Model-Based Whitebox Fuzzing for Program Binaries

Thuan Pham

Marcel Böhme

Abhik Roychoudhury

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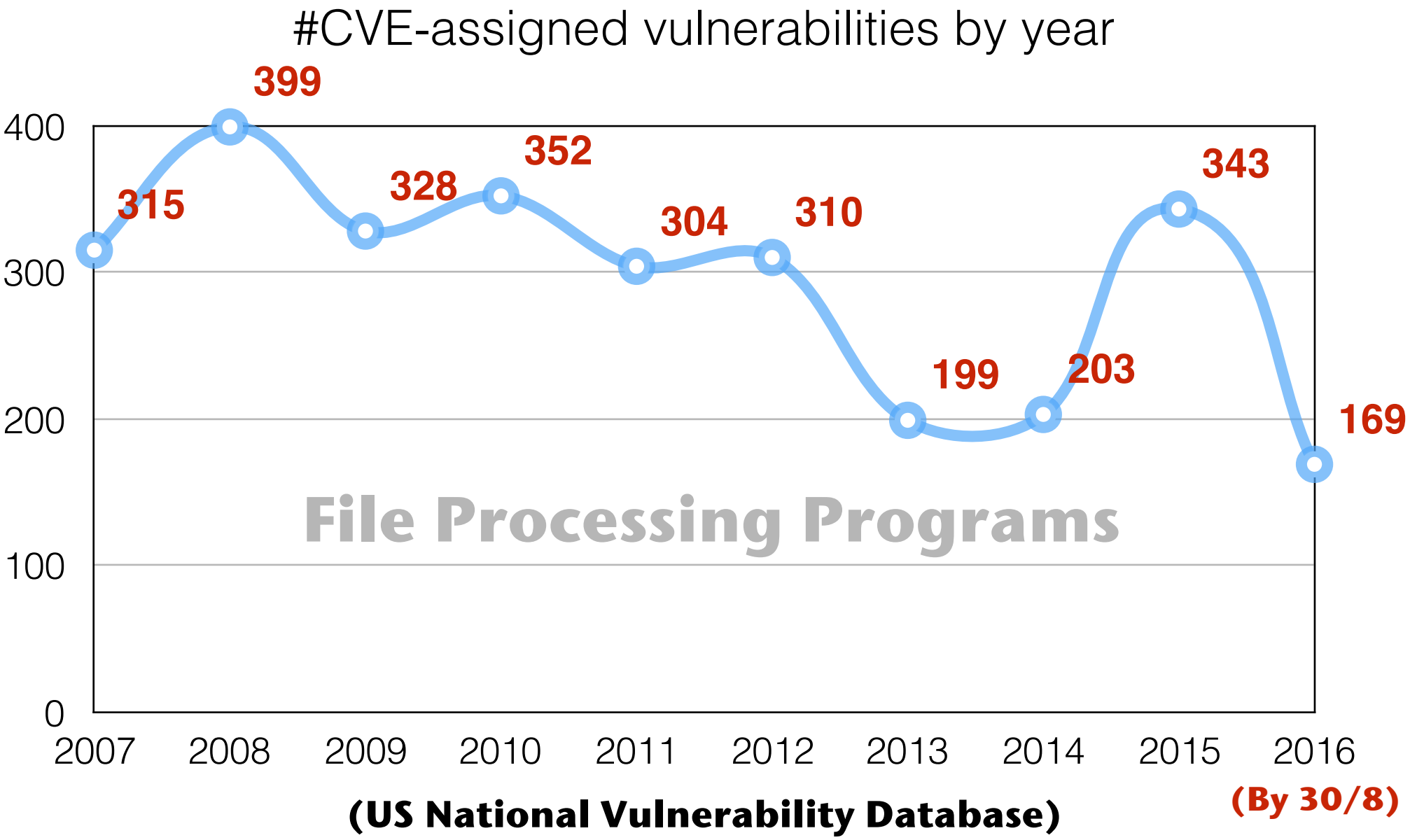
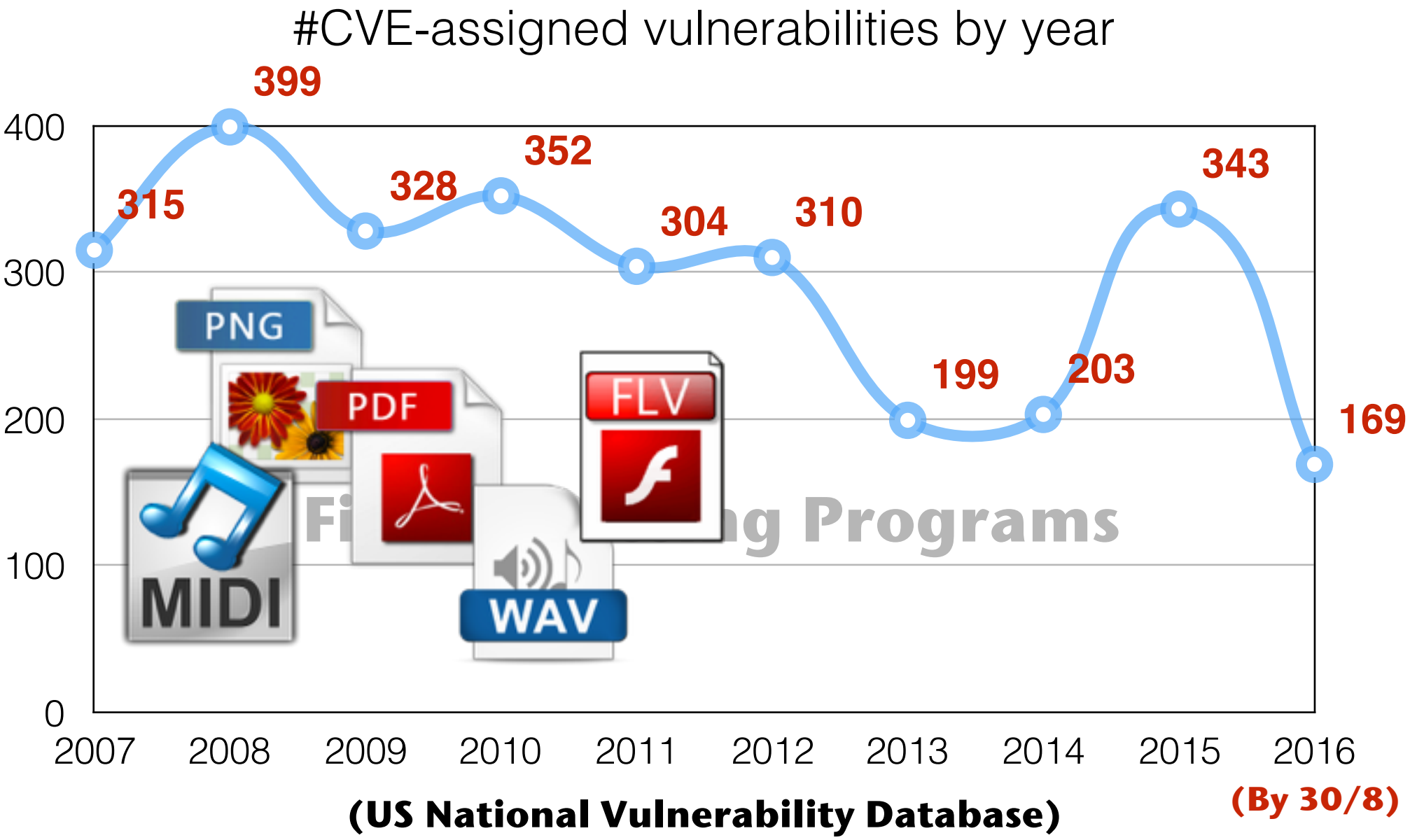
Vulnerabilities in file-processing programs



(US National Vulnerability Database)

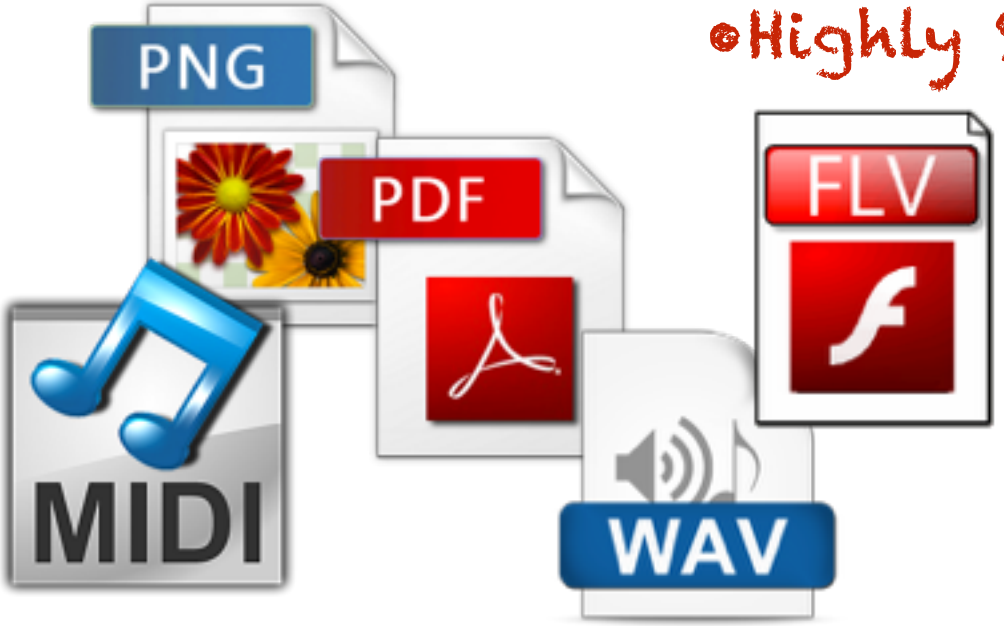
(By 30/8)

Vulnerabilities in file-processing programs



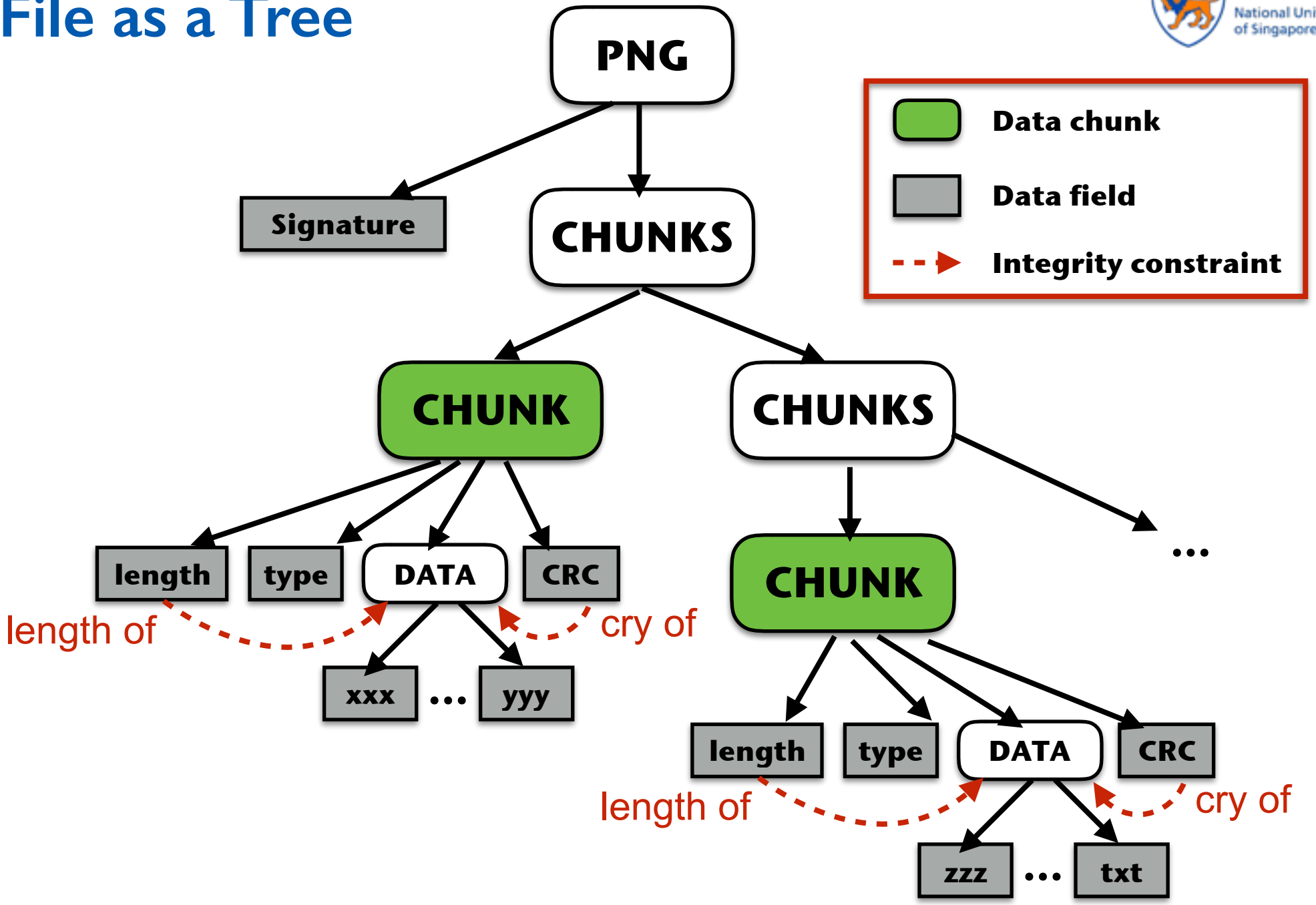
Challenge

- Generating test cases to expose vulnerabilities in file-processing software is challenging !



- Highly Structured
- Having both syntactic and semantic relationships
- Integrity constraints e.g., Checksums
- Compression/decompression algorithms

File as a Tree



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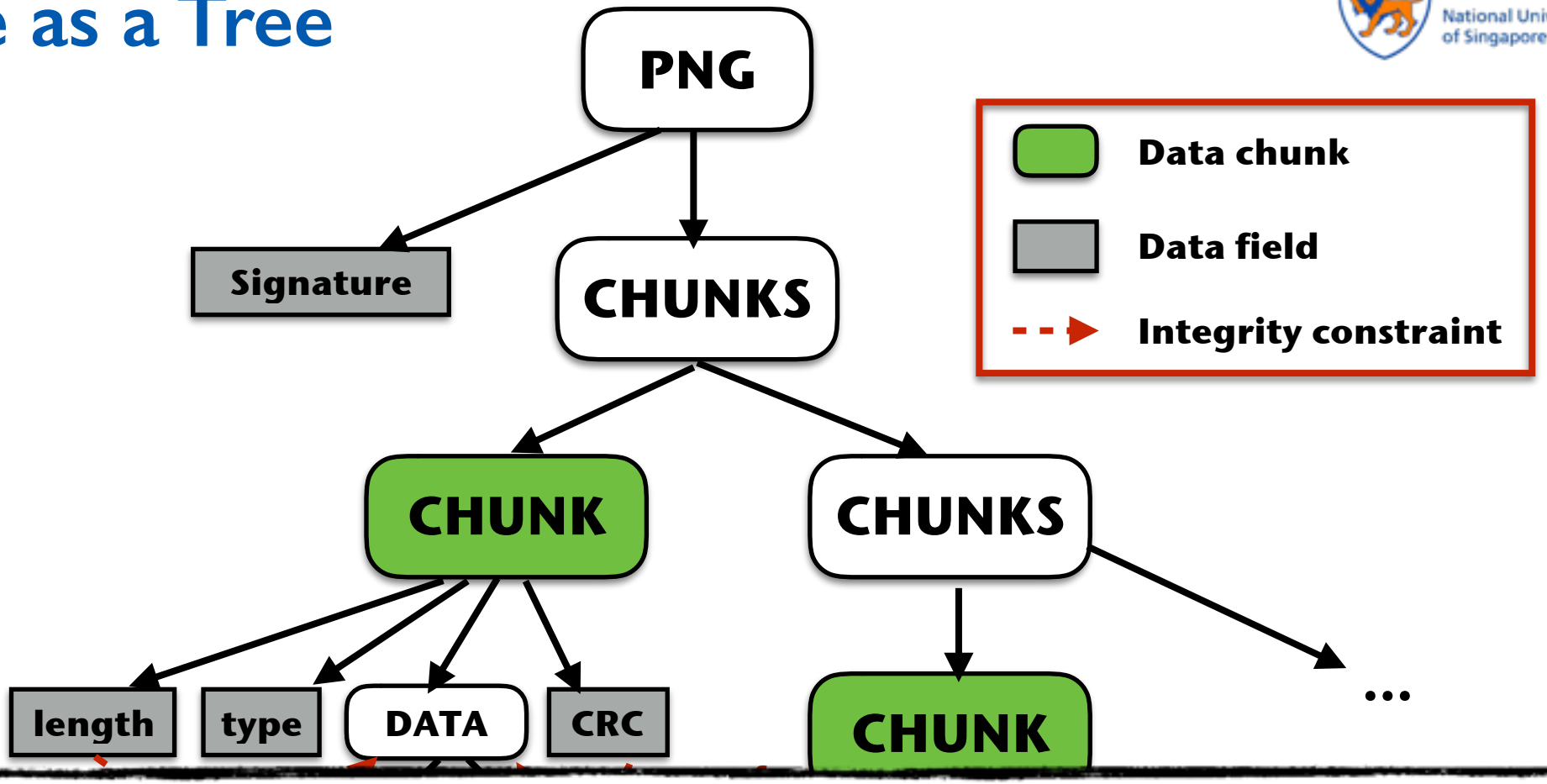
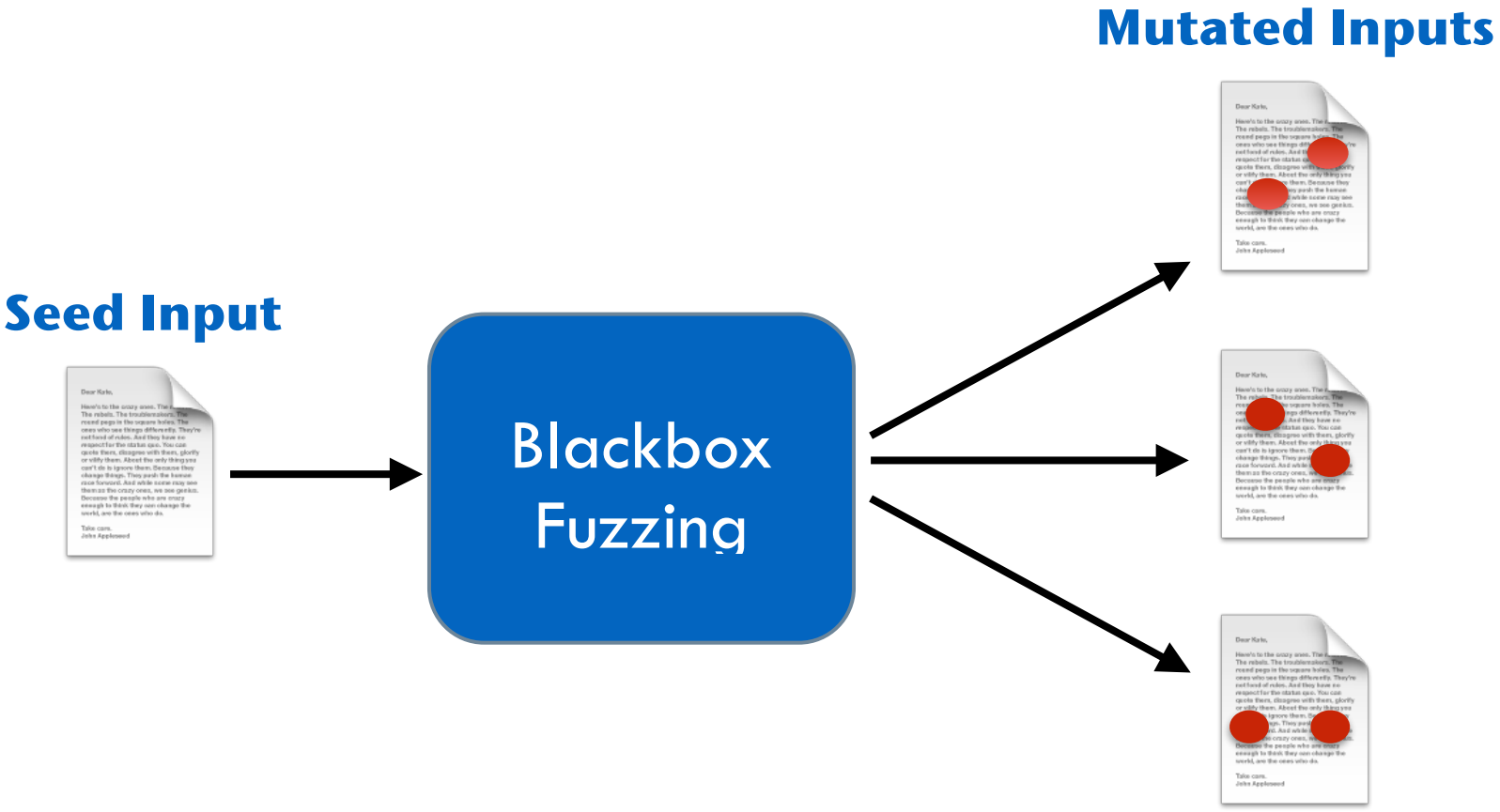


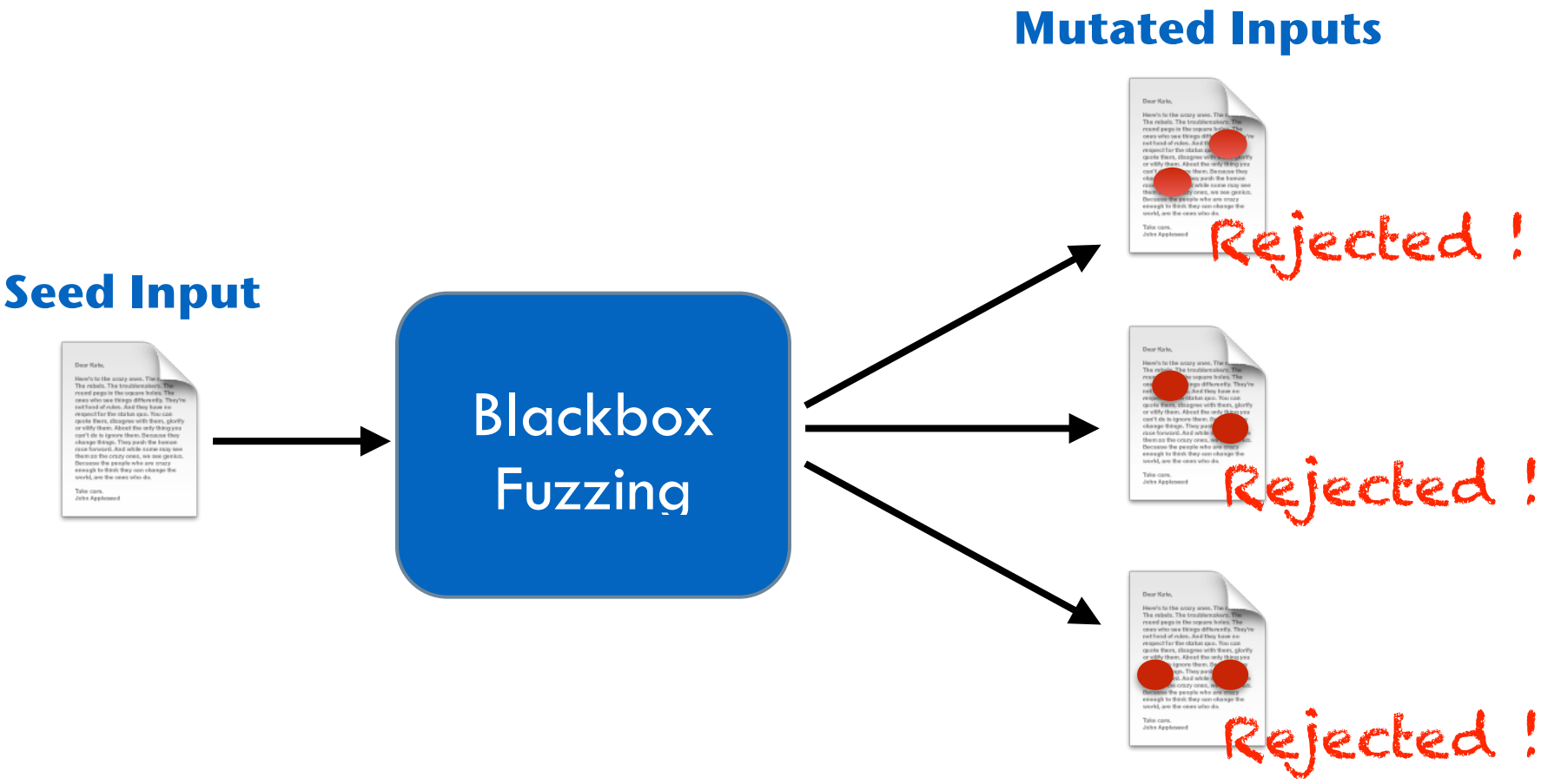
1. (Model-Based) Blackbox Fuzzing
2. Whitebox Fuzzing

zzz ... txt

Blackbox Fuzzing



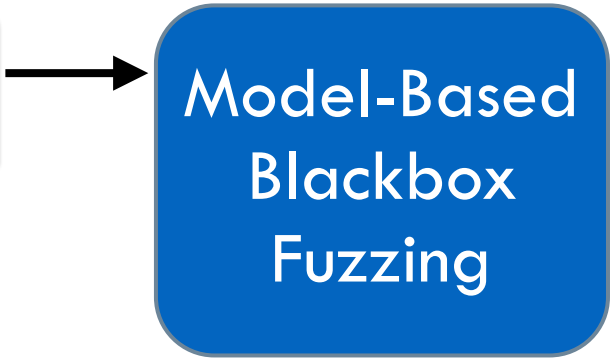
Blackbox Fuzzing



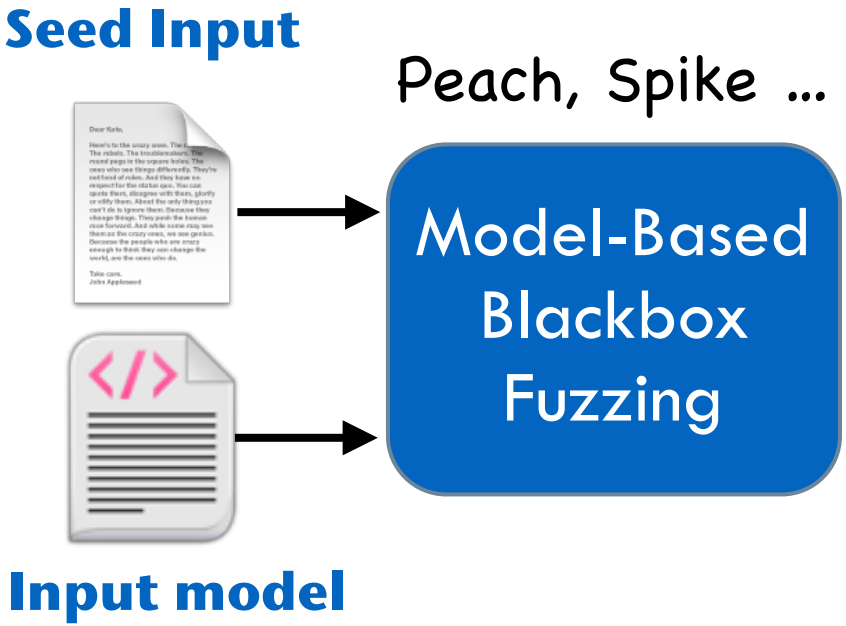
Model-Based Blackbox Fuzzing

Seed Input

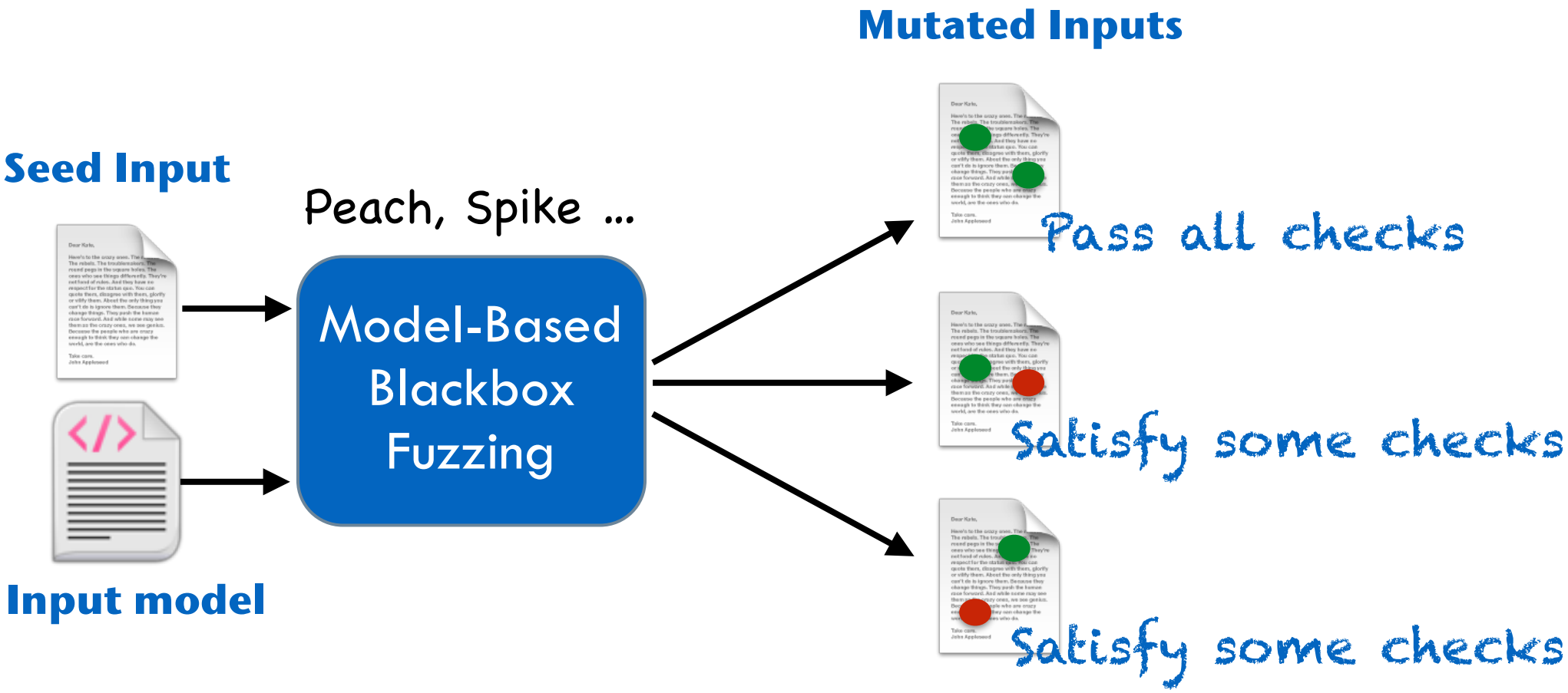
Peach, Spike ...



Model-Based Blackbox Fuzzing



Model-Based Blackbox Fuzzing



Model-Based Blackbox Fuzzing (MoBF)

MoBF struggles at generating specific values for data fields !

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One 32-bit data field:	**1/2^32**
Two 32-bit data fields:	**1/2^64**
Three 32-bit data fields:	**1/2^96**

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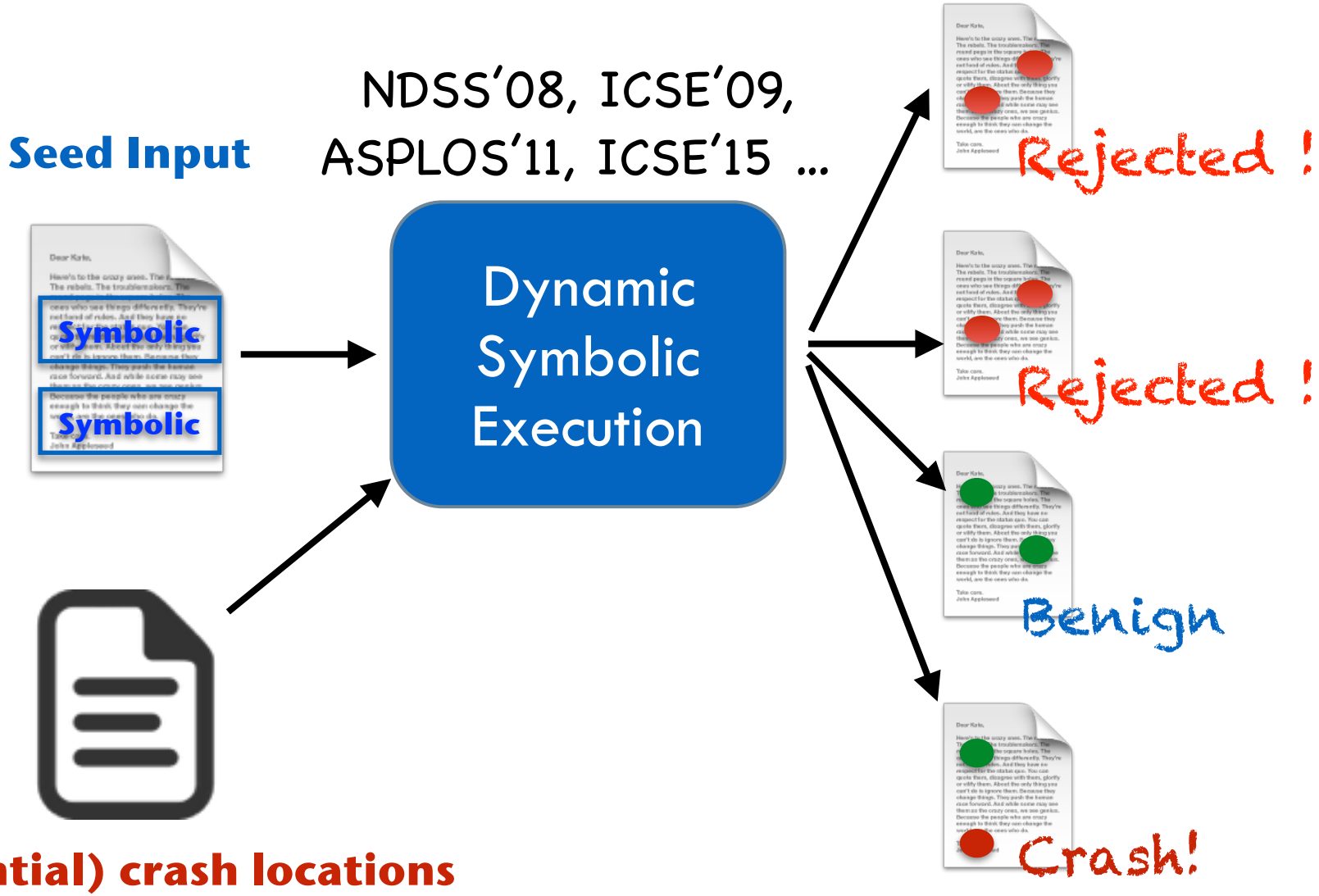
…

Whitebox Fuzzing



Whitebox Fuzzing (WF)

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WF comfortably generates specific values for data fields

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WF comfortably generates specific values for data fields

WF easily gets bogged down by large space of invalid inputs while

- adding missing data chunk(s) or
- enforcing integrity constraints like checksums, size-of, offset-of ...

Motivating Example

A PNG file triggers a crash in VLC media player

```
"\x89\x50\x4E\x47\x0D\x0A\x1A\x0A" # PNG signature
"\x00\x00\x00\x0D" # IHDR size
"\x49\x48\x44\x52" # IHDR chunk
"\x7F\xFF\xFF\xFF" # width
"\x00\x00\x01\x02" # height
"\x01" # bit depth
"\x03" # color type
"\x00" # compression method
"\x00" # filter method
"\x00" # interlace method
"\xBA\x1B\xD8\x84" # IHDR chunk CRC
"\x00\x00\x00\x03" # PLTE size
"\x50\x4C\x54\x45" # PLTE chunk
"\xFF" # red
"\xFF" # green
"\xFF" # blue
"\xA7\xC4\x1B\xC8" # PLTE chunk CRC
"\x00\x00\x00\x01" # tRNS size
"\x74\x52\x4E\x53" # tRNS chunk
"\x00" # alpha
"\x40\xE6\xD8\x66" # tRNS chunk CRC
"\x00\x00\x00\x01" # IDAT size
"\x49\x44\x41\x54" # IDAT chunk
"\xFF" # image data
"\x05\x3A\x92\x65" # IDAT chunk CRC
"\x00\x00\x00\x00" # IEND size
"\x49\x45\x4E\x44" # IEND chunk
"\xAE\x42\x60\x82" # IEND chunk CRC
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Requires an optional data chunk

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MOBF & WF are very unlikely to generate the crashing input IF the selected seed file does not have optional tRNS data chunk

Observation & Solution

- A missing data chunk can be obtained from other seed inputs in the test suite
- OR it can be directly instantiated from the ***input model***

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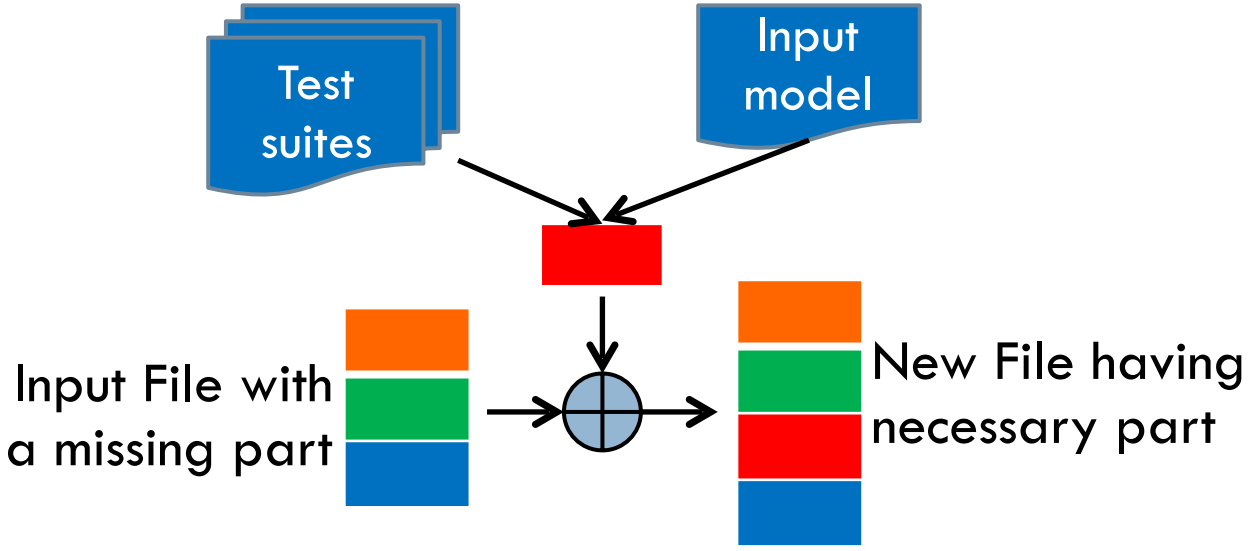
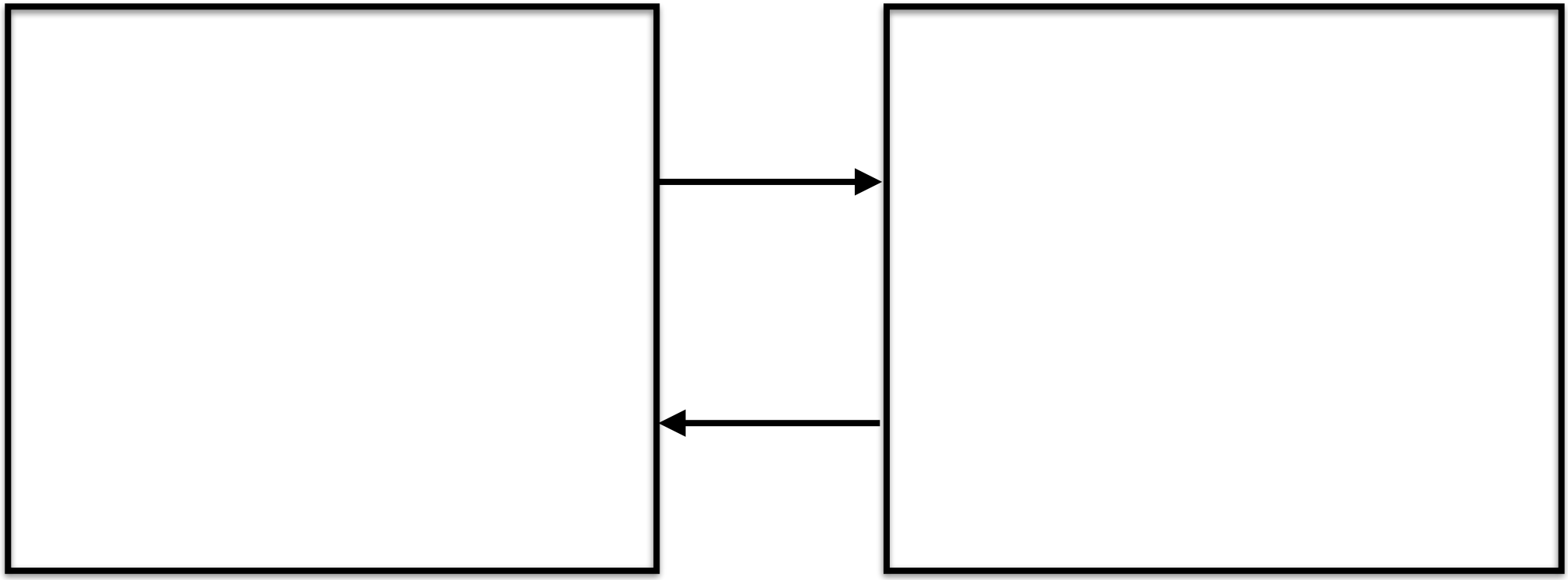


Data chunk Transplantation

Model-Based Whitebox Fuzzing



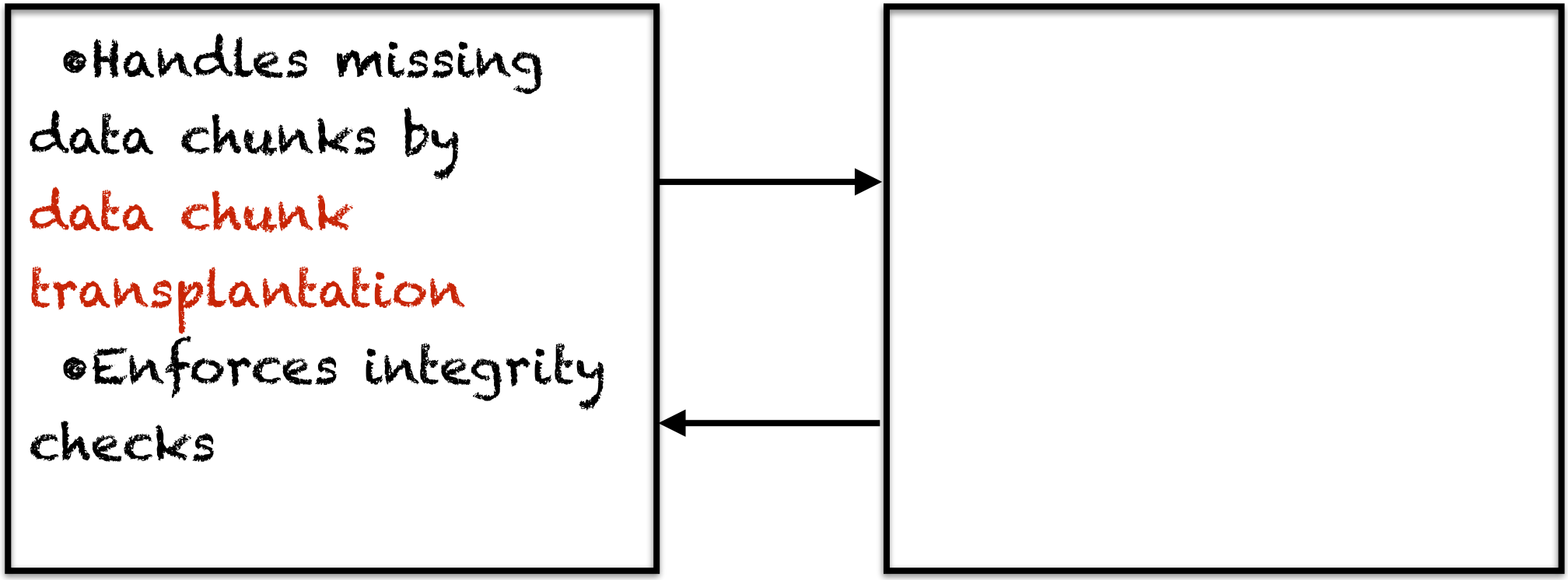
Augmented MoBF

MoBF + Transplantation

Selective and Targeted

Whitebox Fuzzing

Model-Based Whitebox Fuzzing



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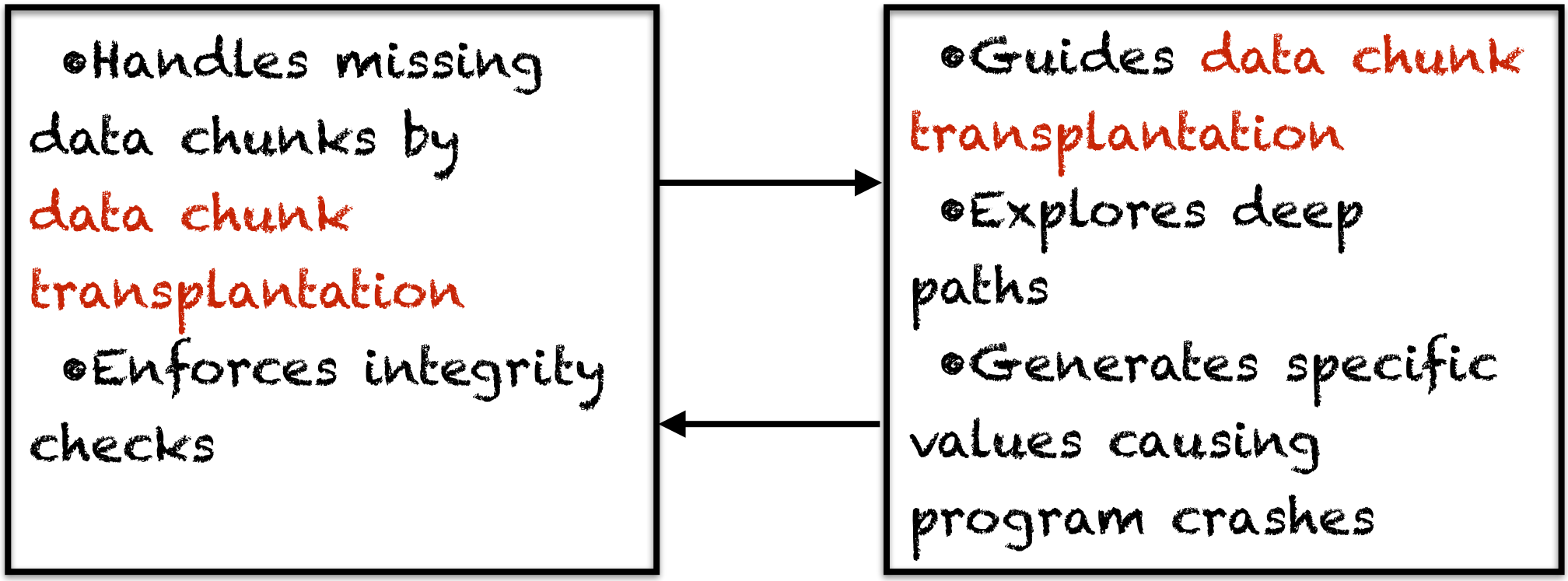

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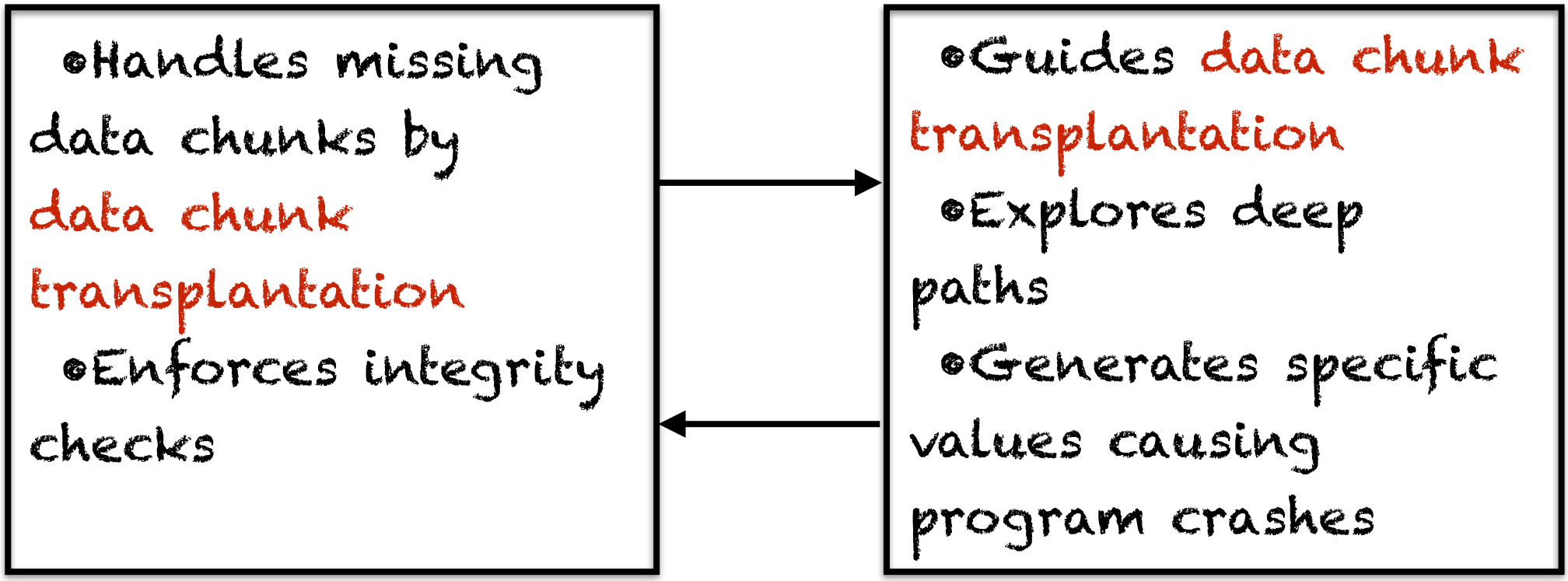

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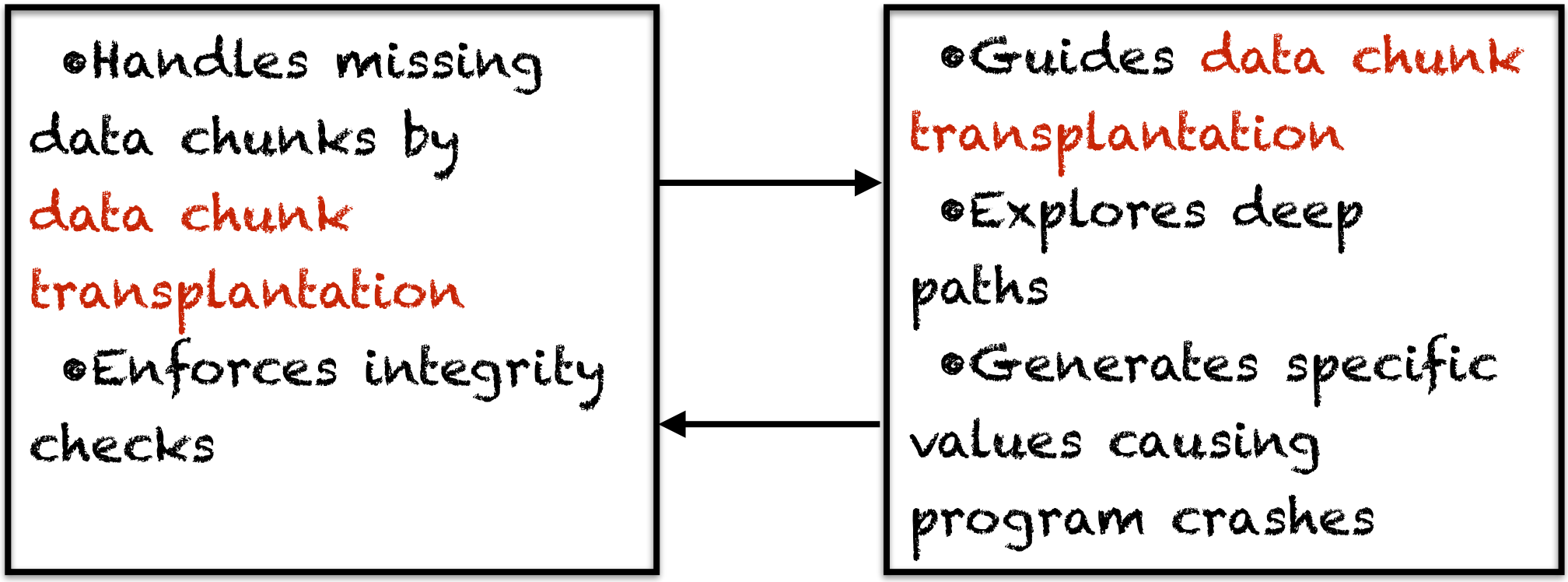
Peach Fuzzer
Production-quality MoBF

Model-Based Whitebox Fuzzing



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MoBF + Transplantation

Peach Fuzzer
Production-quality MoBF

Selective and Targeted

Whitebox Fuzzing

Hercules (ICSE'15)
Scale to WMP, Adobe Reader

What the input model looks like?

XML-based Input Model (Peach Fuzzer)

Data model for a generic data chunk

```
<DataModel name="Chunk">
    <Number name="Length" size="32" endian="big">
        <Relation type="size" of="Data" />
    </Number>
    <Block name="TypeData">
        <String name="Type" length="4" />
        <Blob name="Data" />
    </Block>
    <Number size="32" endian="big">
        <Fixup class="Crc32Fixup">
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```
<DataModel name="Chunk_IHDR" ref="Chunk">
    <Block name="TypeData">
        <String name="Type" value="IHDR" length="4"
        token="true"/>
        <Block name="Data">
            <Number name="width" size="32" />
            <Number name="height" size="32" />
            <Number name="bits" size="8" />
            <Number name="color_type" size="8" />
            <Number name="compression" size="8" />
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inherits common data fields & relationships

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        </Block>
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</DataModel>
```

Data model for PNG image files

```
<DataModel name="Png">
    <Number name="Signature" valueType="hex"
    value="89504e470d0a1a0a" size="64"
    token="true" />
    <Choice maxOccurs="30000">
        <Block ref="Chunk_IHDR"/>
        <Block ref="Chunk_PLTE"/>
        <Block ref="Chunk_IDAT"/>
        ...
        <Block ref="Chunk_IEND"/>
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    </Choice>
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    <Number name="Signature" valueType="hex"
    value="89504e470d0a1a0a" size="64"
    token="true" />
    <Choice maxOccurs="30000">
        <Block ref="Chunk_IHDR"/>
        <Block ref="Chunk_PLTE"/>
        <Block ref="Chunk_IDAT"/>
        ...
        <Block ref="Chunk_IEND"/>
        <Block ref="Chunk"/>
    </Choice>
</DataModel>
```

XML-based Input Model (Peach Fuzzer)

Data model for a generic data chunk

```
<DataModel name="Chunk">
    <Number name="Length" size="32" endian="big">
        <Relation type="size" of="Data" />
    </Number>
    <Block name="TypeData">
        <String name="Type" length="4" />
        <Blob name="Data" />
    </Block>
    <Number size="32" endian="big">
        <Fixup class="Crc32Fixup">
            <Param name="ref" value="TypeData"/>
        </Fixup>
    </Number>
</DataModel>
```

inherits common data fields & relationships

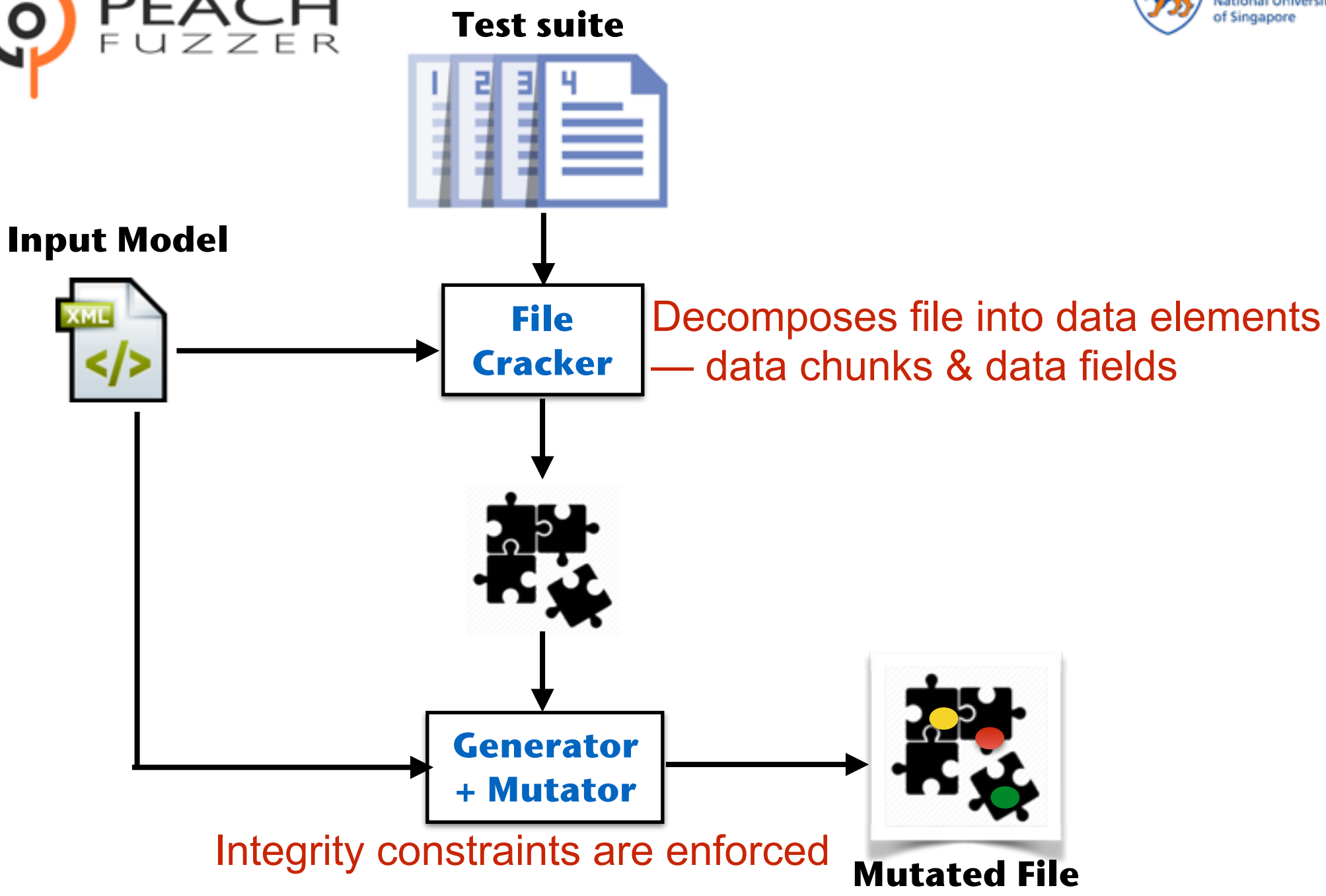
```
<DataModel name="Chunk_IHDR" ref="Chunk">
    <Block name="TypeData">
        <String name="Type" value="IHDR" length="4"
        token="true"/>
        <Block name="Data">
            <Number name="width" size="32" />
            <Number name="height" size="32" />
            <Number name="bits" size="8" />
            <Number name="color_type" size="8" />
            <Number name="compression" size="8" />
            <Number name="filter" size="8" />
            <Number name="interlace" size="8" />
        </Block>
    </Block>
</DataModel>
```

Data model for PNG image files

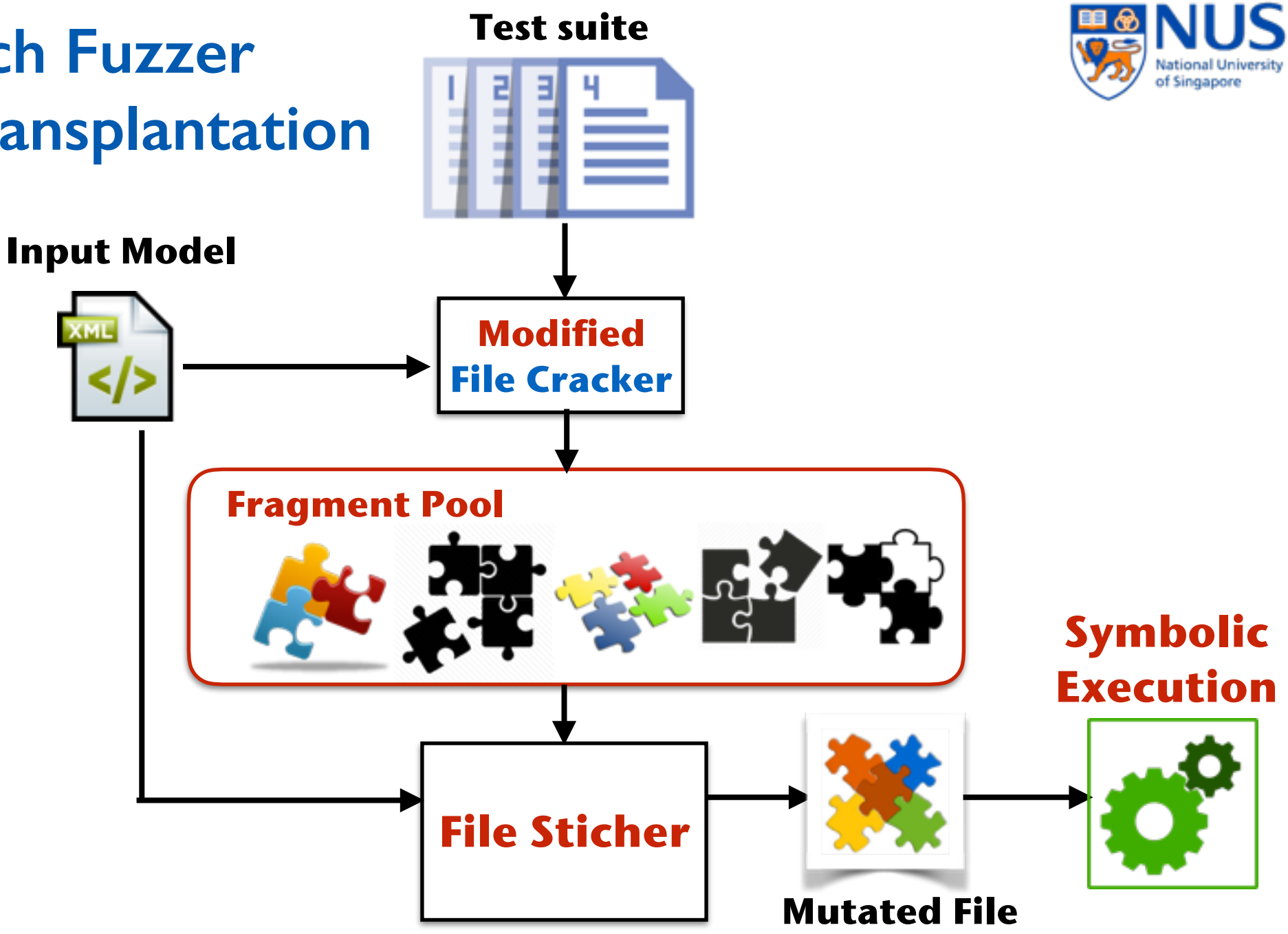
```
<DataModel name="Png">
    <Number name="Signature" valueType="hex"
    value="89504e470d0a1a0a" size="64"
    token="true" />
    <Choice maxOccurs="30000">
        <Block ref="Chunk_IHDR"/>
        <Block ref="Chunk_PLTE"/>
        <Block ref="Chunk_IDAT"/>
        ...
        <Block ref="Chunk_IEND"/>
        <Block ref="Chunk"/>
    </Choice>
</DataModel>
```

PEACH FUZZER

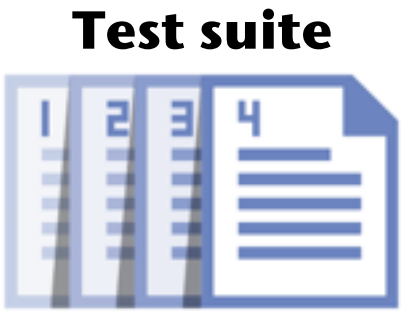
NUS National University of Singapore

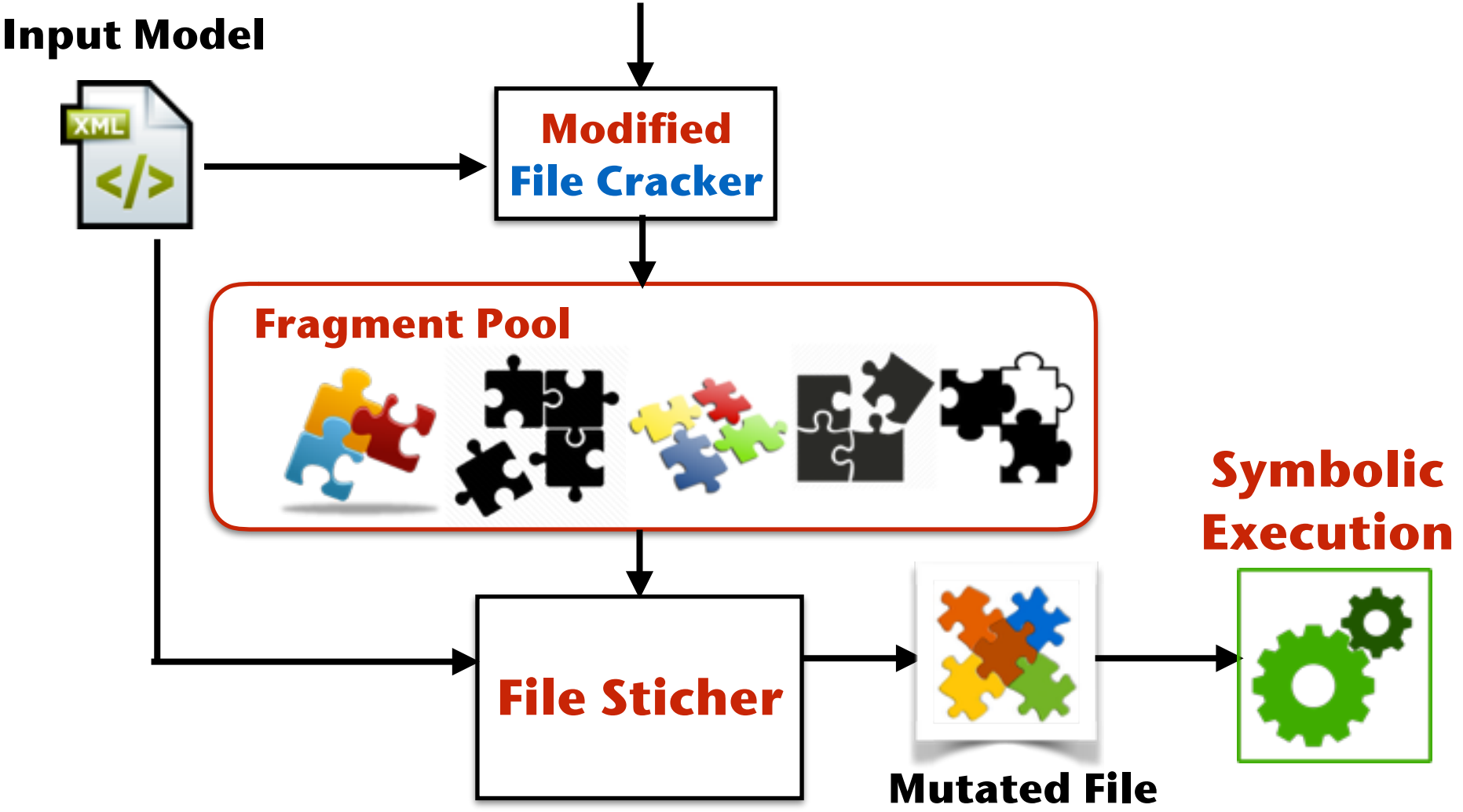


Peach Fuzzer + Transplantation

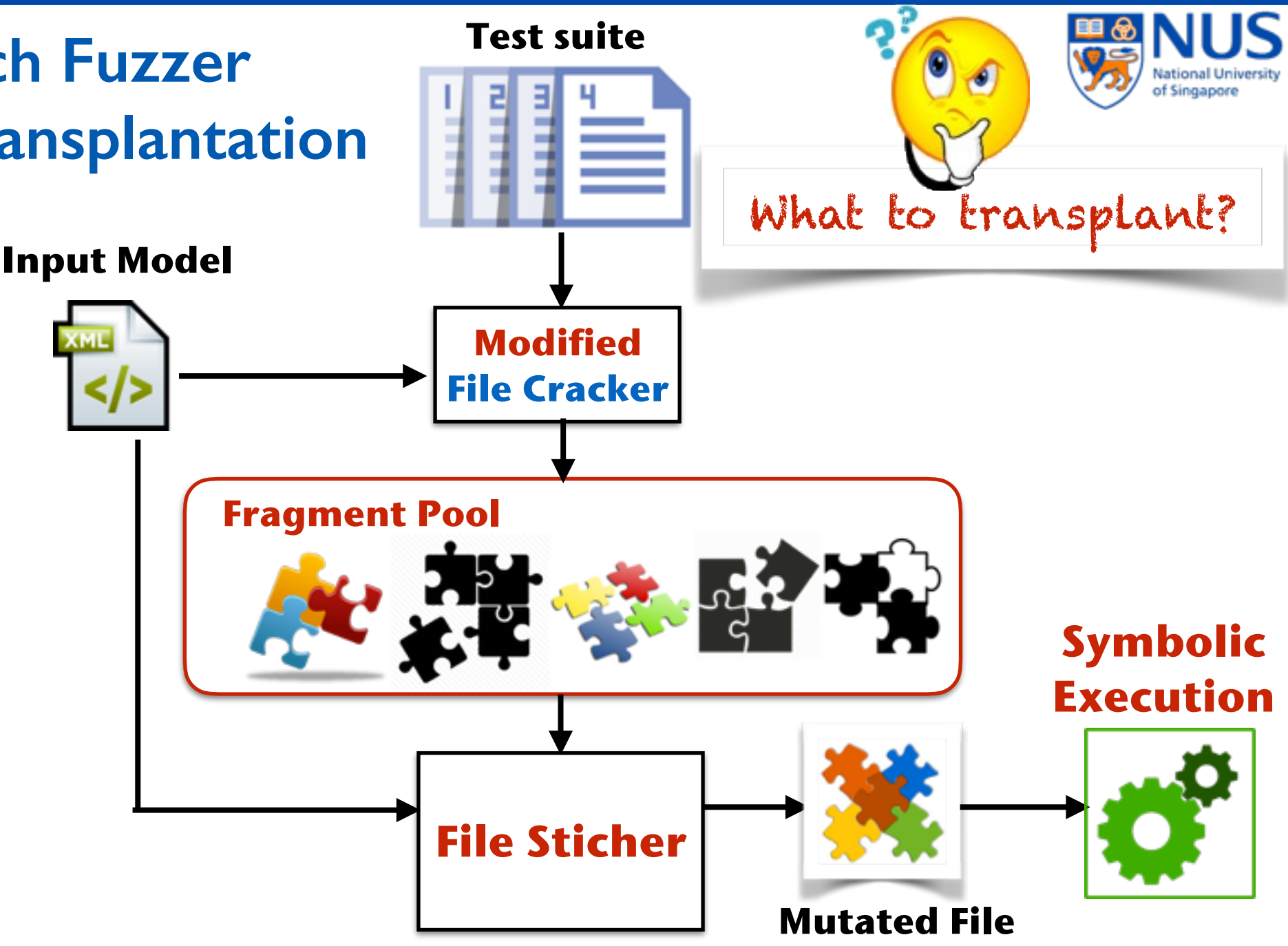


Peach Fuzzer + Transplantation

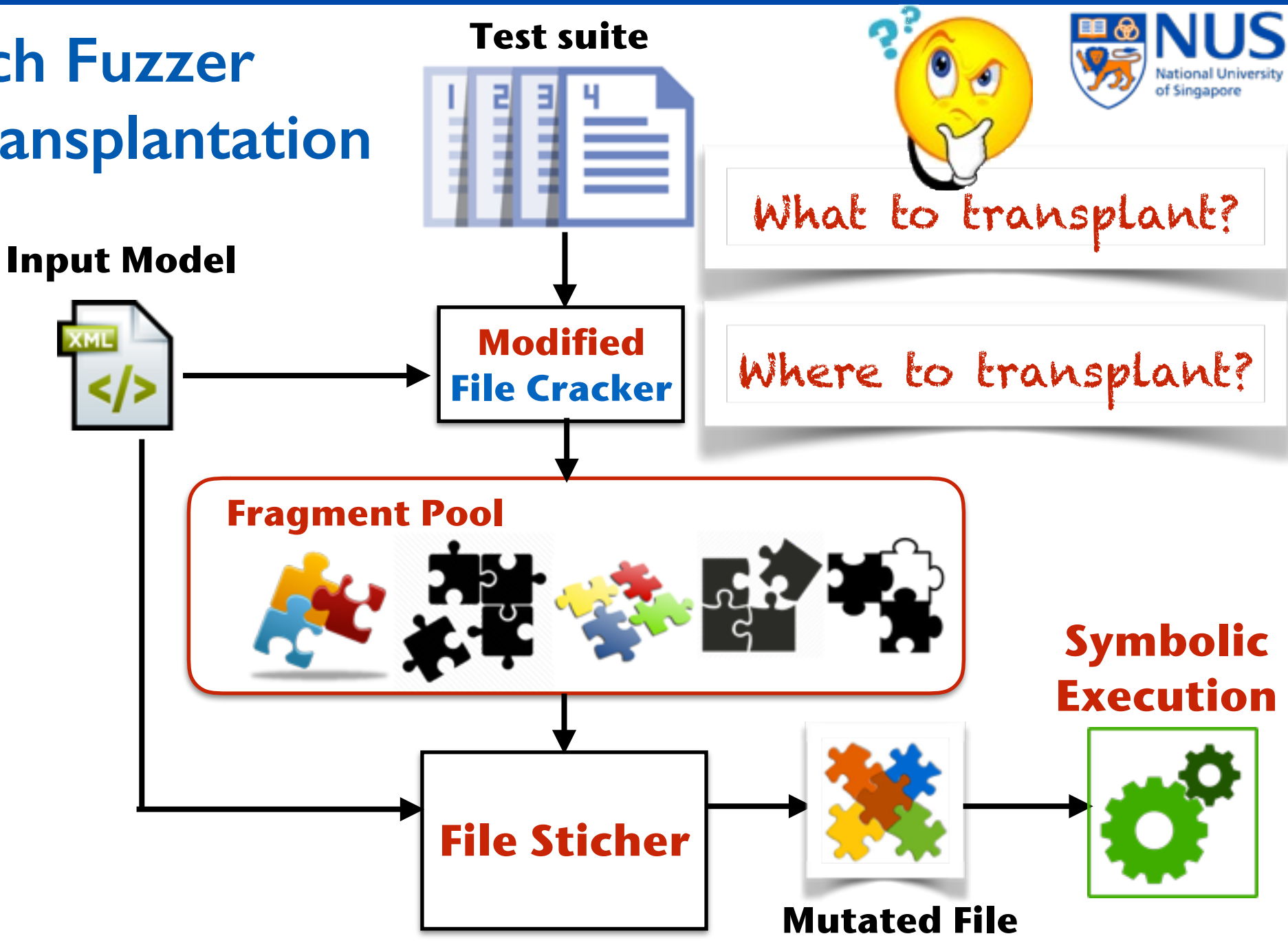




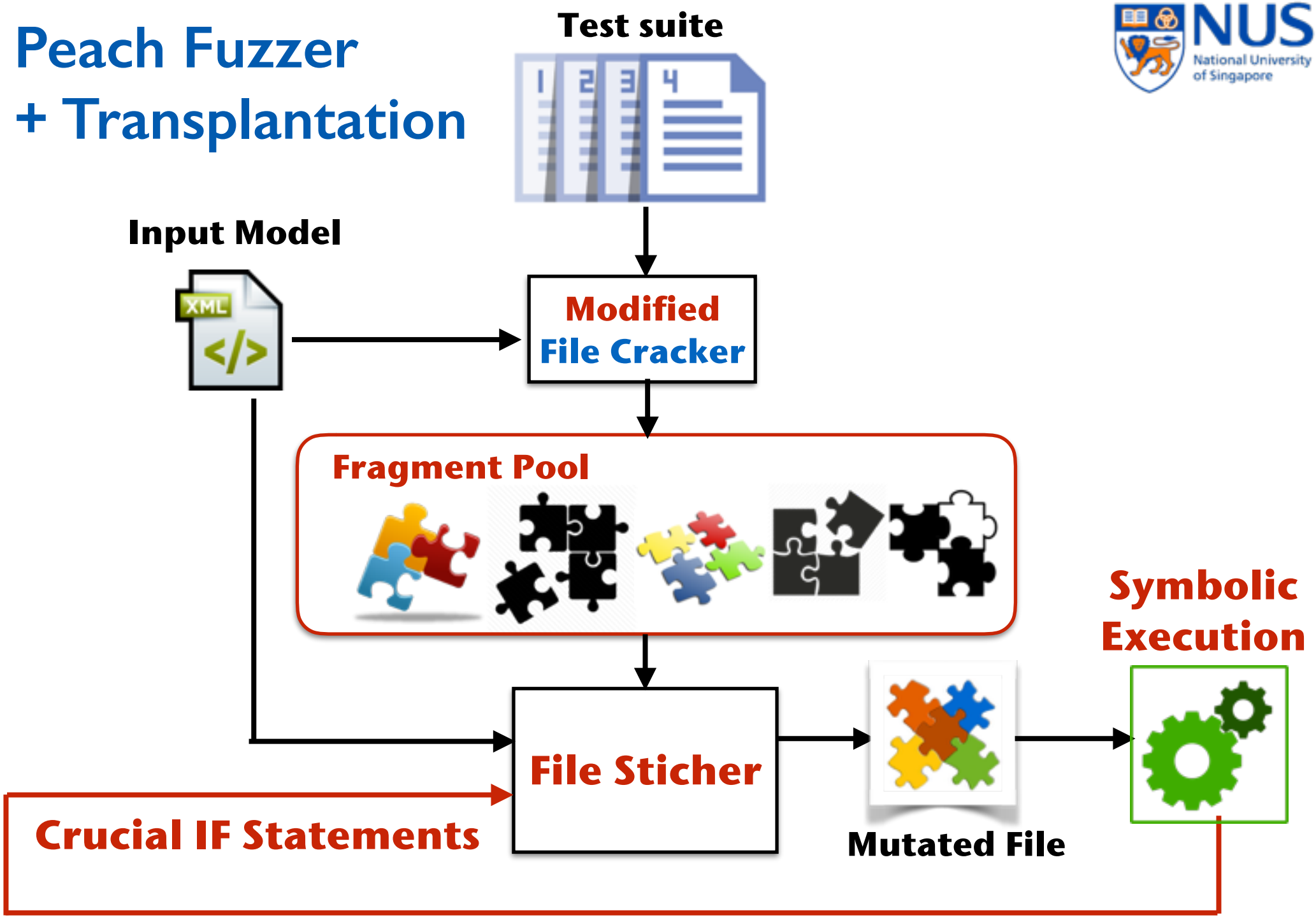
Peach Fuzzer + Transplantation



Peach Fuzzer + Transplantation



Peach Fuzzer + Transplantation



Crucial IF Statements

```
1  // read chunks' info before first IDAT chunk
2  void png_read_info(png_structp ptr)
3  {
4  // read and check the PNG file signature
5  read_sig(f);
6  for (;;)
7  {
8    // get current chunk's information
9    uint_32 length = read_chunk_header(ptr);
10   uint_32 chunk_name = ptr->chunk_name;
11   // mandatory chunks
12   if (chunk_name == png_IHDR)
13      handle_IHDR(ptr, length);
14   else if (chunk_name == png_IEND)
15      handle_IEND(ptr, length);
16   else if (chunk_name == png_PLTE)
17      handle_PLTE(ptr, length);
18   else if (chunk_name == png_IDAT)
19   {
20      ptr->idat_size = length;
21      break;
22   }
23   // optional chunks
24   else if ...
25   else if (chunk_name == png_tRNS)
26      handle_tRNS(ptr, length);
27   else if ...
28 }
29 }
30 // initialize row buffer for reading data from file
31 void png_read_start_row(png_structp ptr)
32 {
33    size_t buf_size;
34    ...
35    buf_size = calculateBufSize(ptr);
36    ptr->row_buf = png_malloc(ptr, buf_size);
37    png_memset(ptr->row_buf, 0, ptr->rowbytes);
38 }
```

Code extracted from LibPNG

Crucial IF Statements

```
1  // read chunks' info before first IDAT chunk
2  void png_read_info(png_structp ptr)
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37    png_memset(ptr->row_buf, 0, ptr->rowbytes);
38 }
```

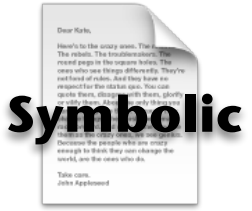
Code extracted from LibPNG

A Crucial IF Statement
- Only one branch has been taken
- depends on the presence of a data chunk in the input file

Detecting Crucial IF Statements

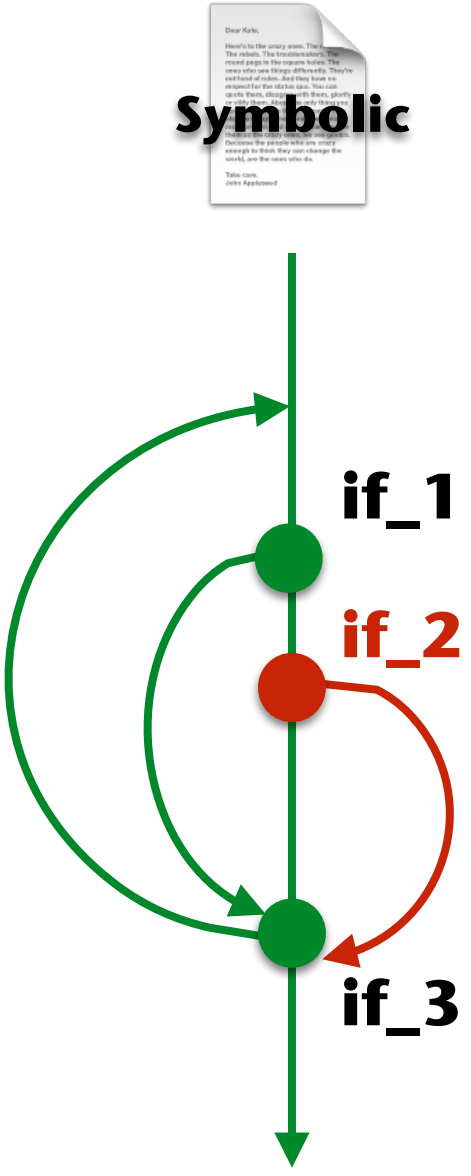
Detecting Crucial IF Statements

- **Step 1.** Mark input file (partially) symbolic



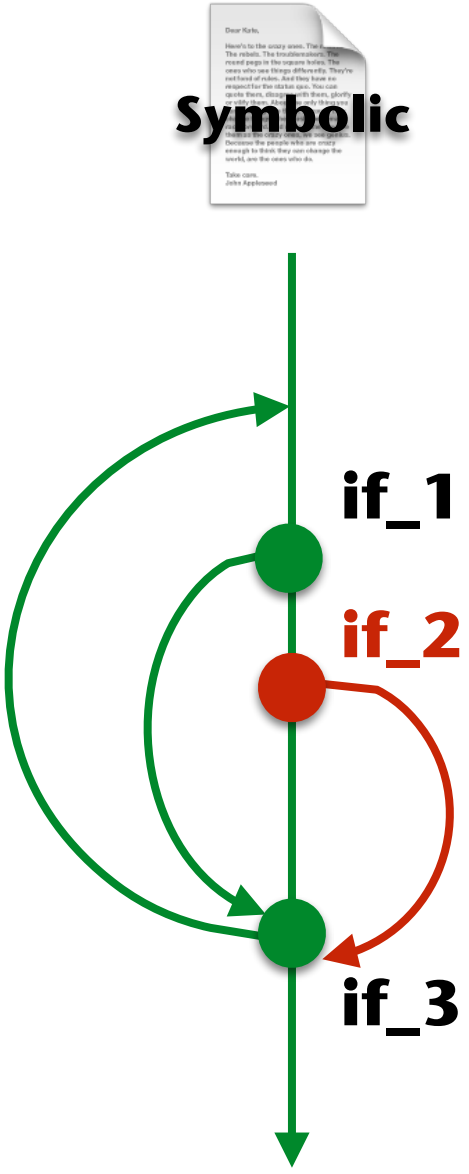
Detecting Crucial IF Statements

- **Step 1.** Mark input file (partially) symbolic
- **Step 2.** Concolically execute program in one path - *same path as concrete input*



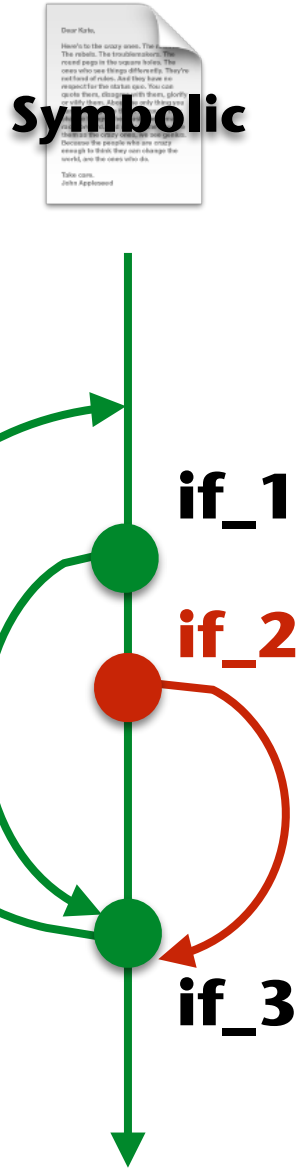
Detecting Crucial IF Statements

- **Step 1.** Mark input file (partially) symbolic
- **Step 2.** Concolically execute program in one path - *same path as concrete input*
- **Step 3.** Collect branch conditions of IF statements at which *only one branch has been taken (e.g., if_2)*



Detecting Crucial IF Statements

- **Step 1.** Mark input file (partially) symbolic
- **Step 2.** Concolically execute program in one path - *same path as concrete input*
- **Step 3.** Collect branch conditions of IF statements at which *only one branch has been taken (e.g., if_2)*
- **Step 4.** Use symbolic-execution-based *taint analysis & input model* to analyse branch conditions (at *if_2*) to validate crucial IFs statements



Evaluation - Subjects & Input Models

Evaluation - Subjects & Input Models

9 subject programs

Program	Version	Buggy module	Size	Errors
Video Lan Client	2.0.7	libpng.dll	184 KB	1
Video Lan Client	2.0.3	libpng.dll	182 KB	1
Libpng Test Program	1.5.4	libpng.dll	176 KB	1
XnView	1.98	XnView.exe	4.46 MB	0 + 3
Adobe Reader	9.2	cooltype.dll	2.32 MI	1
Windows Media Playe	9.0	quartz.dll	1.22 MI	2 + 1
Real Player SP	1.0	realplay.exe	60 KB	1
MIDI Player	0.35	mamplayer.ex	336 KB	1
Orbital Viewer	1.04	ov.exe	538 KB	1
			Total:	9 + 4

Evaluation - Subjects & Input Models

9 subject programs

Program	Version	Buggy module	Size	Errors
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Video Lan Client	2.0.3	libpng.dll	182 KB	1
Libpng Test Program	1.5.4	libpng.dll	176 KB	1
XnView	1.98	XnView.exe	4.46 MB	0 + 3
Adobe Reader	9.2	cooltype.dll	2.32 MI	1
Windows Media Playe	9.0	quartz.dll	1.22 MI	2 + 1
Real Player SP	1.0	realplay.exe	60 KB	1
MIDI Player	0.35	mamplayer.ex	336 KB	1
Orbital Viewer	1.04	ov.exe	538 KB	1
			Total:	9 + 4

6 Input models

Format	Size	Time spent	#Files	Average size
PDF	4.5 KB	12 hours	10	200 KB
PNG	8.3 KB	4 hours	10	55 KB
MIDI	13.9 KB	4 hours	10	20 KB
FLV	6.0 KB	4 hours	10	300 KB
ORB	6.0 KB	8 hours	10	4 KB
WAV*	7.5 KB	2 hours	10	260 KB

One-time effort

34 hrs

Evaluation - Effectiveness of MoWF

Time bound: 24hrs

Program	Advisory ID	Input Model	#Seed files	MoWF	Peach	Hercules
VLC 2.0.7	OSVDB-95632	PNG	10	✓	✗	✗
VLC 2.0.3	CVE-2012-5470	PNG	10	✓	✗	✗
LTP 1.5.4	CVE-2011-3328	PNG	10	✓	✗	✗
XNV1.98	Unknown-1	PNG	10	✓	✓	✗
XNV1.98	Unknown-2	PNG	10	✓	✓	✗
XNV1.98	Unknown-3	PNG	10	✓	✓	✗
WMP 9.0	Unknown-4	WAV	10	✓	✓	✗
WMP 9.0	CVE-2014-2671	WAV	10	✓	✗	✓
WMP 9.0	CVE-2010-0718	MIDI	10	✓	✗	✓
AR 9.2	CVE-2010-2204	PDF	10	✓	✗	✓
RP 1.0	CVE-2010-3000	FLV	10	✓	✗	✓
MP 0.35	CVE-2011-0502	MIDI	10	✓	✓	✓
OV 1.04	CVE-2010-0688	ORB	10	✓	✓	✓

Evaluation - Seed Input Dependence

Program	Advisory ID	Input Model	#Seed files	Hercules++
VLC 2.0.7	OSVDB-95632	PNG	0	✓
VLC 2.0.3	CVE-2012-5470	PNG	0	✓
LTP 1.5.4	CVE-2011-3328	PNG	0	✓
XNV1.98	Unknown-1	PNG	0	✓
XNV1.98	Unknown-2	PNG	0	✓
XNV1.98	Unknown-3	PNG	0	✓
WMP 9.0	Unknown-4	WAV	0	✗
WMP 9.0	CVE-2014-2671	WAV	0	✗
WMP 9.0	CVE-2010-0718	MIDI	0	✓
AR 9.2	CVE-2010-2204	PDF	0	✗
RP 1.0	CVE-2010-3000	FLV	0	✗
MP 0.35	CVE-2011-0502	MIDI	0	✓
OV 1.04	CVE-2010-0688	ORB	0	✓

Evaluation - Seed Input Dependence

Program	Advisory ID	Input Model	#Seed files	Hercules++
VLC 2.0.7	OSVDB-95632	PNG	0	✓
VLC 2.0.3	CVE-2012-5470	PNG	0	✓
LTP 1.5.4	CVE-2011-3328	PNG	0	✓
XNV1.98	Unknown-1	PNG	0	✓
XNV1.98	Unknown-2	PNG	0	✓
XNV1.98	Unknown-3	PNG	0	✓
WMP 9.0	Unknown-4	WAV	0	✗
WMP 9.0	CVE-2014-2671	WAV	0	✗
WMP 9.0	CVE-2010-0718	MIDI	0	✓
AR 9.2	CVE-2010-2204	PDF	0	✗
RP 1.0	CVE-2010-3000	FLV	0	✗
MP 0.35	CVE-2011-0502	MIDI	0	✓
OV 1.04	CVE-2010-0688	ORB	0	✓

70%
No seed file is needed

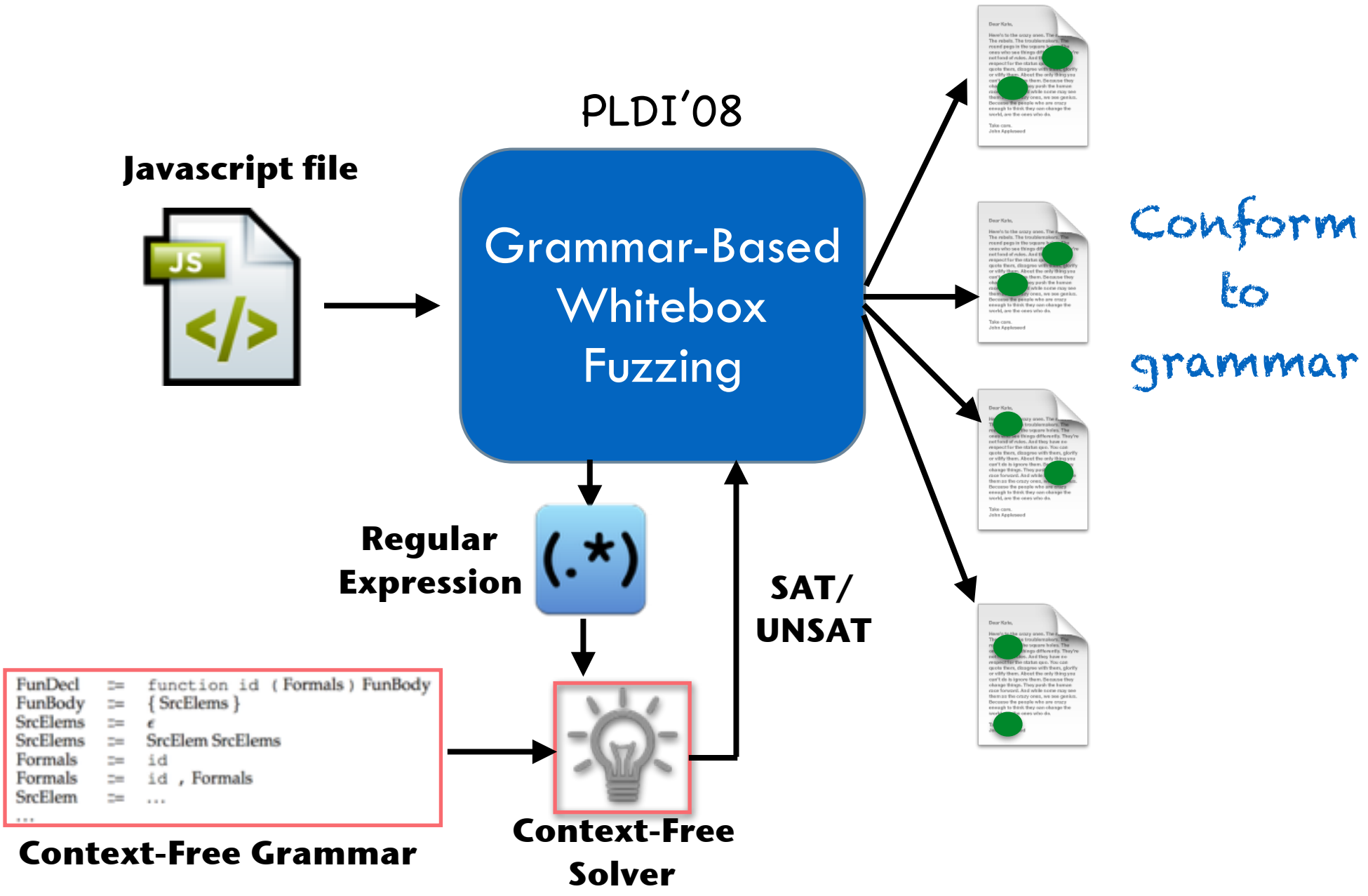
Related Work

NUS National University of Singapore

Related Work

Grammar-based whitebox fuzzing (PLDI'08)

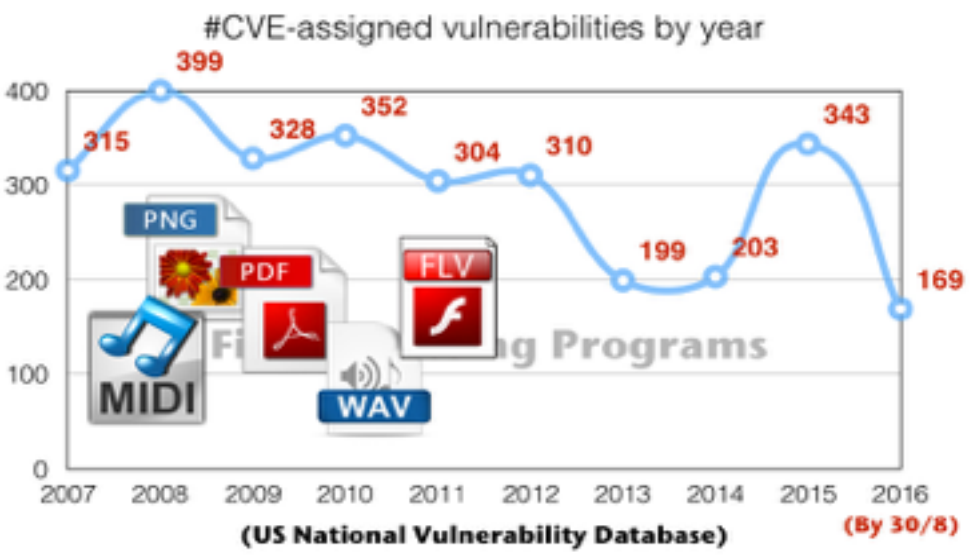
Grammar-based Whitebox Fuzzing (GWF)



MoWF vs GWF

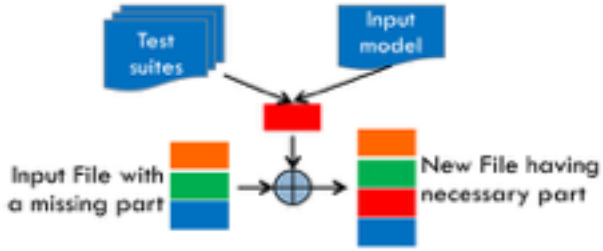
- Regular Expression (GWF) is much weaker than full Path Condition - it cannot encode simple arithmetic constraint like "x<y"
- MoWF maintains full Path Condition and has no impact on the soundness and completeness of Whitebox Fuzzing technique
- MoWF leverages File format input model - more expressive yet simple than Context-Free Grammar. It can comfortably handle integrity constraints like length-of, offset-of and checksums

Vulnerabilities in file-processing programs



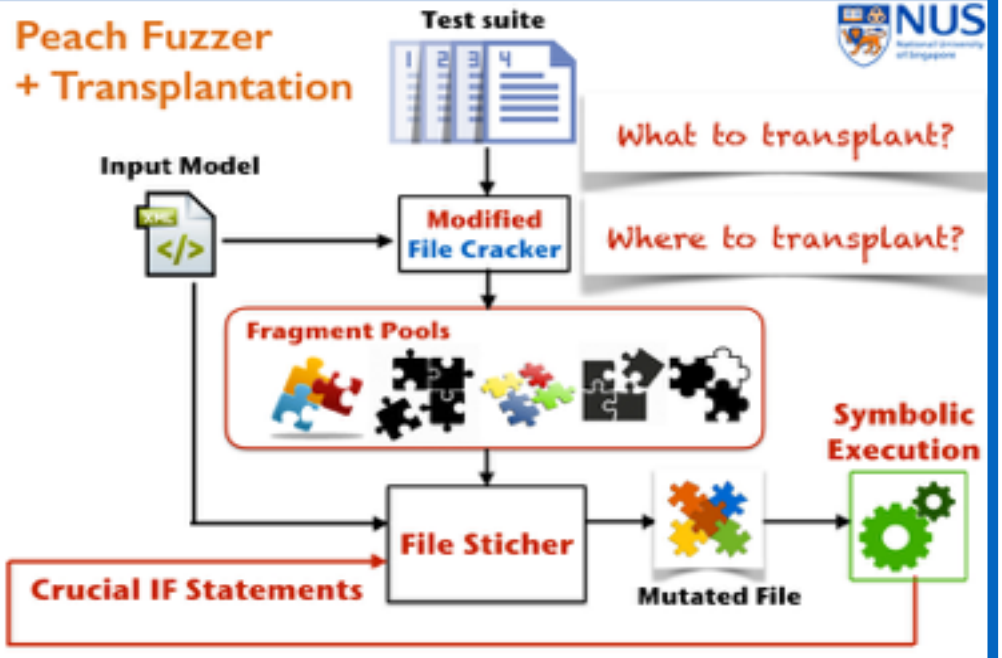
Observation & Solution

- A missing data chunk can be obtained from other seed inputs in the test suite
- OR it can be directly instantiated from an ***input model***



Data chunk Transplantation

Peach Fuzzer + Transplantation



Evaluation - Effectiveness of MoWF

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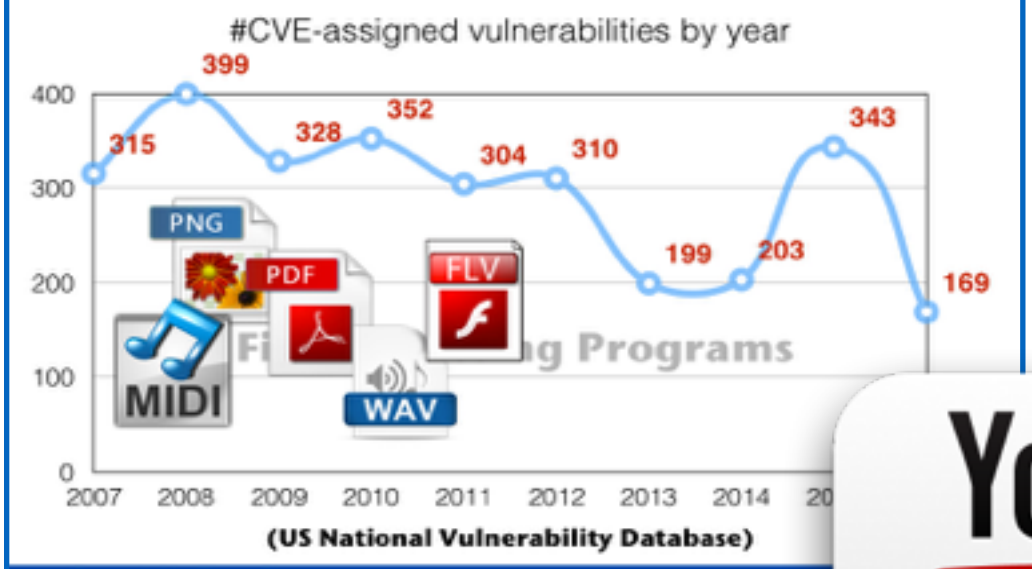
RP 1.0	CVE-2010-3000	FLV	10	✓	✗	✓
MP 0.35	CVE-2011-0502	MIDI	10	✓	✓	✓
OV 1.04	CVE-2010-0688	ORB	10	✓	✓	✓

Vulnerabilities in file-processing programs



Presented by Thuan Pham

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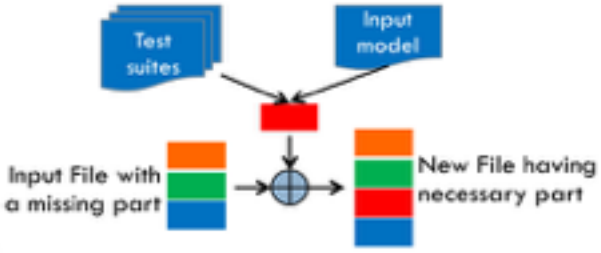
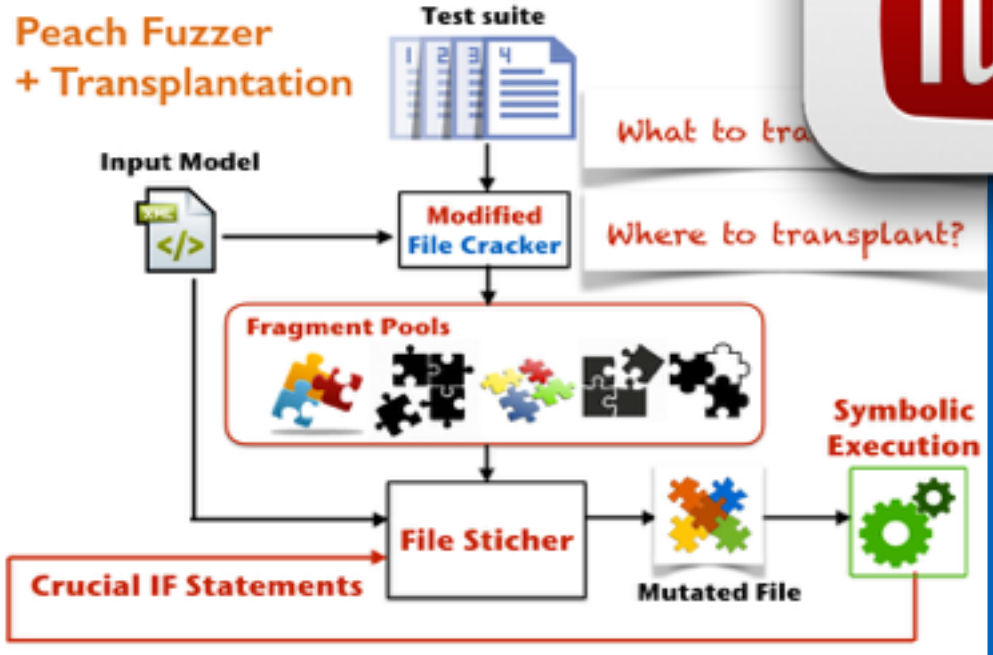


Data chunk Transplantation

Thuan Pham 11

Peach Fuzzer + Transplantation



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on - Effectiveness of MoWF

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