Automated Black Hats
Application Memory

Kernel Space

User Space

Up to 128 TiB

47 bit

Stack

Memory Mapping Area

Heap

BSS

Data

Code

64 bit

47 bit

45 bit

32 bit

0 bit

0 bit


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int global;

int main()
{
    int local;
    printf("global: %16p\n", &global);
    printf("main: %16p\n", &main);
    printf("local: %16p\n", &local);
    printf("heap: %16p\n", malloc(4));
}

global: 0x108f41020
main: 0x108f40ed0
local: 0x7fff56cbf8dc
heap: 0x7ff5814026d0
What is the Stack used for?

• The stack enables functions/procedures
• Stores
  – Procedure-local data
  – Return address of calls
• Benefits:
  – More economical
  – Permits recursion
void f(void)
{
    char buffer[100];
    
    ...  // Code...
    
    strcpy(buffer, INPUT);
    ...
}

void g(void)
{
    ...
    f();
    ...
}
void f(void) {
    char buffer[100];
    ...
    strcpy(buffer, INPUT);
    ...
}

void g(void) {
    ...
    f();
    ...
}
void f(void)
{
    char buffer[100];
    ...
    strcpy(buffer, INPUT);
    ...
}

void g(void)
{
    ...
    f();
    ...
}
void f(void) {
    char buffer[100];
    ...  
    strcpy(buffer, \texttt{INPUT});
    ...
}

void g(void) {
    ...
    f();
    ...
}
void f(void)
{
    char buffer[100];

    ...
    strcpy(buffer, INPUT);
    ...
}

void g(void)
{
    ...
    f();
    ...
}
Other Options

• C++ gives rise to a large number of *function pointers* to implement virtual methods
• These are typically on the heap
• Exploit like return addresses
• There are similar pointers for dynamically loaded libraries
Countermeasures

• Address space layout randomization (ASLR)
• Execution protection (NX) for stack and heap
• Read-only code segments ($W^X$)
• Stack canaries
• Control-flow integrity
Countermeasure: ROP

• “Return-oriented programming”
• Rummage through existing code (say libc) to find return instructions (0xc3)
• Any instructions before these can do useful work
• Place address of next instruction on stack
• Countermeasure: ASCII armoring
A Harder Bug

“I believe that these two files summarize well some of the reasons why code analysis tools are not very good at finding sophisticated bugs with a very low false positive rate.”

-- Halvar Flake talking about the Sendmail crackaddr bug.

Let's analyse those two files...
The crackaddr Bug

We need to alternate between these two branches several times

...So that we can eventually push this write beyond the end of the buffer

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Hacking with BMC

We can unwind loops a fixed number of times

```c
char A[100];
char c;
int i = 0;

while(c = read()) {
    A[i++] = c;
}

i_0 = 0;
c_0 = read();
assume(c_0 != 0);
A[i_0] = c_0;
assert(i_0 < 100);
i_1 = i_0 + 1;
c_1 = read();
assume(c_1 == 0);
```

This gives us a problem we can pass to SAT solver
The SAT problem we just generated doesn't have a solution (which means we couldn't find a bug).

That's because the bug doesn't show up until the loop has run 101 times.

That means we have to unwind the loop 101 times. This is really slow!

Worse still, we don't know how many times we need to unwind!
Acceleration

- Replace a loop with a single expression that encodes an \textit{arbitrary number} of loop iterations
- We call these \textit{closed forms}

```c
while (i < 100)
{
    i++; 
}
```

```c
niterations = nondet();
i += niterations;
assume(i <= 100);
```

Number of loop iterations
Calculating Closed Forms

We need some way of taking a loop and finding its closed form. There are many options:

- Match the text of the loop
- Find closed forms with constraint solving
- Linear algebra

We use constraint solving, since it allows us to reuse a lot of existing code.
Dotting i's, Crossing t's

There are a few more things we need to do to make an accelerator:

- Ensure that the loop is able to run as many times as we'd like it to (weakest precondition)
- Make sure we handle integer overflows correctly (path splitting)
- Add the effects of array update (quantifiers)

For more details, see our CAV 2013 paper.
Example

```c
int sz = read();
char *A = malloc(sz);
char c;
int i = 0;

while (c = read()) {
    A[i++] = c;
}
```

```c
int sz = read();
char *A = malloc(sz);
char c;
int i = 0;

int niters = nondet();
assume(forall i < j <= niters .
    A[j] != 0);
i += niters;
assert(i <= sz);
```

**Unwind once**

**BUG:**

```c
int niters = sz + 1
```

**SAT solve**

```c
sz = read();
i_0 = 0;
niters = nondet();
assume(forall i < j <= niters .
    A[j] != 0);
i_1 = i_0 + niters;
assert(i_1 <= sz);
```

**Note:** there's no fixed number of unwindings that will always hit this bug!

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Accelerating crackaddr

We **unroll the loop twice** and accelerate the result

```c
int niters = nondet();
assume(forall 0 <= j < niters .
upperlimit += niters;

and

int niters = nondet();
d += niters;
assume(d < upperlimit);
assert(d < &localbuf[200]);
```

These are enough to find the bug!
Download me!

- Prototype accelerator available as part of goto-instrument
- Source-to-source transformation: use your favourite program analyser!
- Get via www.github.com/diffblue/cbmc
Making this Real

- Actual exploits require more work
- Requires precise heap and stack models
- Address space randomization
- ROP for non-executable stacks

- Frequently done for binaries
  (really want hybrid source/binary)
# The Hemiptera Bug Suite

<table>
<thead>
<tr>
<th>Project</th>
<th># Invalid Accesses</th>
<th># Failed Asserts</th>
<th># Div By Zero</th>
<th># Dang Ptr. Use</th>
<th>Avg. Lines of C Code</th>
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<td><strong>8</strong></td>
<td><strong>3</strong></td>
<td><strong>276,050</strong></td>
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</tbody>
</table>
Analysis of Binaries using Taint

- Adobe Acrobat executes ca. 1bn instructions before dealing with the PDF
- Just too much even for the best solvers
- Idea: build partial formula, focussing on parts that are influenced by input
Overview: Taint Analysis

Inputs

- Binary Application
- Crashing Input
- Shell-Code

Outputs

- A1: Obtained beforehand e.g. via fuzzing
- A2: Crafted Beforehand

exploit

SMT Solver

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Overview: Taint Analysis

1) Record Instruction trace in SSA form
2) Record controllable memory locations
Overview: Taint Analysis

Inputs

Binary Application

Crashing Input

Shell-Code

Construct Exploit Formula
Path Constraints \land Shell-Code Constraints \land IP Constraints

Dynamic Taint Analysis

Symbolic Execution

SMT Solver

Exploit

Outputs

Check if sat & ask for solution

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Overview: Taint Analysis

Inputs

- Binary Application
- Crashing Input
- Shell-Code

Dynamic Taint Analysis

Outputs

- Symbolic Execution
- SMT Solver
- Generate Exploit (if sat)
- Exploit

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The Future

- Accelerate more complex arithmetic in loops
- Accelerate loops that do weird things to heap data structures
- (Also: accelerate floating-point loops)
- Engineering effort to scale up to huge codebases
  (we're eyeing up Debian...)
Goal: Exploit Stitching

Inputs

- Crashes

<table>
<thead>
<tr>
<th>Primitive Identification</th>
</tr>
</thead>
</table>

| Exploit Stitching |

Outputs

| Exploit |

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References

- Under-Approximating Loops in C Programs for Fast Counterexample Detection
  Daniel Kroening, Matt Lewis, Georg Weissenbacher, CAV 2013

- Verification and Falsification of Programs with Loops using Predicate Abstraction
  Daniel Kroening, Georg Weissenbacher, FACJ 2010