Software Model Checking

for Security

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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
  - Dynamic 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,…)

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 (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

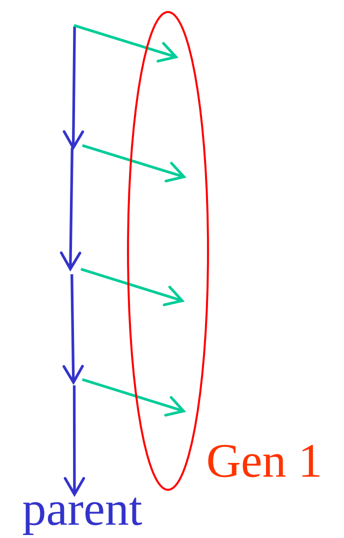
DART Implementations

- 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!

good

Gen 1

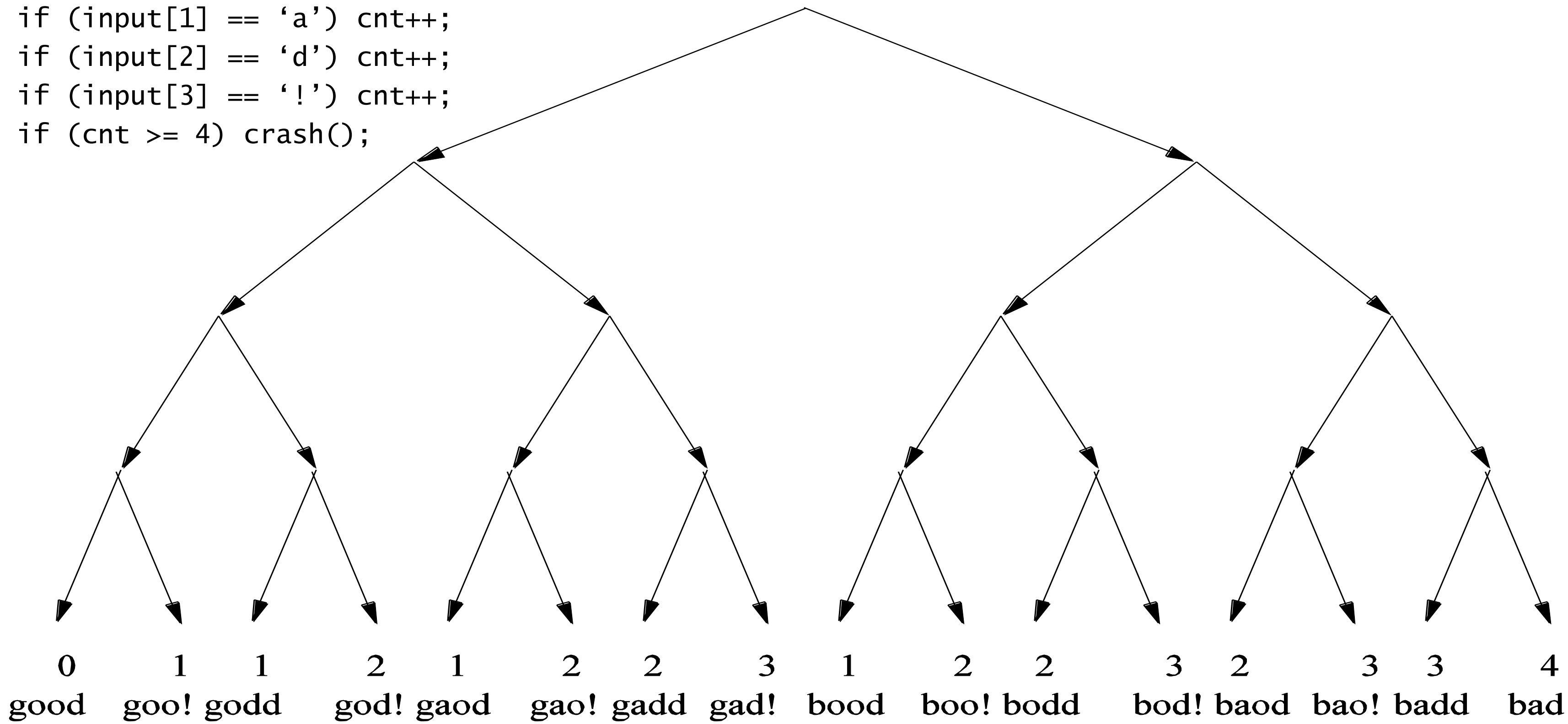
Negate each constraint in path constraint

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();
}
```

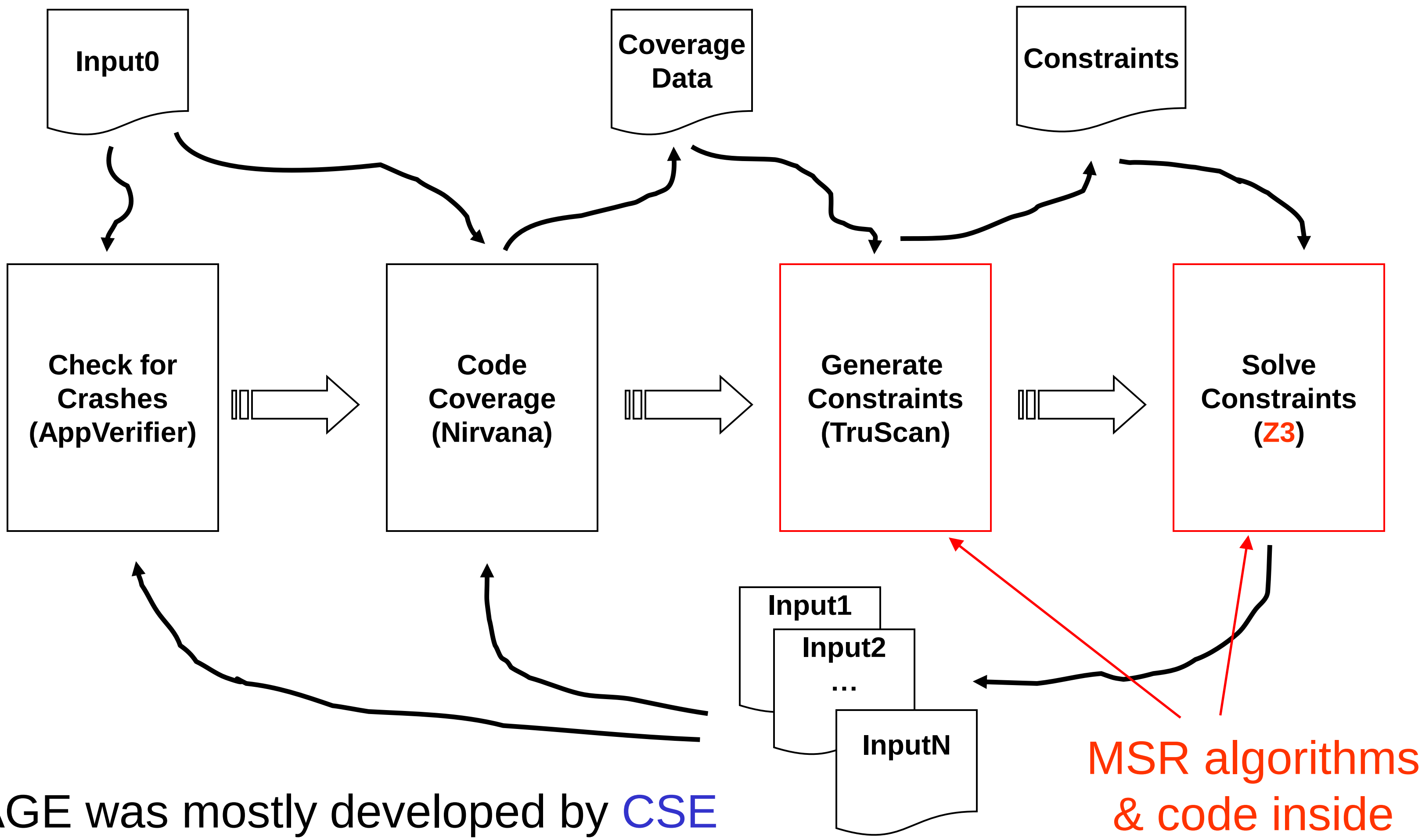
If symbolic execution is perfect and search space is small, this is verification !



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 (2006-2012)

Some Experiments

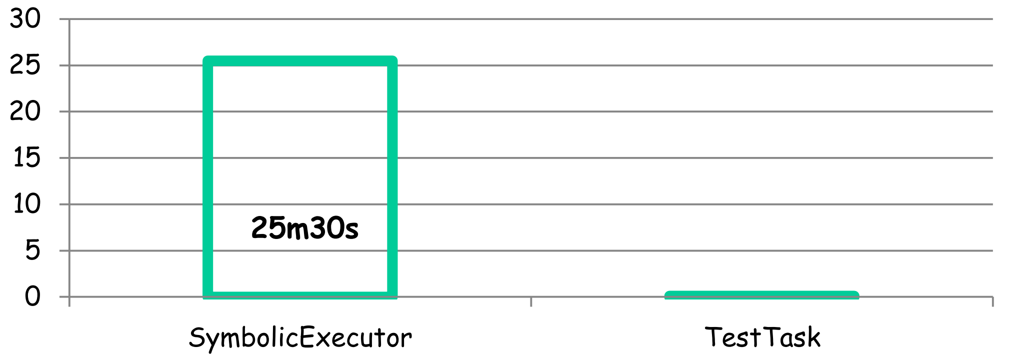
Most much (100x) bigger than ever tried before!

- 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

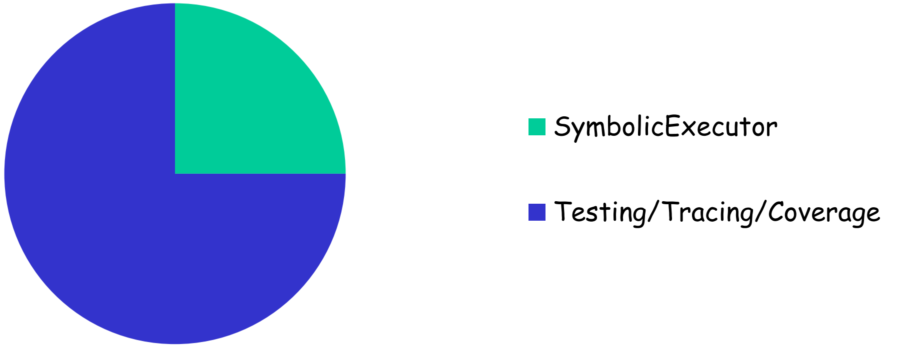
- Each symbolic execution is expensive



X1,000

- Yet, symbolic execution does not dominate search time

10 hours



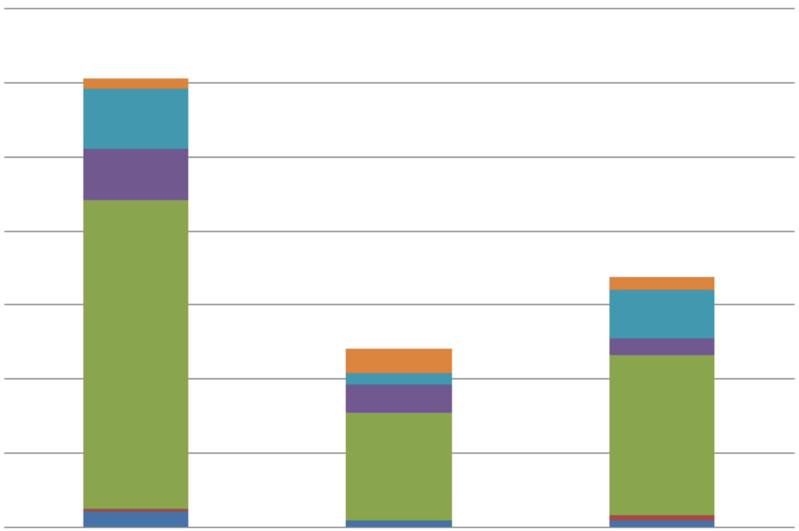
SAGE Results

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 was then 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

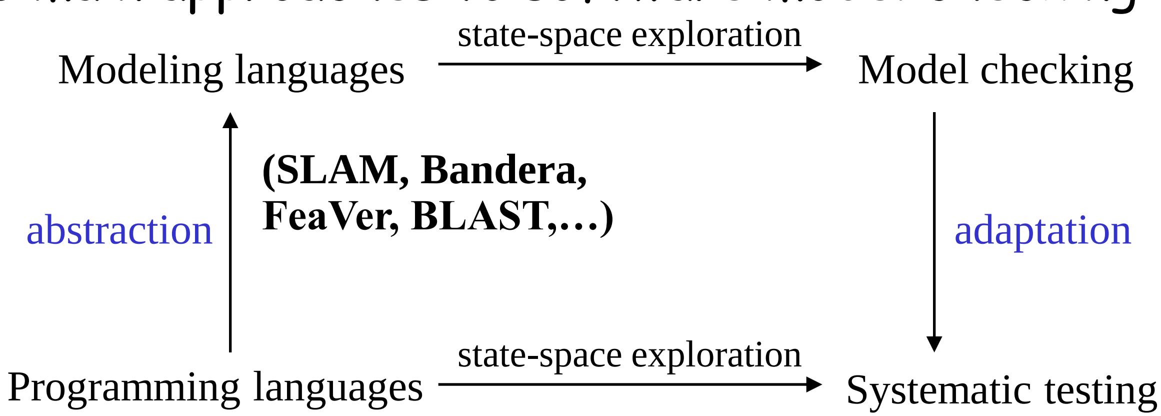
More On the Research Behind SAGE

- 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 (Z3, disolver,...)

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:



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 Win7 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?

- Practical goals: (easier?)
  - Eradicate all remaining buffer overflows in all Windows parsers
  - Reduce costs & risks for Microsoft: when to stop fuzzing?
  - Increase costs & risks for Black Hats !
    - Many have probably moved to greener pastures already… (Ex: Adobe)
    - Ex: <5 security bulletins in all the SAGE-cleaned Win7 parsers
    - If noone can find bugs in P, P is observationally equivalent to "verified"!

How to Get There?

1. Identify and patch holes in symbolic execution + constraint solving

2. Tackle "path explosion" with compositional testing and symbolic test summaries [POPL'07,TACAS'08,POPL'10]

The Art of Constraint Generation

- Static analysis: abstract away "irrelevant" details
  - Good for focused search, can be combined with DART (Ex: [POPL'10])
  - But for bit-precise analysis of low-level code (function pointers, in-lined assembly,...) ? In a non-property-guided setting? Open problem…
- Bit-precise VC-gen: statically generate 1 formula from a program
  - Good to prove complex properties of small programs (units)
  - Does not scale (huge formula encodings), asks too much of the user
- SAT/SMT-based "Bounded Model Checking": stripped-down VC-gen
  - Emphasis on automation
  - Unrolling all loops is naïve, does not scale
- "DART": the only option today for large programs (Ex: Excel)
  - Path-by-path exploration is slow, but "whitebox fuzzing" can scale it to large executions + zero false alarms !
  - But suffers from "path explosion"…

DART is Beautiful

- Generates formulas where the only "free" symbolic variables are whole-program inputs
  - When generating tests, one can only control inputs !
- Strength: scalability to large programs
  - Only tracks "direct" input dependencies (i.e., tests on inputs); the rest of the execution is handled with the best constant-propagation engine ever: running the code on the computer !
  - (The size of) path constraints only depend on (the number of) program tests on inputs, not on the size of the program

  = the right metric: complexity only depends on nondeterminism!
- Price to pay: "path explosion" [POPL'07]
  - Solution = symbolic test summaries

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 >= 3) crash();
}
```

input = "good"

Path constraint:

I_0 != 'b'

I_1 != 'a'

I_2 != 'd'

I_3 != '!'

Compositionality = Key to Scalability

- 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)

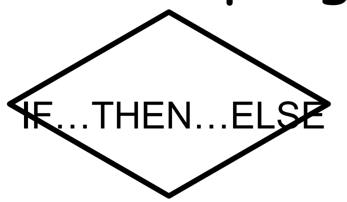
- Can provide same path coverage exponentially faster !
    - See details and refinements in [POPL'07,TACAS'08,POPL'10]

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
  - THE KEY to scalable bit-precise whole-program analysis ?
    - Necessary, but sufficient? In what form(s)?
      - Computed statically? [POPL'10, ISSTA'10]
    - Stay tuned…

Summaries Cure Search Redundancy

- Across different program paths



- Across different program versions
  - "Incremental Compositional Dynamic Test Generation" [SAS'11]
- Across different applications →
- Summaries avoid unnecessary work
- What if central server of summaries for all code?...

DLL	JPEG	GIF	ANI	All instr.
advapi32	✓	✓	✓	156442
clbcatq	✓	✓		114240
comctl32		✓	✓	376620
gdi32	✓	✓	✓	81834
GdiPlus		✓		476642
imm32	✓	✓	✓	26178
kernel32	✓	✓	✓	15958
lpk	✓	✓	✓	5389
msctf	✓	✓	✓	159228
msvcrt	✓	✓	✓	147640
ntdll	✓	✓	✓	207815
ole32	✓	✓		367226
oleaut32	✓	✓		148777
rpcrt4	✓	✓	✓	240231
shell32		✓	✓	-
shlwapi		✓	✓	73092
user32	✓	✓	✓	121223
usp10	✓	✓	✓	79990
uxtheme	✓	✓	✓	62276
WindowsCodecs	✓			193415
JPEG (Total)				2127862
GIF (Total)				2860801
ANI (Total)				1753916

SAGAN: Fuzzing in the (Virtual) Cloud

- Since June 2010, new centralized server collecting stats from all SAGE runs !
  - 150+ machine-years of SAGE data
- Track results (bugs, concrete & symbolic test coverage), incompleteness (unhandled tainted x86 instructions, Z3 timeouts, divergences, etc.)
- Help troubleshooting (SAGE has 100+ options…)
- Tell us what works and what does not

Conclusion: Impact of SAGE (In Numbers)

- 300+ machine-years
  - Runs in the largest dedicated fuzzing lab in the world
- 1 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: Bunny-the-fuzzer (taint-flow, source-based, fuzz heuristics from input usage), Flayer (fault injection, not necessarily feasible), 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)

Acknowledgments

- Joint work with:
  - MSR: Ella Bounimova, David Molnar,…
  - CSE: Michael Levin, Chris Marsh, Lei Fang, Stuart de Jong,…
  - Interns Dennis Jeffries (06), David Molnar (07), Adam Kiezun (07), Bassem Elkarablieh (08), Marius Nita (08), Cindy Rubio-Gonzalez (08,09), Johannes Kinder (09), Daniel Luchaup (10), Nathan Rittenhouse (10), Mehdi Bouaziz (11), Ankur Taly (11)…

- Thanks to the entire SAGE team and users !
  - Z3 (MSR): Nikolaj Bjorner, Leonardo de Moura,…
  - Windows: Nick Bartmon, Eric Douglas, Dustin Duran, Elmar Langholz, Isaac Sheldon, Dave Weston,…
    - Win8 TruScan support: Evan Tice, David Grant,…
  - Office: Tom Gallagher, Eric Jarvi, Octavian Timofte,…
  - SAGE users all across Microsoft!