The Automated Exploitation Grand Challenge

Tales of Weird Machines

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You are an inspiration for the Automated Exploitation Grand Challenge

Thank you

What is Automated Exploitation?

- The ability to generate a successful computer attack with reduced or entirely without human interaction.
- It is important to understand the hardness of AE to measure the risk on critical infrastructure and online properties.
- There are many domains of attack: network, web, kernel, system, hardware, applications. Our focus today is on **software security.**

What are Weird Machines?

- Weird Machine (WM): “The underlying capacity of a program to perform runtime computations that escape the program specification”

(1) If extra computations are consistent with the intended program specification, the WM can lead to a covert execution of code within the program.

(2) If extra computations violate the intended program specification, the WM can lead to a security exploit (what we will talk about today).

Today's exploits techniques

Modern history of exploit techniques :

- Code-reuse attacks: Computations without code injection
  - Started with "Return into Libc" (Solar Designer's 1997)
  - Advanced by "Return into PLT" (Rafal Wojtczuk's 1998)
  - Generalized by Chunk reuse ("borrowing") technique (Richarte 2000, Krahmer 2005)
  - Since 2008, known as "Return Oriented Programming"

- Meta-data corruption
  - "Smashing C++ VPTRs" (Eric Landuiyt, 2000)
  - "V00d00 malloc tricks" (Michel Kaempf, 2001)
  - Many, many other papers.

Today’s exploits techniques (2)

- Information disclosure attacks
  - Format bugs (tf8 wu-ftpd 2.6 site-exec exploit, ~ 2000)
  - Weaknesses where content or address of target variables/functions can be read (BIND TSIG Exploit by LSD-PL, Openssl-too-open exploit by Sotirov, ~ 2001)
  - “Return into printf/send” (“Bypassing PaX ASLR protection”, Vanegue 2002)
- Heap chunks alignment techniques
  - “Advanced DL malloc exploit” (JP @ core-st , 2003)
  - “Heap Feng Shui”, (Sotirov, 2007)
- JIT attacks : make target generate “chosen” new code
  - “Pointer inference and JIT spraying” (Blazakis, 2010)

Exploit Mitigations

- Data Execution Prevention (DEP/Openwall/PaX/W^X/etc)
- Address Space Layout Randomization (ASLR)
- Control-Flow Integrity (CFI)
- Intra-modular displacement randomization (IDR)
- Heap randomization (non-deterministic fitness algorithms)
- Many others targeted protections (UDEREF, SEHOP, canary insertion, meta-data encoding, etc)

Full AE Models: The Automated Exploitation (AE) problem is solved if mitigations can be bypassed using minimal to no human interaction.

Restricted AE Models: Academic exercise where mitigations are ignored. Not the subject of this talk.

Control Flow Integrity

- Early implementation by Determina called "Program Shepherding" early 2000. Formalized by Martin Abadi et al. in 2005. A lot of work done at Microsoft, Intel, and more to make it practical – its hard.
- In a nutshell (idealized) :
  - Enforce strict transitions on the control flow graph, in particular between functions.
  - If A → B and B –ret→ A , then A → C is forbidden, so is B –ret→ D (for C and D any other two functions)
- Consequence: Exploit cannot easily corrupt a function pointer or a return address and execute a ROP payload.

Intra-modular Displacement Randomization

- [Miller, Johnson, Goel, Vanegue, 2011] at Microsoft Security. (http://ip.com/IPCOM/000210875)
- Core idea: randomize address space not only using module base address randomization, but also within a module (ex: between functions).
  - Ability to change function relative address from the base address every time a program is executed.
- Consequences:
  - Base address information disclosure is not enough to predict addresses of ALL gadgets in a module.
  - Attacker worst case: need one information disclosure per randomization point inserted in the module.

Exploit primitives

- Two major families of exploit primitives are write primitives (write address space) and read primitives (read address space).
- Early classification done by Gerardo Richarte at core-st : “About exploit writing”, 2002.
- Modern classification done by Matt Miller: “Modeling the exploitation and mitigation of memory safety vulnerabilities”, 2012.

Exploit write primitive

General form: *(basepointer + offset) = value

(1) Base, offset and values are attacker-controlled

→ Write controlled value at controlled location

(2) Base and offset are controlled

→ Write uncontrolled value at controlled relative location

→ With an information disclosure, can always be used to uncover new state space or elevate privileges

(3) Only RHS Value is controlled (totally or partially)

→ Write anything at fixed location

→ Can be useful if value is:

- Later used as base pointer, index, or offset (we fall into case 1 or 2)
- Used in a control predicate and can uncover new "weird" state space
- Controlling privilege level of application

Exploit read primitive

General form: value = *(basepointer + offset)

(1) Base, offset and values are attacker-controlled
→ Read value at desired location and store it at desired location

(2) Base and offset are controlled
→ Read value at desired location, store it at uncontrolled location
→ Only useful if uncontrolled location can be read by attacker

(3) Only LHS Value is controlled
→ Read internal program value and store it at desired location
→ Can be useful if value is:

- Internal program value is a direct code or data address
- Internal program value contains credentials (password, key, token, etc)
- Internal program value help deduce useful address info or credentials

Rising exploit techniques

- Data-only attacks (DOA)
  - Change internal program values to elevate privileges without changing Program control flow.
  - Infer address of data in program without direct memory read primitives.
- Program Likelihood Inference (PLI)
  - Probabilistic attacks: discover most likely executions to successful exploitation in non-deterministic environment.
  - Timing attacks: discover internal program information via run time execution measurements.

Tools Armory

Exploit Generation

- Automated Exploitation focuses on discovery and combination of write primitives and read primitives.
- Automated Exploitation in Full Model is a very hard problem. Anybody telling you otherwise is a fool or an impostor.
- Existing AE work focused on Restricted Models:
  - Sean Heelan’s “Automatic Generation of Control Flow Hijacking Exploits for Software Vulnerabilities” : http://www.cprover.org/dissertations/thesis-Heelan.pdf
  - David Brumley et al. (AEG, MAYHEM, etc)

  http://users.ece.cmu.edu/~dbrumley/pubs.html

Analysis and Exploit Automation

- Compilers (Program transformation)
- Fuzz testers (Input generation)
- SMT solvers (Symbolic reasoning)
- Model Checkers (State space exploration)
- Symbolic Execution Eng (Path generation)
- Emulators (Machine modeling)
- Abstract interpreters (Abstraction)

SMT solvers

SMT = Satisfiability Modulo Theories

- Give it a list of variables and constraints on them, will tell you whether the set of constraints is satisfiable.
- A good representation to reason about a program (e.g. translate a program into an SMT formulae)
- Can track feasibility of predicates, eliminate impossible program paths, etc.

EXAMPLE 1: (B >= A) && (A <= B) is SAT

EXAMPLE 2: A && B && NOT(A&&B) is UNSAT

An open-source SMT solver : Z3

- Z3 is a state-of-the-art SMT solver developed in Microsoft Research RiSE group.
- Understand equalities, arrays, bitvectors, uninterpreted functions, and custom theories.
- Makes SMT a good symbolic representation to reason about programs (e.g. by translating it into SMT formulae).

Try by yourself on **http://rise4fun.com/Z3/**

Example of translation from C to SMT

```
F(int c)
{
  int ret;
  if (c < 10)
     ret = 1;
 else
   ret = 2;
}
```

```
(declare-fun x () Int)
(declare-const ret Int)
(declare-const c Int)
(assert (=> (>= c 10) (= ret 2)))
(assert (=> (<  c 10) (= ret 1)))
(assert (= ret 1)) // check me!
(check-sat)
(get-model)
```

Output model for constraint set

- A model is a valuation of the variables for which a (SMT) formula is true.
- In this example, the constraints set is satisfiable if variable C = 9 and RET = 1
- Change the last assertion of previous slide and see what happens to the model.

Z3 output:

```
sat (model
  (define-fun c () Int 9)
  (define-fun ret () Int 1) )
```

HAVOC: static analysis for C/C++

- HAVOC: Verifier for C(++) programs

  http://research.microsoft.com/en-us/projects/havoc/
- Translate C/C++ code to Boogie IR

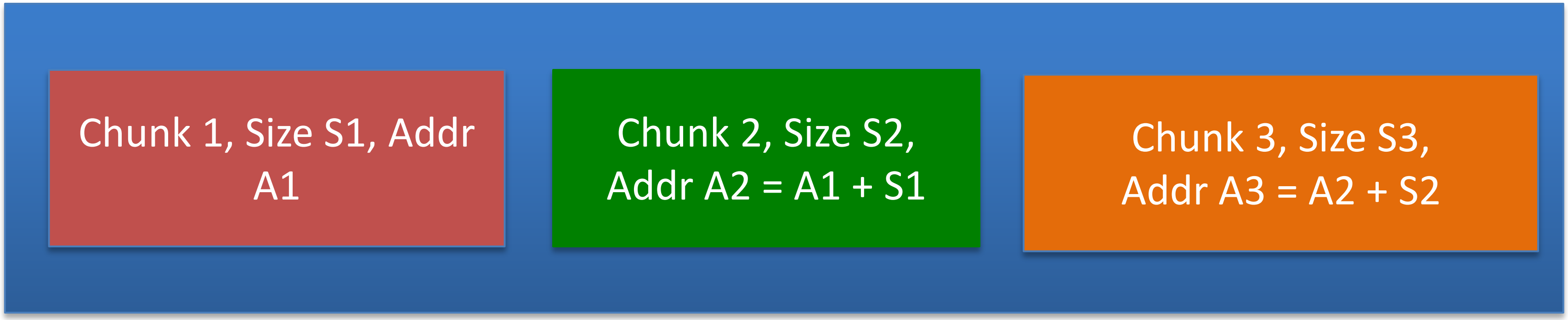
  (Open source at: http://boogie.codeplex.com)
- Boogie IR is then translated to SMT formulae understood by Z3, which performs SMT check and give you a model.
- At Microsoft, HAVOC found 100+ security vulnerabilities in Windows and Internet Explorer.
- Experiments documented in: “Towards practical reactive security audit using extended static checkers” http://research.microsoft.com/pubs/185784/paper.pdf

Problem: non-deterministic programs

Assume an attacker can overflow chunk 1 and chunk 3 is a target:

Heap in 90% of executions of program P :

S1 =



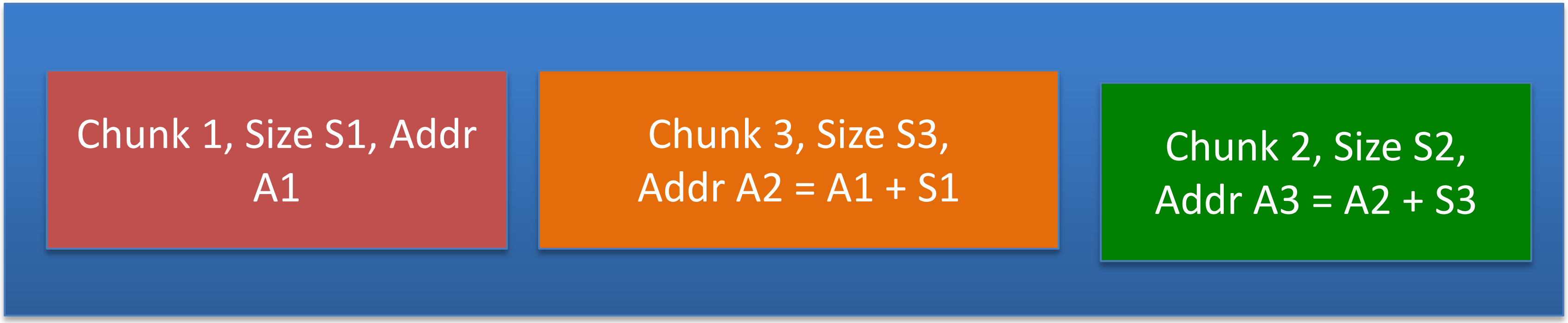
Chunk 1, Size S1, Addr A1

Chunk 2, Size S2, Addr A2 = A1 + S1

Chunk 3, Size S3, Addr A3 = A2 + S2

Heap in 10% of executions of program P :

S2 =



Chunk 1, Size S1, Addr A1

Chunk 3, Size S3, Addr A2 = A1 + S1

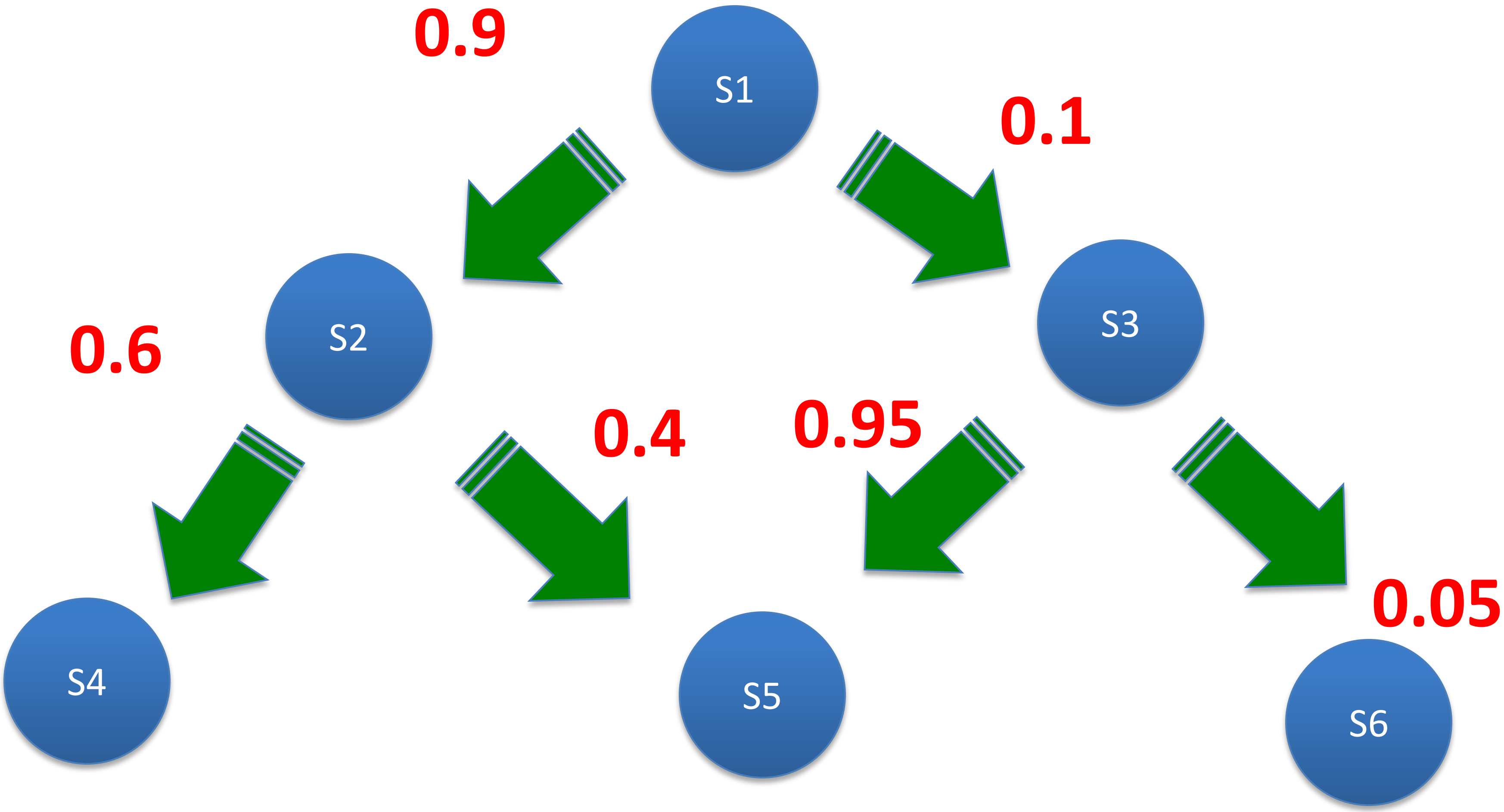
Chunk 2, Size S2, Addr A3 = A2 + S3

SMT solvers are unable to reason about non-determinism

Idea: Markov exploits

- Andrei Markov (1856-1922)
- Systems (Programs) may seem to act randomly, but have a hidden probabilistic regularity.
- Instrument program and deduce from sampling which paths have most chance to bring the heap in a desired exploitable state.

Markov transition system



The transition system model the set of all possible random walks.

Markov transition system

Previous slide explained:

- We computed the probability of reaching every heap states in a maximum of two heap interactions (malloc, free, etc)
- Probability of reaching S4 is:
  P(S4) = P(S4|S2) * P(S2|S1) = 0.6 * 0.9 = 0.54 (54%)
- Probability of reaching S5 is:
  P(S5) = P(S5|S2) * P(S2|S1) + P(S5|S3) * P(S3|S1)
  = 0.9*0.4 + 0.95*0.1 = 0.455 (45.5%)
- Probability of reaching S6 is:
  P(S6) = P(S6|S3) * P(S3 | S1) = 0.1 * 0.05 = 0.005 (0.5%)

Assuming S5 and S6 are the only two desired exploitable states, the most exploitable random walk ends in S5.

Markov Exploit Food for thoughts

- Paths exploration strategy can be static or dynamic (planned, or constructed on the fly)
- If one creates an accurate heap manager specification, heap state measurement could be static, but this is a very hard and allocator-dependent task.
- Most likely, one needs to execute program and instrument debugger to measure heap state when heap operations are performed.
- After monitoring, one can construct the Markov transition system based on sampled program paths. More samples means heap model is more accurate.

Markov Exploit Food for thoughts (2)

- Determine list of possible heap interactions (malloc, free, etc) sequences in a given program. A single unique sequence may be represented by multiple random walks due to non-deterministic heap manager behavior.
- Determine sequence maximizing probability of reaching desired heap state in a minimum amount of steps. A SMT solver can be used to craft corresponding input based on encountered path predicates.
- A range of Markov models can be used to facilitate encoding of heap structure into a probabilistic transition system (Markov chain, Markov network, etc)

Challenge problems

Hilbert’s program

- In 1900, German mathematician David Hilbert formulates a list of 23 hard problems touching the foundations of mathematics. Five of these problems remain unsolved today.

  http://en.wikipedia.org/wiki/Hilbert's_program

A Program for Automated Exploitation

- Inspired by David Hilbert and many ones after him, we define a list of problems whose solutions pave the way for years to come in the realm of software security and exploitation.
- The Grand Challenge consists of a set of 11 problems in the area of vulnerability discovery and exploitation that vary in scope and applicability.
- Most problems relate to discovering and combining exploit primitives to achieve elevation of privilege.

Exploit challenges are not new

- Gerardo Richarte's insecure programming (from 10 years ago!) constitutes great training for manual exploit writing:

  http://community.coresecurity.com/~gera/InsecureProgramming/

- Many of the "Capture the Flag" events are, in essence, manual exploit challenges.
- In this challenge, we expect exploits to be generated automatically instead of written manually.

Nature of Grand Challenge problems

- Exploit Specification problem (A, H)
- Input generation problems (B, C, D, E)
- Exploit Primitive composition problem (F)
- Environment determination (I, J, K)
- State space representation (G)

Not all problems need to be resolved for a given target as different problems cover different exploit scenarios.

Grand Challenge Evaluation

Two main problems of Automated Exploitation are **Vulnerability Discovery** and **Vulnerability Exploitation.** Solutions to challenge problems must be evaluated on their varying degree of:

- Soundness (Precision and Signal/Noise ratio)
- Expressivity (Applicable domain and Configurability)
- Scalability (Automation and Performance)
- Completeness (Coverage)
- Resilience (to Environment and Exploit Mitigations)

Exploit specification

Problem A: Given a program P, determine the set of assertions S for which satisfying any a in S is equivalent to corrupting the program.

In other words, what is the program P

anti-specification ?

Problem A code

```
F(int x, int y)
{
    int loc[4];
    int idx = G(x, y);
    if (idx > 4)
       return -1;
    assert(idx >= sizeof(loc));   // do infer assertion
    loc[idx] = 0x00;
}
```

Pre/post-conditions inference

Problem B: Given a program function and an assertion in the function, determine the necessary and sufficient pre/post conditions such as the assertion is true if and only if the pre/post conditions is true.

This is equivalent to the input generation problem for loop-free programs.

Note: May need to walk over call graph to resolve problem transitively from entry point to assertion.

Problem B code

PRECOND (?)

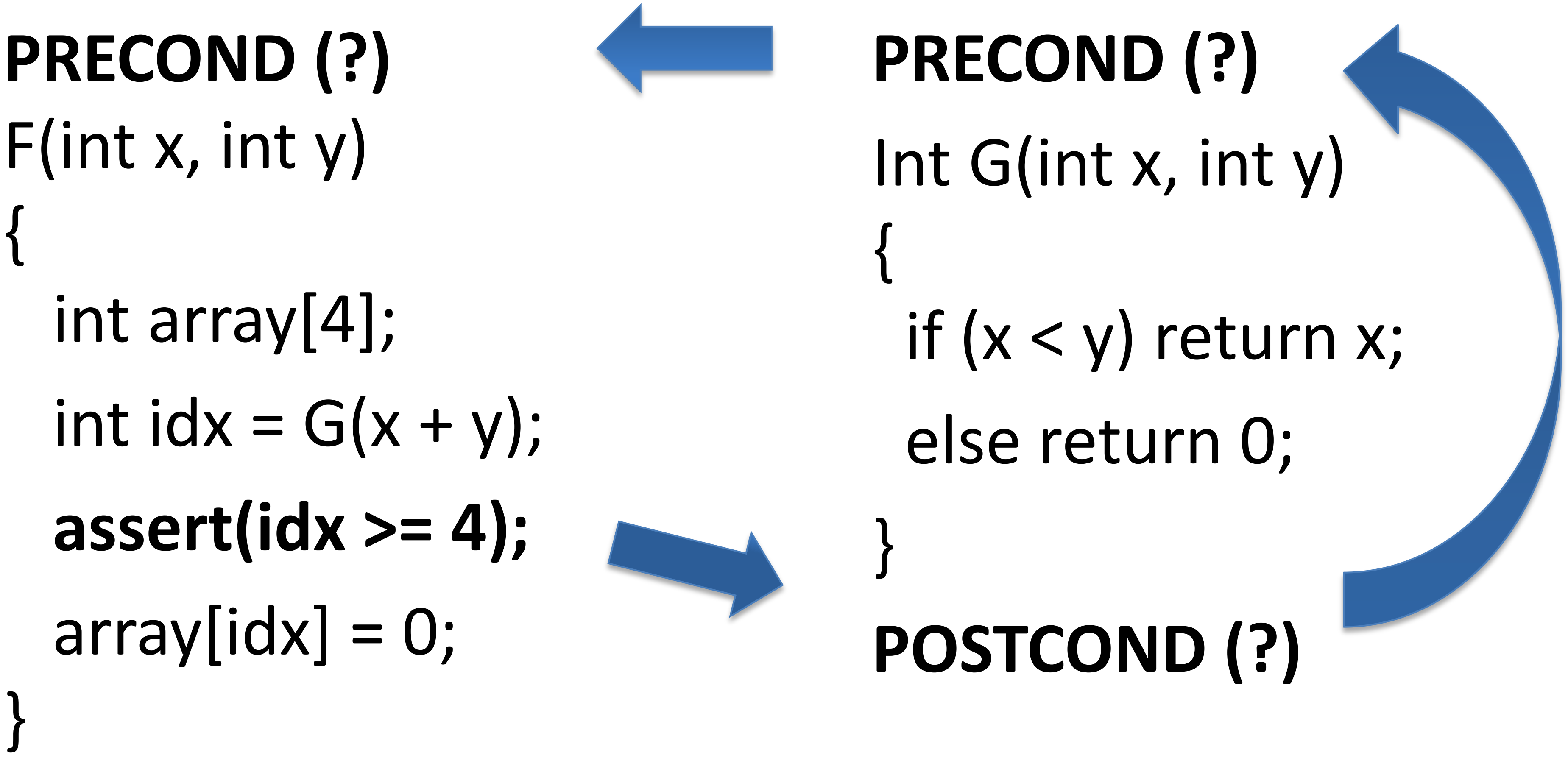
```
F(int x, int y)
{
  int array[4];
  int idx = G(x + y);
  assert(idx >= 4);
  array[idx] = 0;
}
```

PRECOND (?)

```
Int G(int x, int y)
{
 if (x < y) return x;
 else return 0;
}
```

POSTCOND (?)

Problem B code



PRECOND (?)

```
F(int x, int y)
{
  int array[4];
  int idx = G(x + y);
  assert(idx >= 4);
  array[idx] = 0;
}
```

PRECOND (?)

```
Int G(int x, int y)
{
 if (x < y) return x;
 else return 0;
}
```

POSTCOND (?)

Loop contract inference

Problem C: Given a program loop and an assertion A1 within or at the loop exit-node, determine loop-contract assertion A2 such as A1 is true if and only if A2 is true.

Note: A loop invariant is an assertion that must be verified at every iteration of the loop. Given that we work on a program anti-specification, the desired exploit loop contract is not necessarily a loop invariant (it could just be true at some iterations).

Problem C code

```
F(char *buf, int bufsz)
{
  int limit = bufsz;
  int idx = 0;
  loop_invariant(?)
  while (i < limit)
  {
      if (buf[i] == ‘{’) limit++;
      else if (buf[i] == ‘}’) limit--;
      i++;
  }
  assert(i >= sizeof(buf));
  buf[i] = 0;
}
```

Exploit input definability

Problem D: Given an initial state I of a program P with functions and loops, exhibit an algorithm converging to a desired sink state.

A desired sink state can be defined as an assertion in the program (more weakly: as a set of chosen variables values).

Problem D code

```
F(int x, int y)
{
    int loc[4];
    int idx = G(x, y);
    if (idx > 4)
        return -1;
    while (x < y) idx++;
    assert(idx >= sizeof(loc));    // how to reach this?
    loc[idx] = 0x00;
}
```

Exploit derivability

Problem E: Given a concrete program input and associated program crash/log, find the longest crash trace prefix from which the desired exploitable program state can be reached.

The available program crash/log can be:

(1) Full (unlimited access to all values ever)

(2) Partial (only active values are tracked)

(3) Control-only (ex: a stack or instructions trace)

Problem E code

```
F(int x, int y)
{
  int loc[4];
  if ((x + y) > sizeof(log))
       return (loc[x]);                    // program crash here
  else if ((x + y) <= sizeof(loc)) {
      x = G(x, y);
      loc[x] = 0;                          // how to reach here?
      return (0);
    }
}

Int G(int x, int y) { while (x < y) x++; return (x); }
```

Multi-interaction exploit

Problem F: Given a program initial state I, a desired program state U unreachable from I within any single program interaction R, determine all intermediate states T such as multiple interactions Ri can be composed to reach U as in : R1(I,T) + R2(T,U)

Transitive decomposition: determine minimum number of interactions to reach U from I .

Problem F code

```
Char *glob;
F(int x, int y)                    // Ex: F and G are syscalls
{
  glob = malloc(x + y);            // integer overflow
}
G()
{
  glob[x] = 0;                     // array OOB access
}
```

How to construct Trigger() = { F(); G(); } ?

Minimal concurrent exploit

Problem G: Given a program P, a desired exploit state S, and a thread count C, find the minimal state space representation to reach S in some execution of P **while retaining ability to generate corresponding concrete input.**

Note 1: Partial Order Reduction is a generic framework that can help control state space explosion.

Note 2: Minimal state space representation is dependent on desired sink state (as in Abstract Interpretation).

Example of research in this area: “Identifying and Exploiting Windows Kernel Race Conditions via Memory Access Patterns” (Jurczyk / Coldwind, 2013)

Problem G code

```
/* Example of basic TOC/TOU vulnerability */
/* ptr holds a valid non-volatile pointer */
F(unsigned int *ptr)
{
  if (*ptr > 0x10) return;
  global->ptr = malloc(*ptr + 1);
  if (global->ptr == NULL) return;
  global->ptr[*ptr] = 0x00;     // double-fetch!
}
```

If *ptr* is "modified under" by another thread, the second array access can go OOB.

Privilege Separation Inference

<u>Problem H:</u> Given a program P, determine code privilege partitioning. For each partition, determine entry points.

(1) Determine variables guarding privilege level (PL)

(2) Partition functions so that all elements of a given partition share the same PL. If static partitioning does not exist, determine parameters of dynamic partitioning.

Partitioning can determine multi-stage exploits paths:

- Remote → Local → Kernel
- Remote → Sandboxed → Unsandboxed
- Remote → Non-authenticated → Authenticated

Problem H code

```
bool authenticated = false;
Int F()
{
  authenticated = check_creds();
  // execute at authenticated level
  if (authenticated)
  {
    bool res = serve_client();
    if (!res) return (send_error(E_FUNC));
    return (0);
  }
 // execute at non-authenticated level
 return (send_error(E_AUTH));
}
```

Note: send_error() can execute at multiple privilege levels.

Heap likelihood inference

Problem I: Given a program P using a non-deterministic heap allocator, determine most exploitable random walk(s) for P to reach "aligned" exploitable heap state.

(1) Assume existence of heap corruption C in P
(2) Identify set S of exploitable heap states w.r.t. C
(3) Minimize steps to reach any element of S

See previous Markov exploit description. This problem is more relevant in presence of heap randomization.

Problem I code

```
Struct s1 { int *ptr; } *s1a = NULL, *s1b = NULL, *s1c = NULL;
Struct s2 { int authenticated; } *s2 = NULL;

F() {
  s1a = (struct s1*) malloc(sizeof(struct s1));
  s1b = (struct s1*) malloc(sizeof(struct s1));
  s1c = (struct s1*) malloc(sizeof(struct s1));
}
G() { s2 = (struct s2*) malloc(sizeof(struct s2)); }
H() { free(s1b); }
I() { memset(s1a, 0x01, 32); }
J() { if (s1 && s1->authenticated) puts("you win"); } // Print this
K() { if (s2 && s2->ptr) *(s2->ptr) = 0x42; }         // Avoid crash here
```

When allocator reuses s1b's memory to allocate s2 :

Automate best walk = { F(); H(); G(); I(); J(); }

Generalized program timing attack

Problem J: Define the necessary and sufficient execution time analysis conditions to infer value, size, or location of:

(1) A program control structure

- Return address, Function Pointer, Exception Handler, etc.

(2) A program data structure

- Heap chunk, Stack Frame, Global variable, etc.

(3) A program code fragment

- Instruction, Function, Method, etc.

In other words, automate program time inference to defeat stack and heap randomization.

Problem J examples

The problem is stated in very generic terms on purpose.

Resolution depends on target-specific implementation.

For two great starting point on timing inference, see:

Cryptographic timing attacks on DH, RSA, DSS and other systems
(Paul C. Kocher, 1996)
http://www.cryptography.com/public/pdf/TimingAttacks.pdf

Program timing attacks on Firefox hash tables
(Paul @pa_kt, 2012)
http://gdtr.wordpress.com/2012/08/07/leaking-information-with-timing-attacks-on-hashtables-part-1/

Indirect information disclosures

Problem K: Define the necessary and sufficient conditions to infer the value or address of a variable without a direct read primitive, such as:

(1) Data reuse attacks
(example: partial pointer overrides)

(2) Pointer value prediction attacks
(example: pointer inference)

Problem K examples

Resolution of Problem K depends on target-specific implementation.

Prior art on Indirect information disclosures includes:

Flash Pointer Inference (Blazakis, 2010)
http://www.semantiscope.com/research/BHDC2010/BHDC-2010-Paper.pdf

Garbage Collection marking attack (Blazakis, 2013)
http://www.trapbit.com/talks/Summerc0n2013-GCWoah.pdf

Conclusion

- We decomposed the problem of Automated Exploit Generation in a set of challenges with clear intermediate assumptions.
- Resolving one such sub-problem is a step towards existing end-to-end solutions of larger and larger sub-classes of exploits.
- Even though Automated Exploitation is an undecidable problem, observing that most vulnerabilities are shallow allow the problem to be approached.

Questions / Discussion

- Thanks for attending H2HC 10th anniversary

- Questions and feedback welcome by email