Tracks only input dependencies
  - Scales to long paths and large programs
  - But too many paths!
- Can we get the best of both worlds?
  - In theory, yes: compositional testing (symbolic test summaries)
  - In practice, the devil is in the details, and those are still open…

Compositionality = Scalability for *Verification*

- Idea: compositional dynamic test generation [POPL'07]
  - use summaries of individual functions (or program blocks, etc.)
    - like in interprocedural static analysis
    - but here "must" formulas generated dynamically
  - If f calls g, test g, summarize the results, and use g's summary when testing f
  - A summary $\varphi(g)$ is a disjunction of path constraints expressed in terms of g's input preconditions and g's output postconditions:

    $\varphi(g) = \vee\ \varphi(w)$ with $\varphi(w) = pre(w) \wedge post(w)$

  - g's outputs are treated as fresh symbolic inputs to f, all bound to prior inputs and can be "eliminated" (for test generation)

- Can provide same path coverage exponentially faster !
    - See details and refinements in [POPL'07,TACAS'08,POPL'10]

The Engineering of Test Summaries

- Systematically summarizing everywhere is foolish
  - Very expensive and not necessary (costs outweigh benefits)
  - Not scalable without user help (see work on VC-gen and BMC)
- Summarization on-demand: (100% algorithmic)
  - When? At search bottlenecks (with dynamic feedback loop)
  - Where? At simple interfaces (with simple data types)
  - How? With limited side-effects (to be manageable and "sound")
- Goal: use summaries intelligently
  - How? In what form(s)?
    - Computed statically? [POPL'10, ISSTA'10]

Ex: ANI Windows Image Parser 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

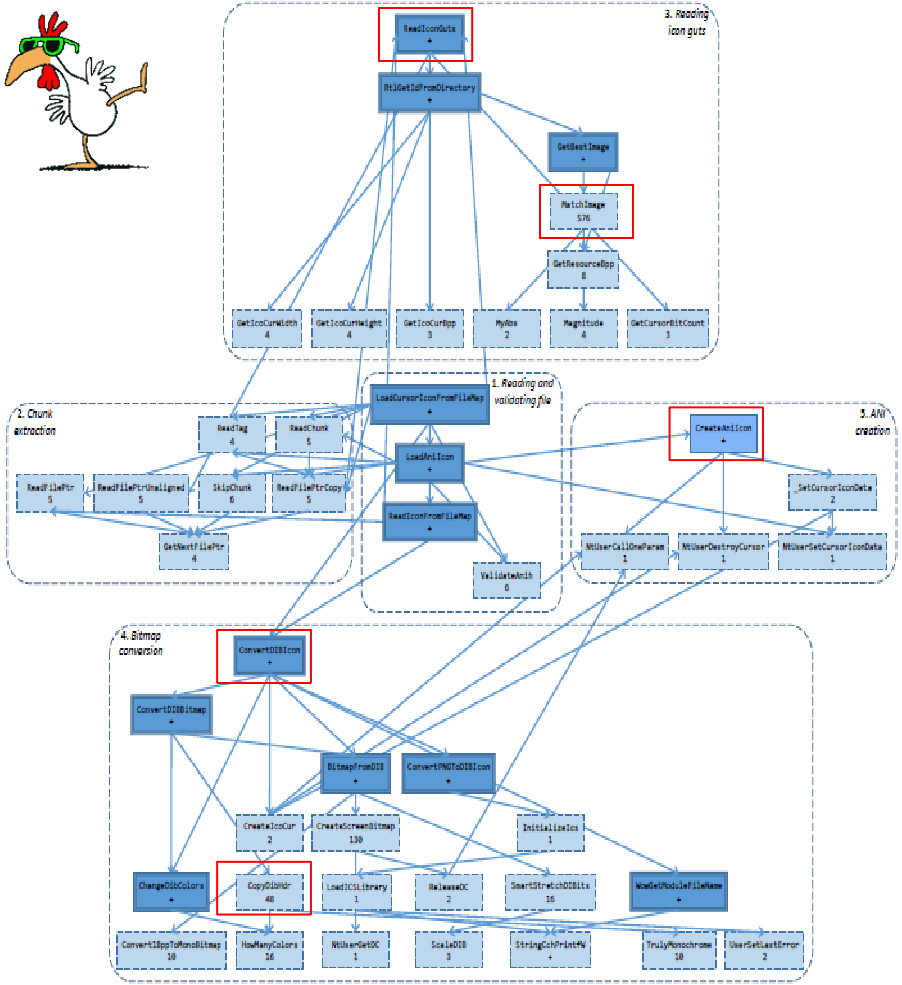


Figure 3. The callgraph of the 47 user32.dll functions implementing the ANI parser core. Functions are grouped based on the architectural component of Fig. 2 to which they belong. The different shades and lines of the boxes denote the verification strategy we used to prove memory safety of each function. 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.

Conclusion: Impact of SAGE (In Numbers)

- 500+ machine-years
  - Runs in the largest dedicated fuzzing lab in the world
- 4 Billion+ constraints
  - Largest computational usage ever for any SMT solver
- 100s of apps, 100s of bugs (missed by everything else)
- Bug fixes shipped quietly (no MSRCs) to 1 Billion+ PCs
- Millions of dollars saved
  - for Microsoft + time/energy savings for the world
- DART, Whitebox fuzzing now adopted by (many) others (10s tools, 100s citations)

Conclusion: Blackbox vs. Whitebox Fuzzing

- Different cost/precision tradeoffs
  - Blackbox is lightweight, easy and fast, but poor coverage
  - Whitebox is smarter, but complex and slower
  - Note: other recent "semi-whitebox" approaches
    - Less smart (no symbolic exec, constr. solving) but more lightweight: Flayer (taint-flow, may generate false alarms), Bunny-the-fuzzer (taint-flow, source-based, fuzz heuristics from input usage), etc.
- Which is more effective at finding bugs? It depends…
  - Many apps are so buggy, any form of fuzzing find bugs in those !
  - Once low-hanging bugs are gone, fuzzing must become smarter: use whitebox and/or user-provided guidance (grammars, etc.)
- Bottom-line: in practice, use both! (We do at Microsoft)

What Next? Towards "Verification"

- Tracking all(?) sources of incompleteness
- Summaries (on-demand…) against path explosion
- How far can we go?
  - Practical Verification: yes!
  - Formal Verification ?
- For history books ?

2000 2005 2010 2015

Blackbox Fuzzing Whitebox Fuzzing "Verification"

"Practical V.": yes! "Formal V.": ?

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  - Office: Tom Gallagher, Eric Jarvi, Octavian Timofte,…
  - SAGE users all across Microsoft!
- References: see http://research.microsoft.com/users/pg