RUB

kAFL: Hardware-Assisted Feedback Fuzzing for OS Kernels

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Motivation

IJG jpeg libjpeg-turbo libpng libtiff mozjpeg PHP Mozilla Firefox Internet Explorer PCRE sqlite OpenSSL LibreOffice poppler freetype GnuTLS GnuPG PuTTY ntpd nginx bash tcpdump JavaScriptCore pdfium ffmpeg libmatroska libarchive ImageMagick BIND QEMU lcms Adobe Flash Oracle BerkeleyDB Android libstagefright iOS ImageIO FLAC audio library libsndfile less lesspipe strings file dpkg rcs systemd-resolved libyaml Info-Zip unzip libtasn1OpenBSD pfctl NetBSD bpf man mandocIDA Pro clamav libxml2glibc clang llvmnasm ctags mutt procmail fontconfig pdksh Qt wavpack OpenSSH redis lua-cmsgpack taglib privoxy perl libxmp radare2 SleuthKit fwknop X.Org exifprobe jhead capnproto Xerces-C metacam djvulibre exiv Linux btrfs Knot DNS curl wpa_supplicant Apple Safari libde265 dnsmasq libbpg lame libwmf uudecode MuPDF imlib2 libraw libbson libsass yara W3C tidy-html5 VLC FreeBSD syscons John the Ripper screen tmux mosh UPX indent openjpeg MMIX OpenMPT rxvt dhcpcd Mozilla NSS Nettle mbed TLS Linux netlink Linux ext4 Linux xfs botan expat Adobe Reader libav libical OpenBSD kernel collectd libidn MatrixSSL jasperMaraDNS w3m Xen OpenH232 irssi cmark OpenCV Malheur gstreamer Tor gdk-pixbuf audiofilezstd lz4 stb cJSON libpcre MySQL gnulib openexr libmad ettercap lrzip freetds Asterisk ytnefraptor mpg123 exempi libgmime pev v8 sed awk make m4 yacc PHP ImageMagick freedesktop.org patch libtasn1 libvorbis zsh lua ninja ruby busybox gcrypt vim Tor poppler libopus BSD sh gcc qemu w3m zsh dropbear wireshark libtorrent git rust gravity e2fsprogs parrot lodepng json-glib cabextract libmspack qprint gpsbabel dmg2img antiword arj unrar unace zoo rzip lrzip libiso libtta duktape splint zpaq assimp cppcheck fasm catdoc pngcrush cmark p7zip libjbig2 aaphoto t1utils apngopt sqlparser mdp libtinyxml freexl bgpparser testdisk photorec btcd gumbo chaiscript teseq colcrt pttbbs capstone dex2oat pillow elftoolchain aribas universal-ctags uriparser jq lha xdelta gnuplot libwpd teseq cimg libiberty policycoreutils libsemanage renoise metapixel openclone mp3splt podofo Apache httpd glslang UEFITool libcbor lldpd pngquant muparserx mochilo pyhocon sysdig Overpass-API fish-shell gumbo-parser mapbox-gl-native rapidjson libjson FLIF MultiMarkdown astyle pax-utils zziplib PyPDF spiffing apk pgpdump icoutils msitools dosfstools

Motivation

Internet Explorer

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Adobe Flash

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OpenSSH

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freetype Gn[illegible] bash tcpdump JavaScriptCore pdfium [illegible]mpeg libmatroska libarchive ImageMagick
BIND QEMU [illegible]leyDB Android libstagefright iOS ImageIO FLAC audio library libsndfile less lesspipe
strings file dpkg rcs systemd-resolved libyaml Info-Zip unzip libtasn1OpenBSD pfctl NetBSD bpf man mandocIDA Pro clamav
libxml2glibc clang llvmnasm ctags mutt procmail fontconfig pdksh Qt wavp[illegible]a-cmsgpack taglib privoxy perl
libxmp radare2 SleuthKit fwknop X.Org exifprobe jhead capnproto Xerces-C metacam djvulibre exiv Linux btrfs Knot DNS curl
wpa_supplicant Apple Safari libde265 dnsmasq libbpg lame libwmf uudecode MuPDF imlib2 libraw libbson libsass yara W3C tidy-html5 VLC FreeBSD syscons John the Ripper screen tmux mosh UPX indent openjpeg MMIX OpenMPT rxvt dhcpcd Mozilla NSS
Nettle mbed TLS Linux netlink Linux ext4 Linux xfs botan expat Adobe Reader libav libical OpenBSD kernel collectd libidn
MatrixSSL jasperMaraDNS w3m Xen OpenH232 irssi cmark OpenCV Malheur gstreamer Tor gdk-pixbuf audiofilezstd lz4 stb cJSON
libpcre MySQL gnulib openexr libmad ettercap lrzip freetds Asterisk ytnefraptor mpg123 exempi libgmime pev v8 sed awk make
m4 yacc PHP ImageMagick freedesktop.org patch libtasn1 libvorbis zsh lua ninja ruby busybox gcrypt vim Tor poppler libopus
BSD sh gcc qemu w3m zsh dropbear wireshark libtorrent git rust gravity e2fsprogs parrot lodepng json-glib cabextract libmspack
qprint gpsbabel dmg2img antiword arj unrar unace zoo rzip lrzip libiso libtta duktape splint zpaq assimp cppcheck fasm catdoc
pngcrush cmark p7zip libjbig2 aaphoto t1utils apngopt sqlparser mdp libtinyxml freexl bgpparser testdisk photorec btcd gumbo
chaiscript teseq colcrt pttbbs capstone dex2oat pillow elftoolchain aribas universal-ctags uriparser jq lha xdelta gnuplot libwpd
teseq cimg libiberty policycoreutils libsemanage renoise metapixel openclone mp3splt podofo Apache httpd glslang UEFITool
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Motivation

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Adobe Flash

OpenSSH

Apple Safari

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Adobe Reader

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OpenSSH

Apple Safari

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Wireshark

Motivation

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Adobe Flash

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Apple Safari

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Wireshark

Apache httpd

Motivation

Stephens, Nick, et al. "Driller: Augmenting Fuzzing Through Selective Symbolic Execution." Proceedings of the Network and Distributed System Security Symposium (NDSS). 2016.

Böhme, Marcel, et al. "Coverage-based greybox fuzzing as markov chain." Proceedings of the 2016 ACM SIGSAC Conference on Computer and Communications Security. ACM. 2016.

Rawat, Sanjay, et al. "Vuzzer: Application-aware evolutionary fuzzing.“ Proceedings of the Network and Distributed System Security Symposium (NDSS). 2017.

Motivation

What about Kernel Security?

Related Work

	Fast	Crash Tolerant	OS Independent	Binary Only

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TriforceAFL (Jesse Hertz & Tim Newsham, NCC Group)	✗	✓	~	✓

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Related Work

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TriforceAFL (Jesse Hertz & Tim Newsham, NCC Group)	✗	✓	~	✓
Syzkaller (Dmitry Vyukov)	✓	✓	✗	✗
AFL Filesystem Fuzzer (Vegard Nossum & Quentin Casanovas, Oracle)	✓	~	✗	✗

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AFL Filesystem Fuzzer (Vegard Nossum & Quentin Casanovas, Oracle)	✓	~	✗	✗
PT Kernel Fuzzer (Richard Johnson, Talos)	✓	✗	✗	✓

Goal

Build a **kernel** fuzzer that is all of this:

- Fast
- Reliable
- (mostly) OS independent
- No source level access required

Fuzzing in a nutshell

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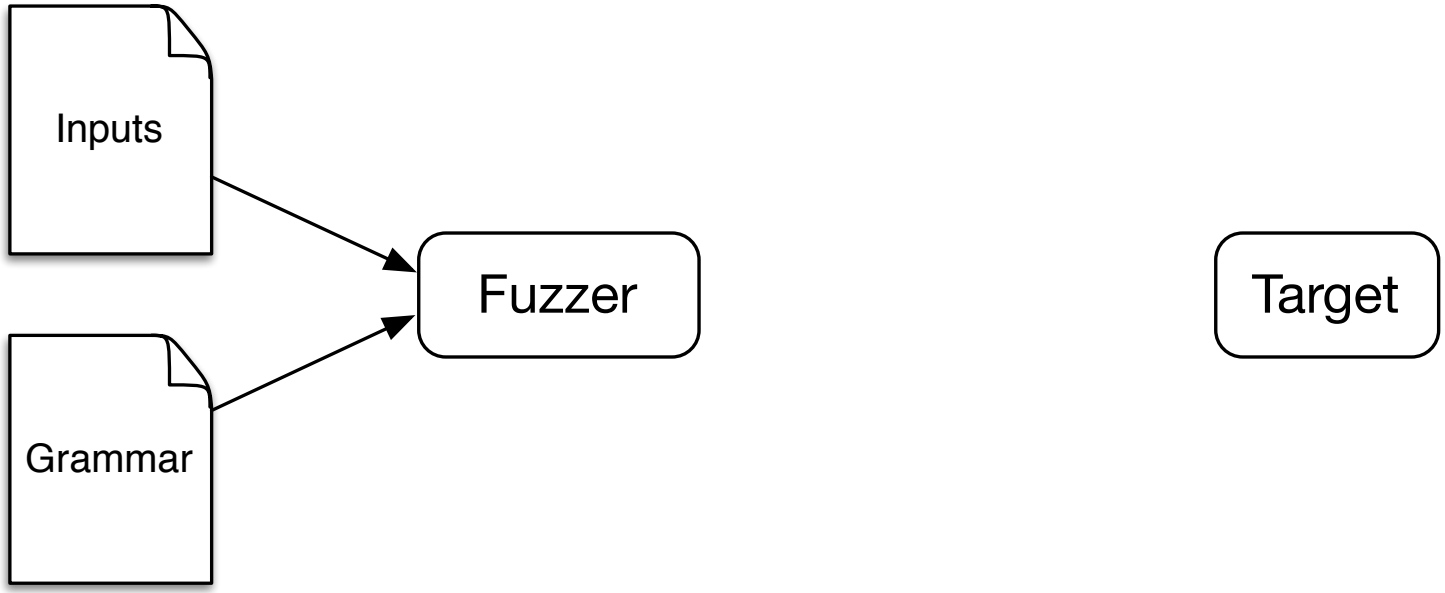

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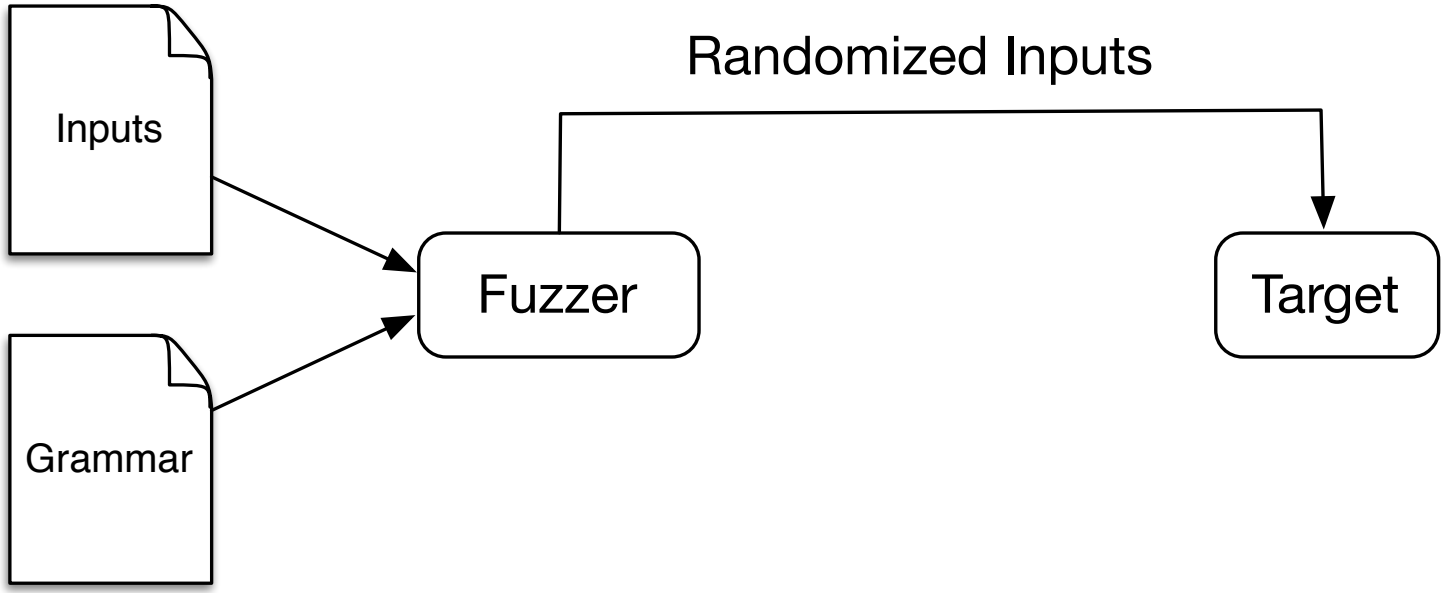

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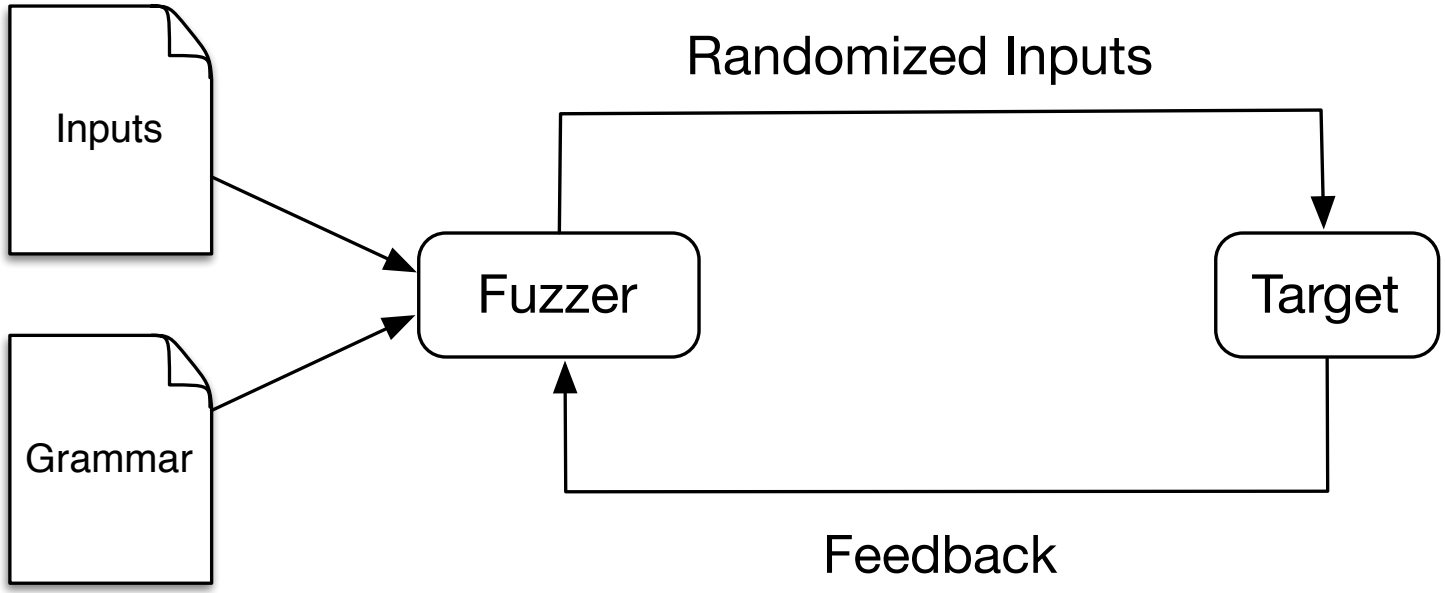
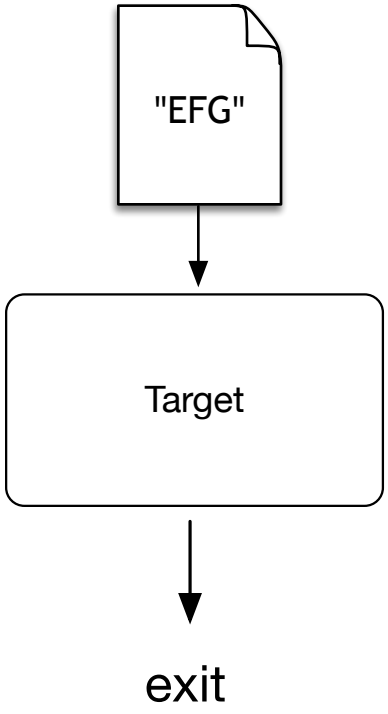


Blackbox Fuzzing



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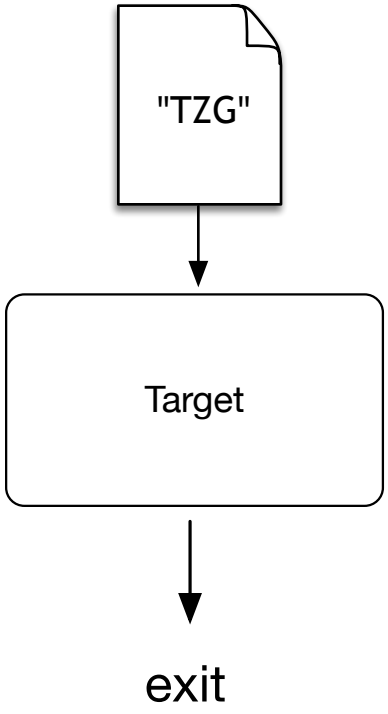

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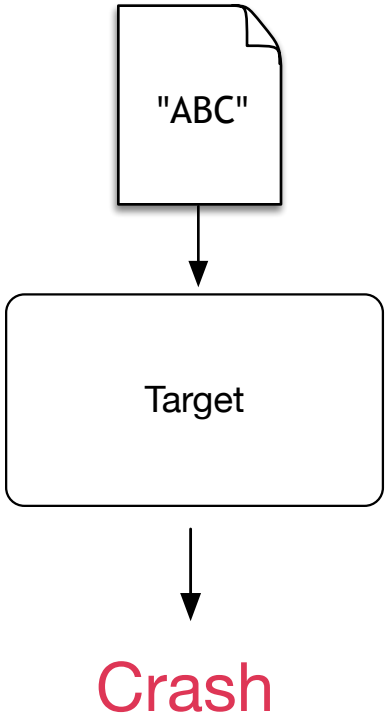

Coverage-Guided Fuzzing

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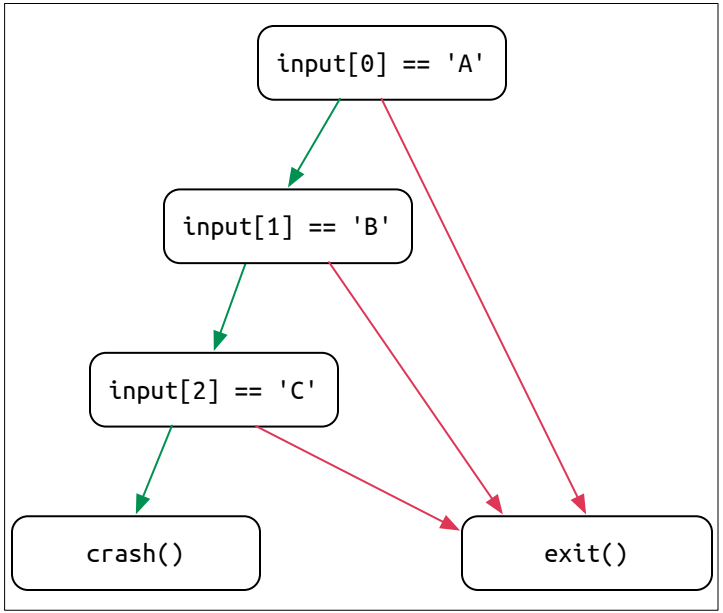

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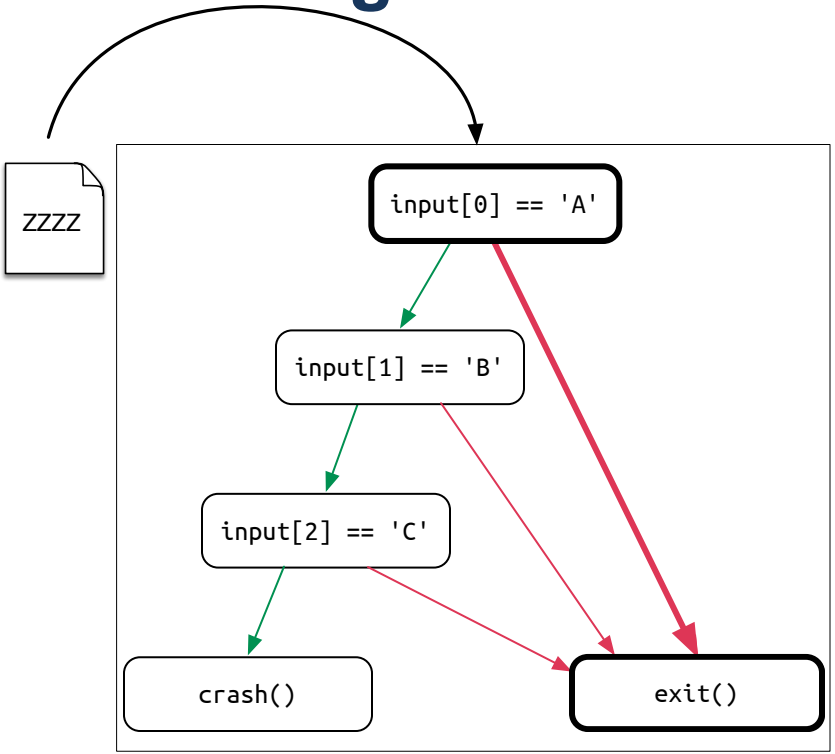

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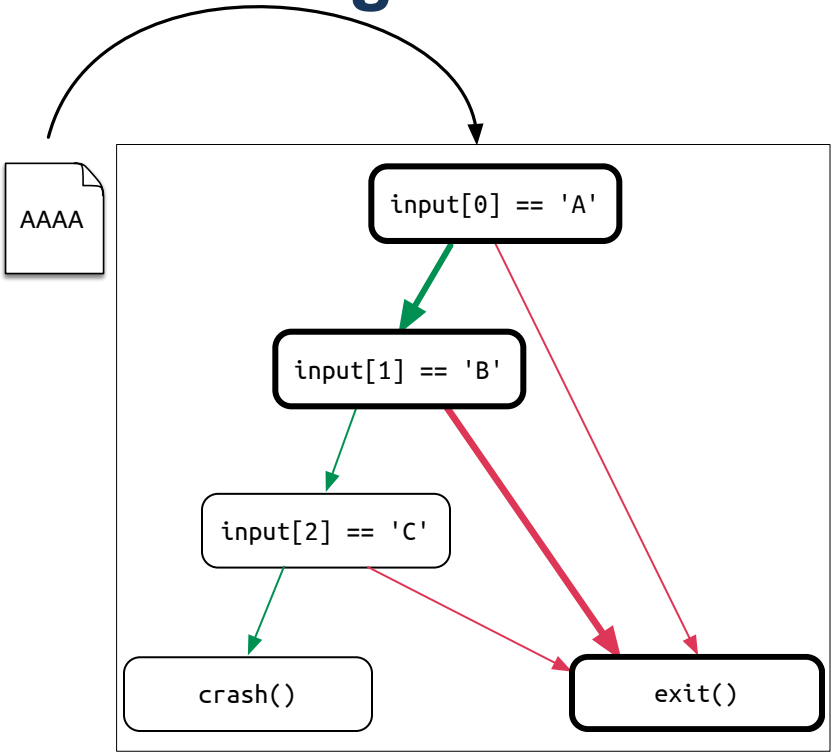

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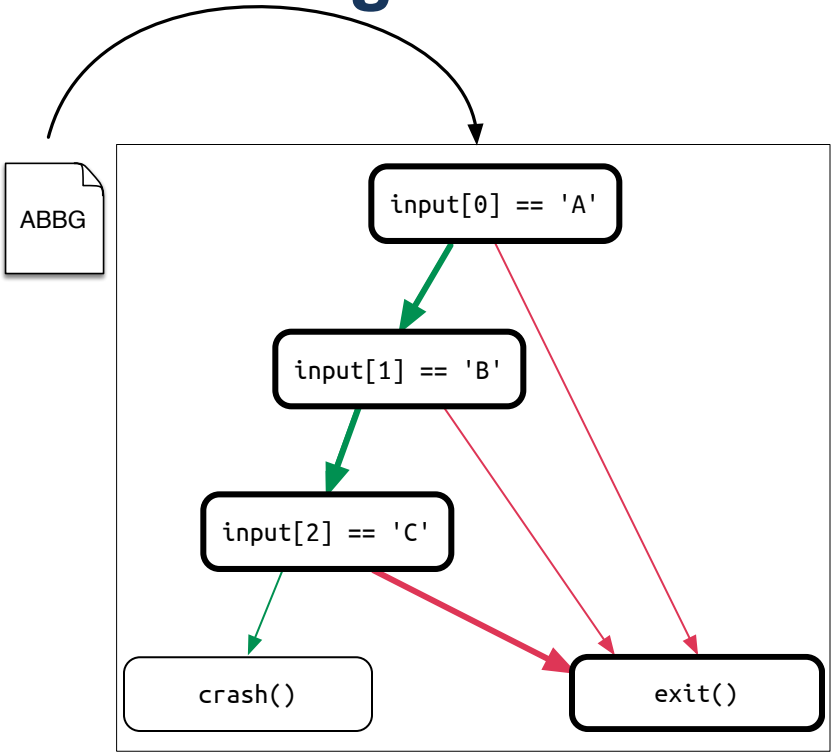

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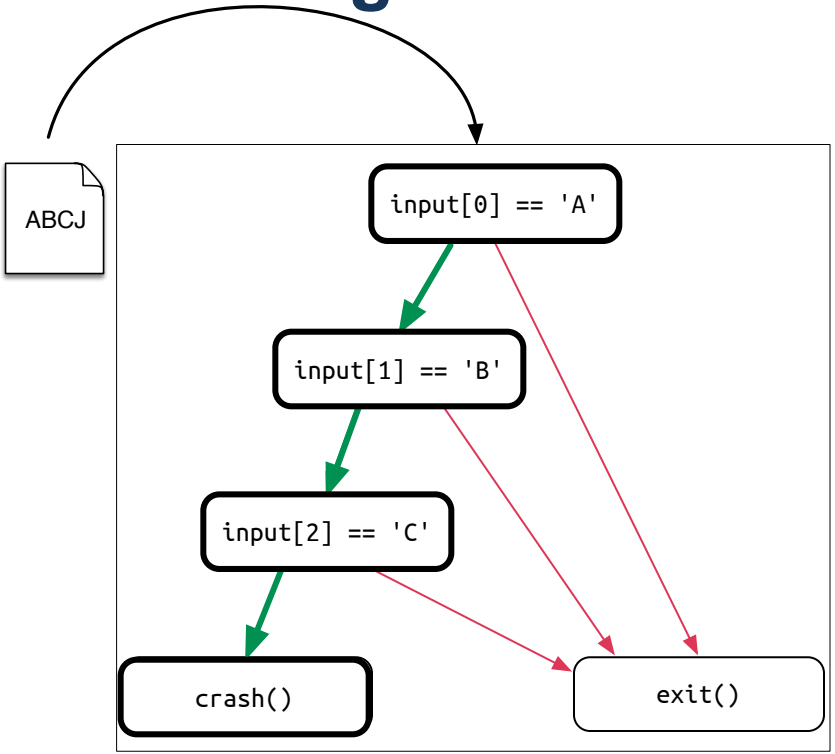

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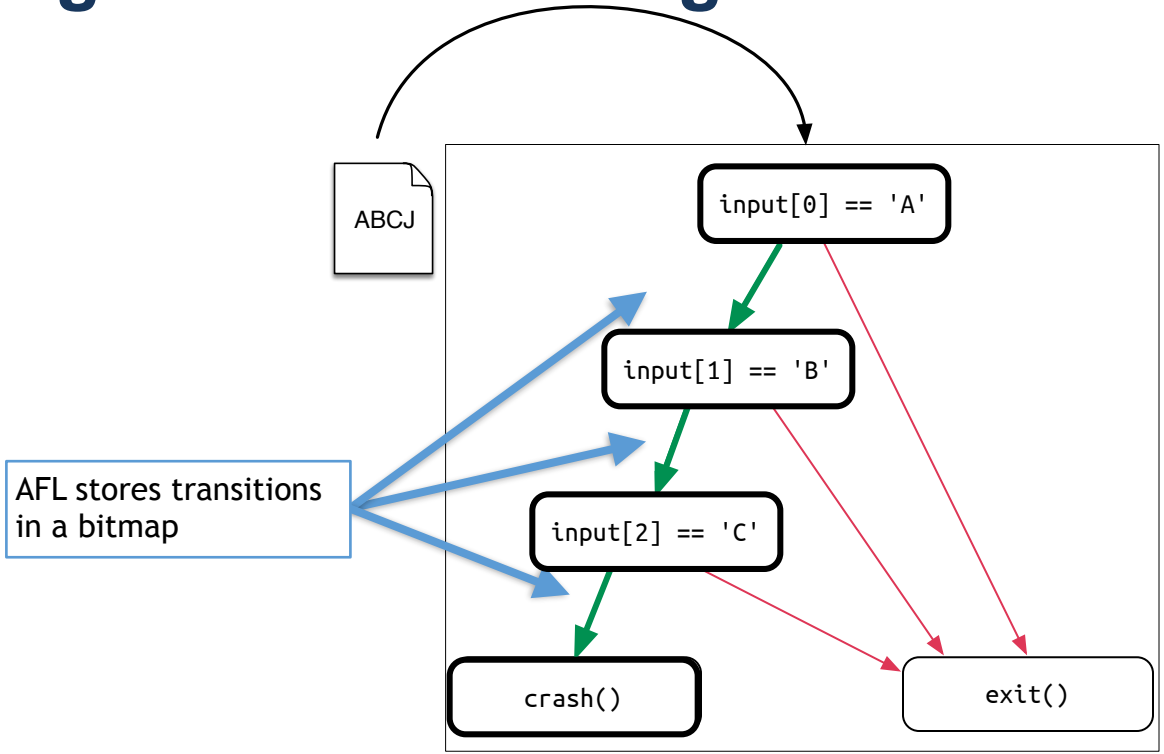

Feedback Mechanism

	Closed-Source	Kernel	Stable	Fast

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* Peter Feiner, et al., DRK: DynamoRIO as a Linux Kernel Module

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Intel Branch Trace Store	✓	✓	✓	+

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Intel Branch Trace Store	✓	✓	✓	+
Intel Processor Trace	✓	✓	✓	+++

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Intel Processor Trace

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`jnz loc_a`	Taken / Not Taken
`jmp/call [eax]`	Target IP
`ret`	Target IP (if required)

Intel Processor Trace

Intel PT Data

```
Not Taken
Target IP (0x1009)
Target IP (0x1055)
```

Intel Processor Trace

Intel PT Data

```
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Target IP (0x1009)
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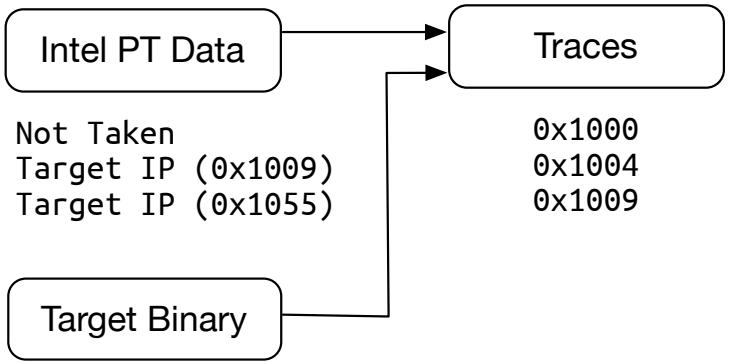
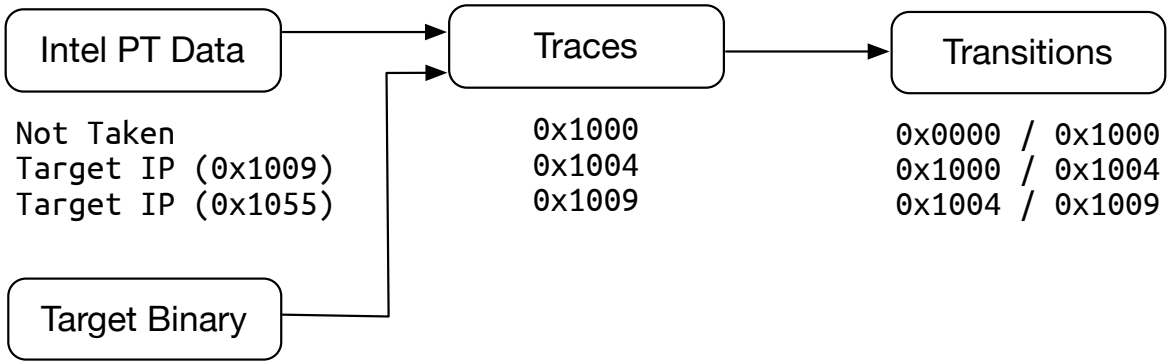
```

Target Binary

Intel Processor Trace



Intel Processor Trace



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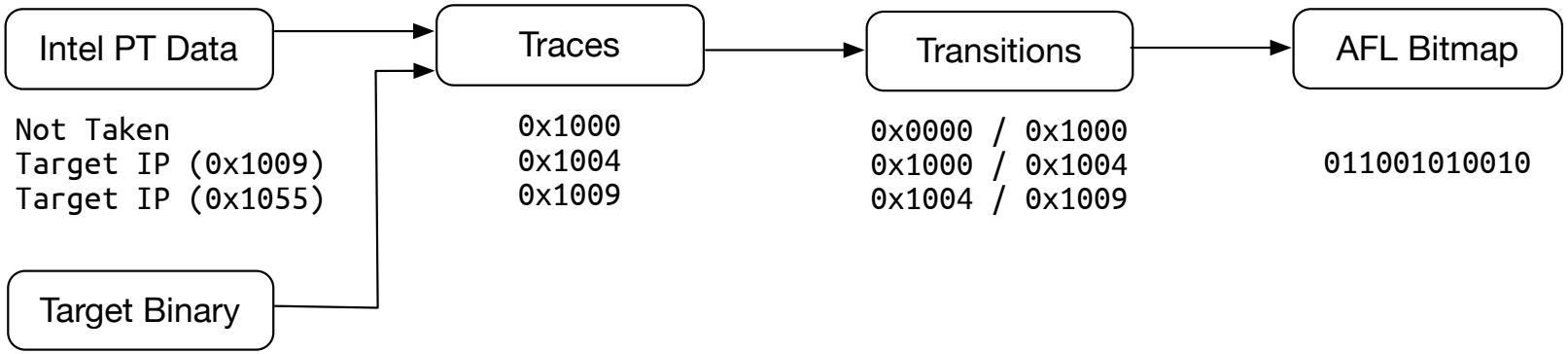

Architecture

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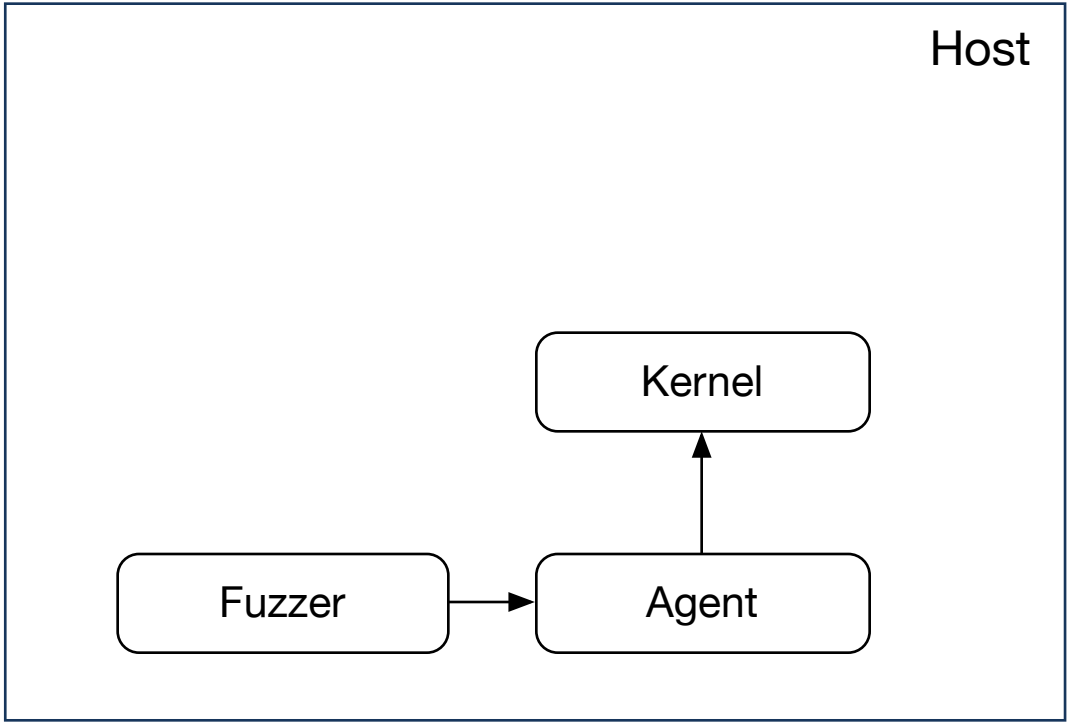
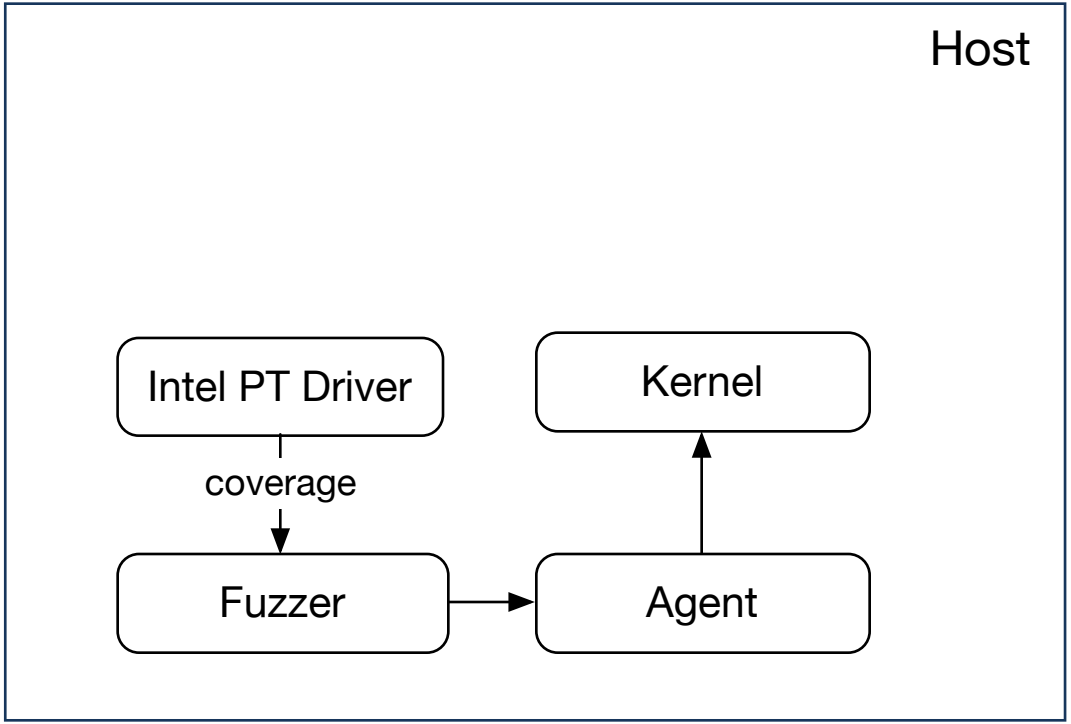


Architecture

Benefits:

✓Coverage



Architecture

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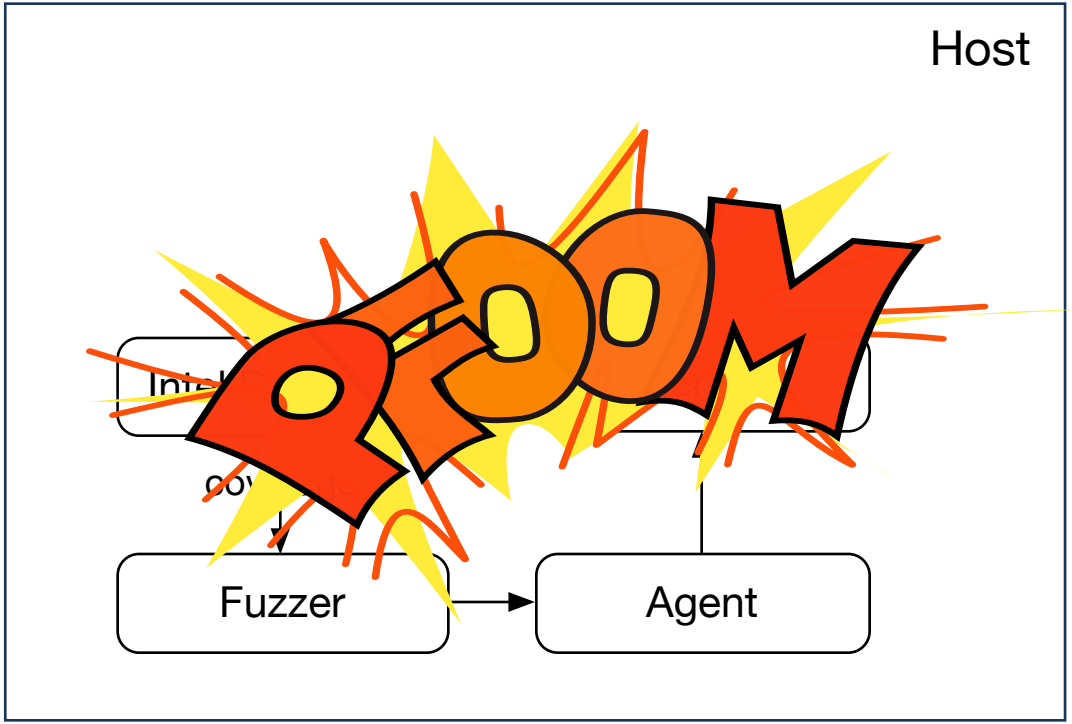

Architecture

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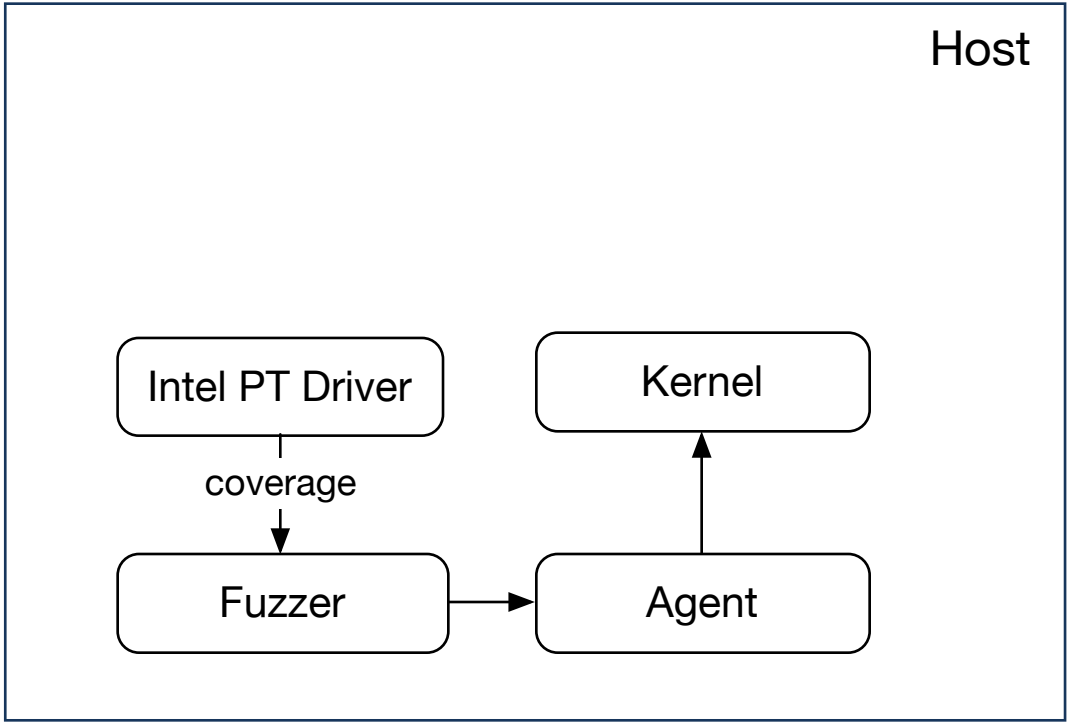
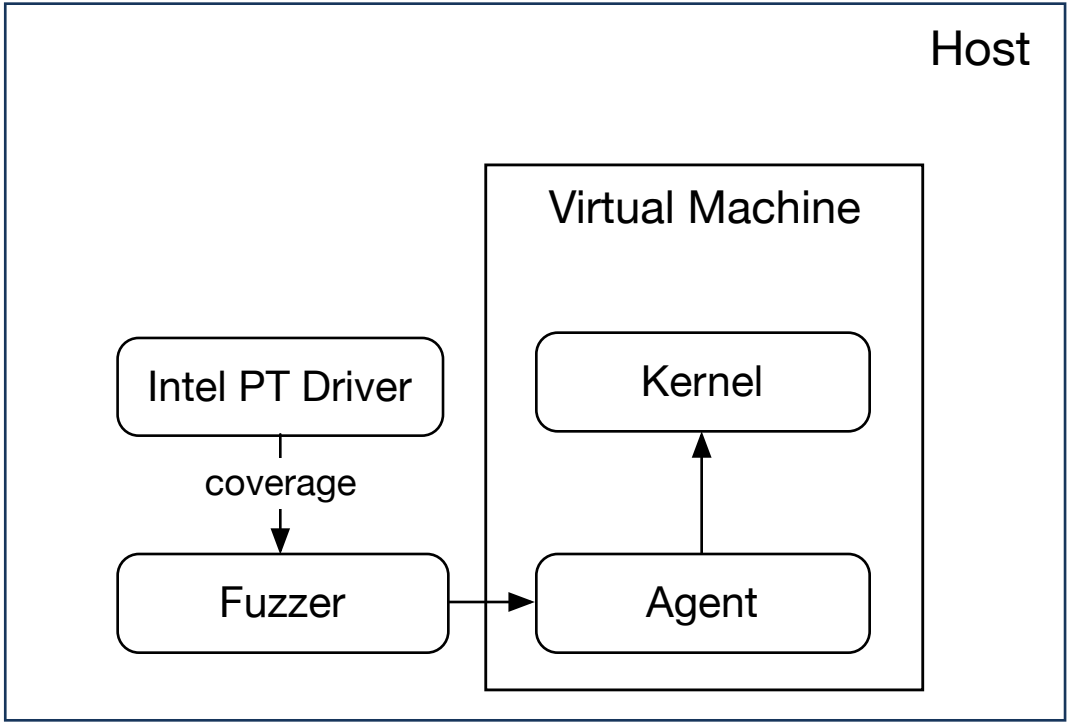


Architecture

Benefits:

✓Coverage

✓Crash Tolerance



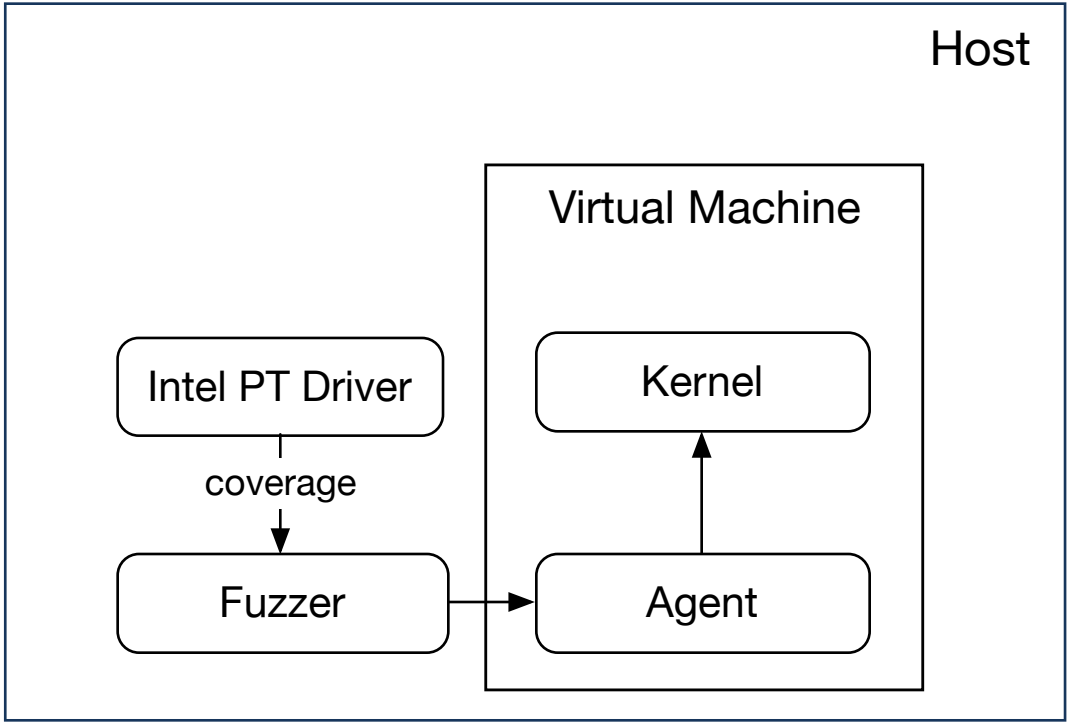
Architecture

Benefits:

✓Coverage

✓Crash Tolerance

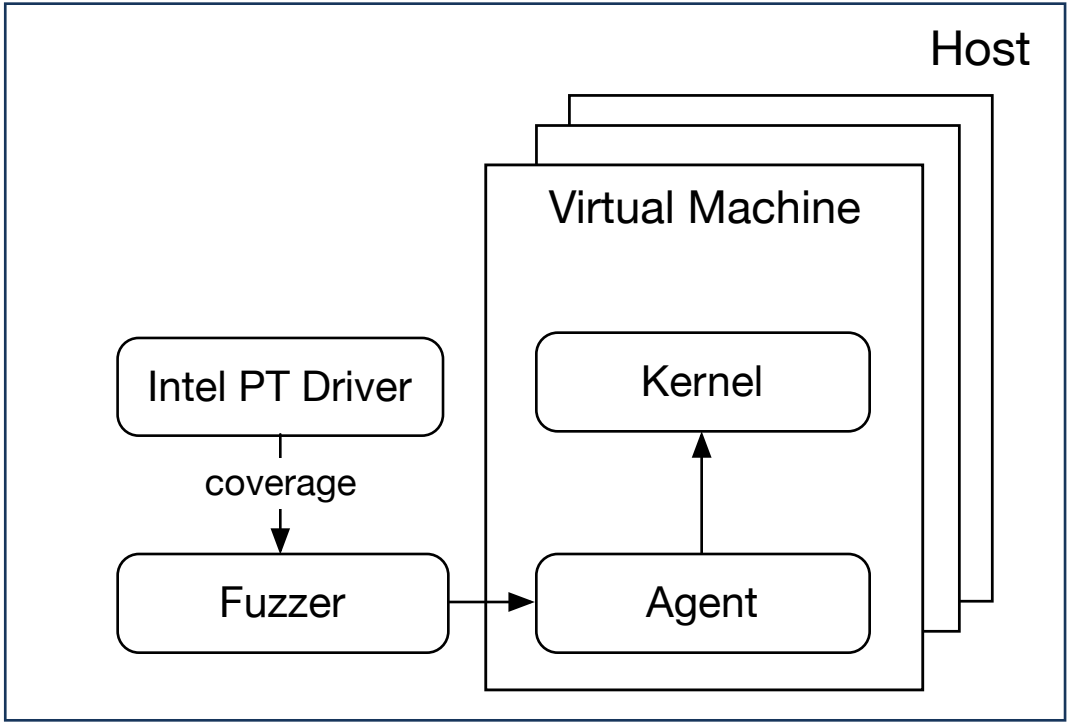
✓OS Independence



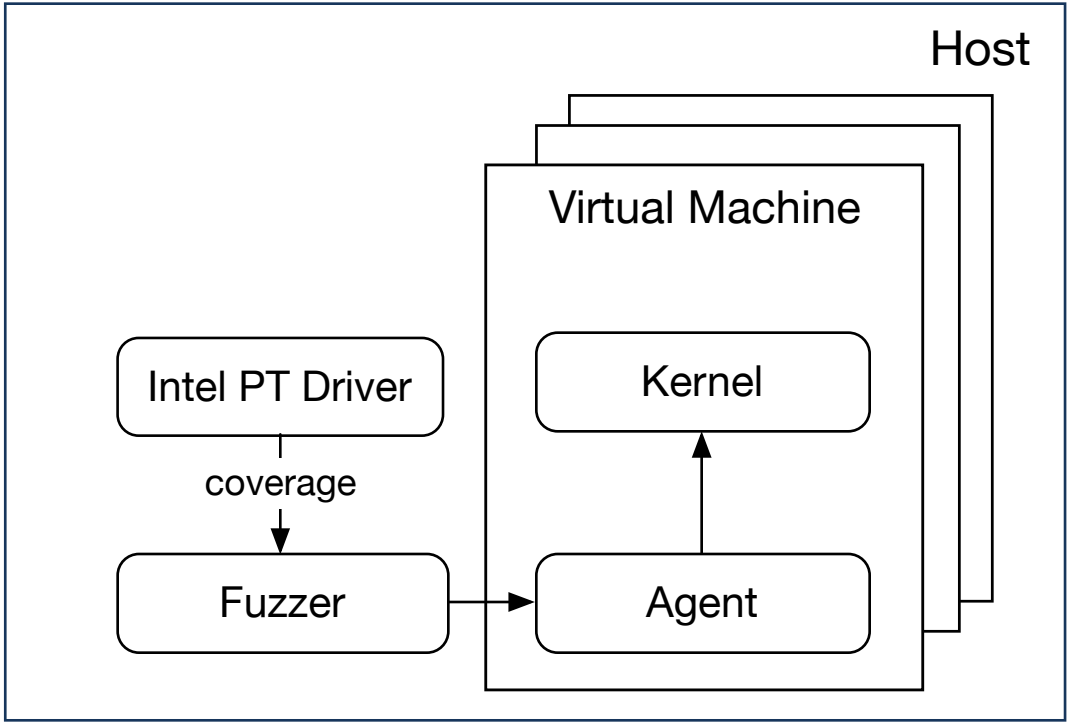
Architecture

Benefits:

- ✓Coverage
- ✓Crash Tolerance
- ✓OS Independence
- ✓Scalable

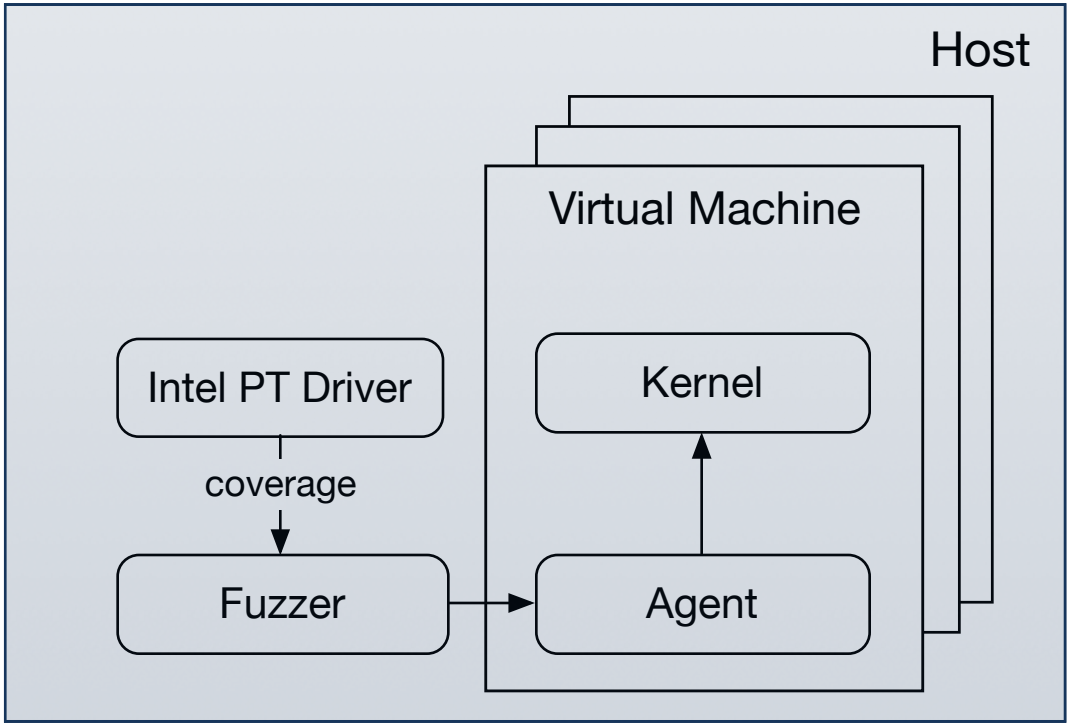


Trace Filtering



Trace Filtering

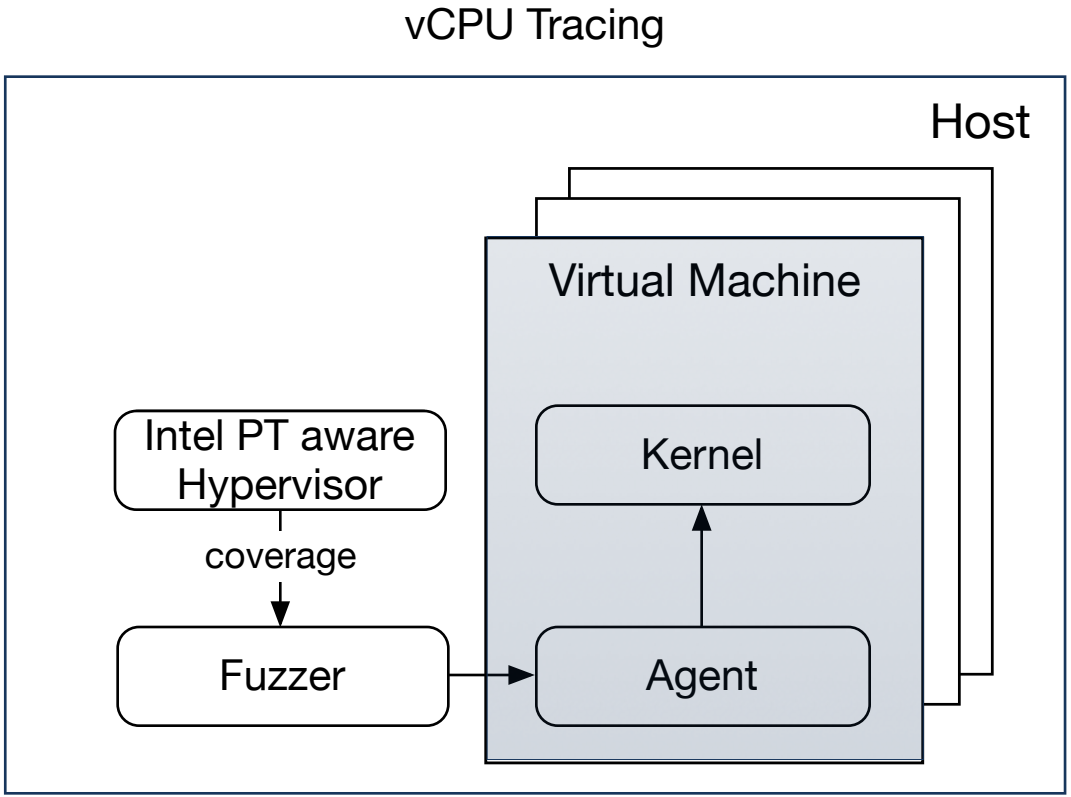
Full System Tracing



Trace Filtering

Filter-Mechanisms:

✓ vCPU

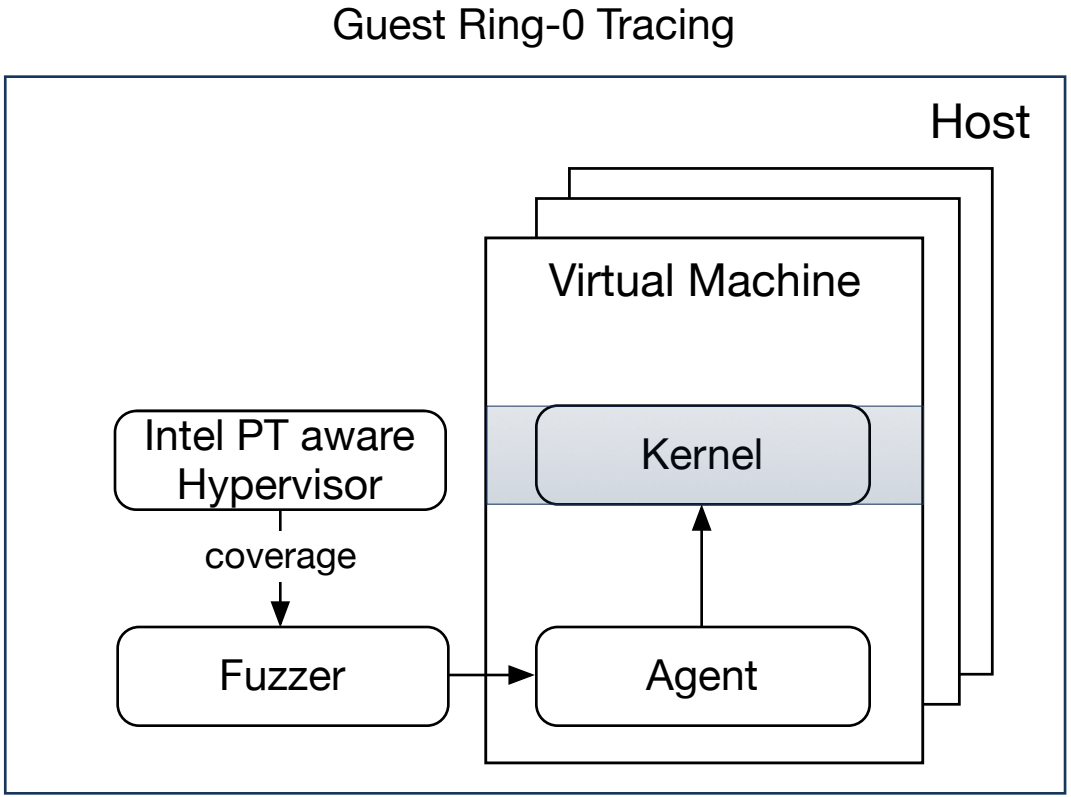


Trace Filtering

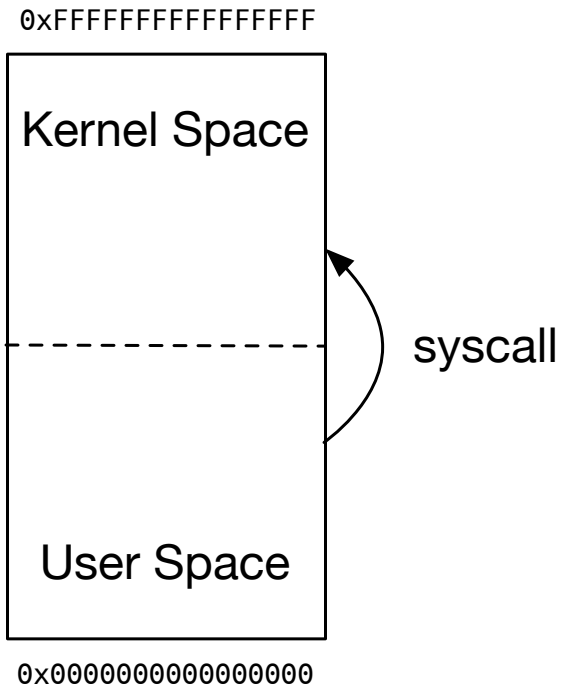
Filter-Mechanisms:

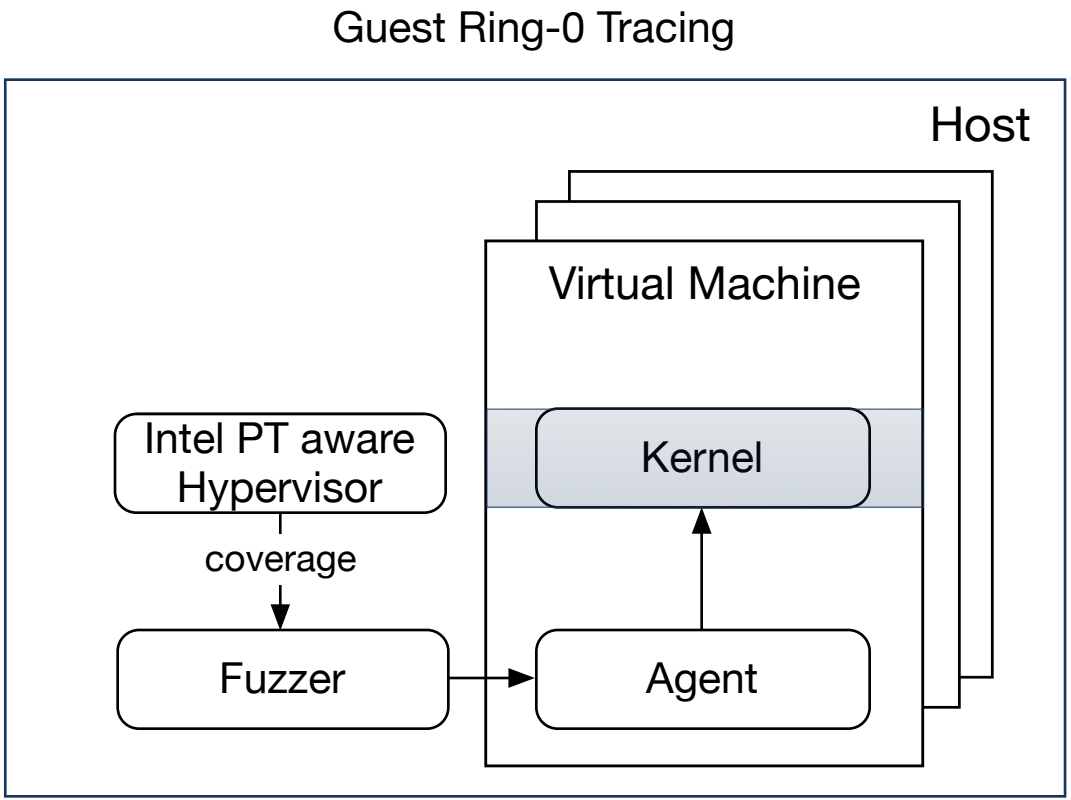
✓ vCPU

✓ Supervisor



Trace Filtering

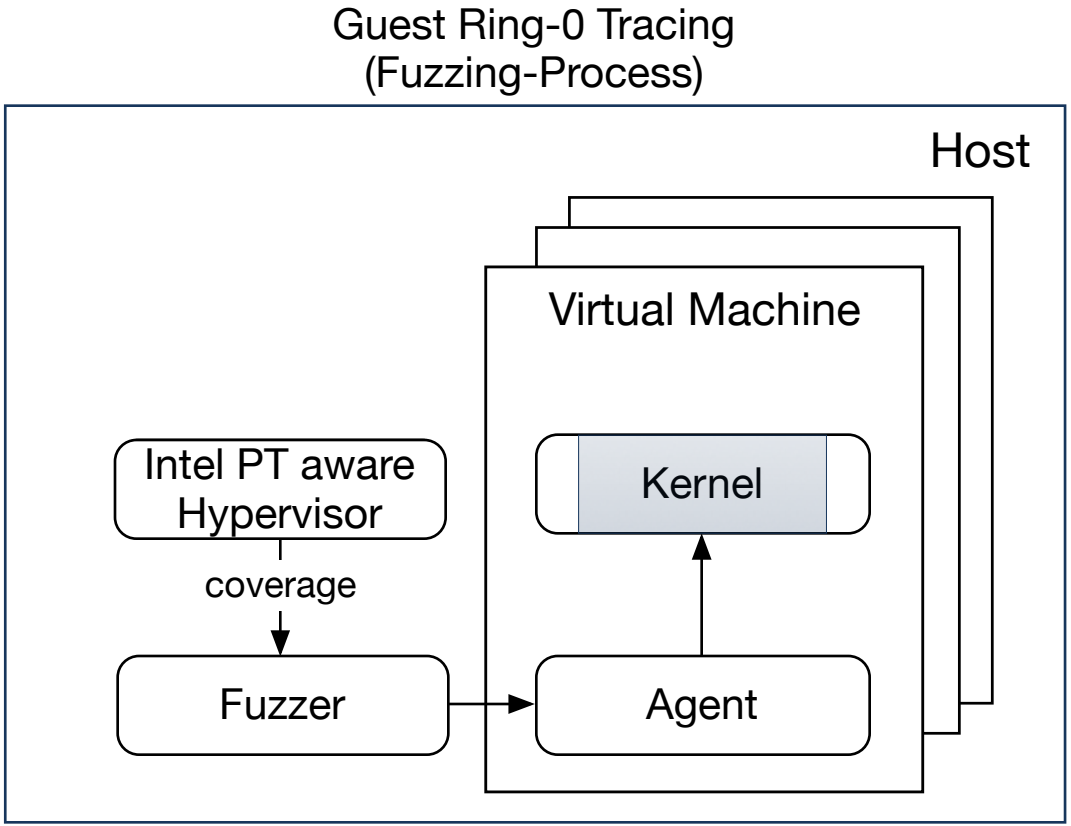




Trace Filtering

Filter-Mechanisms:

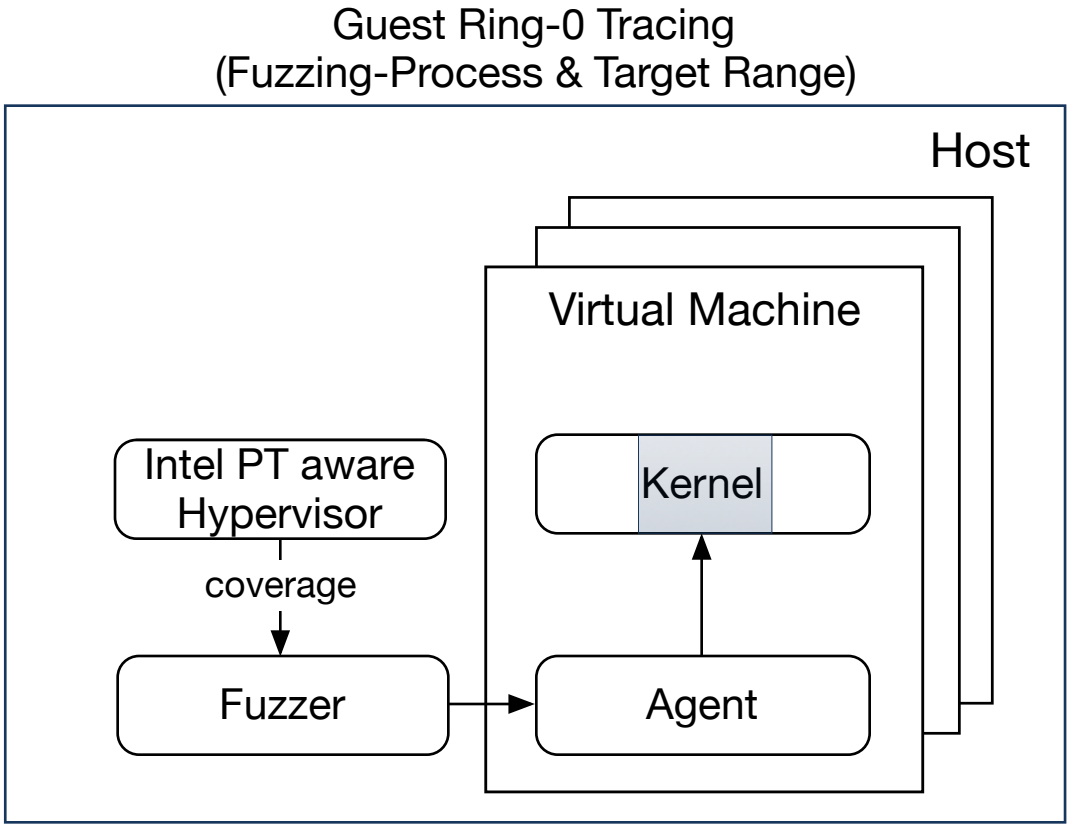
- ✓ vCPU
- ✓ Supervisor
- ✓ CR3



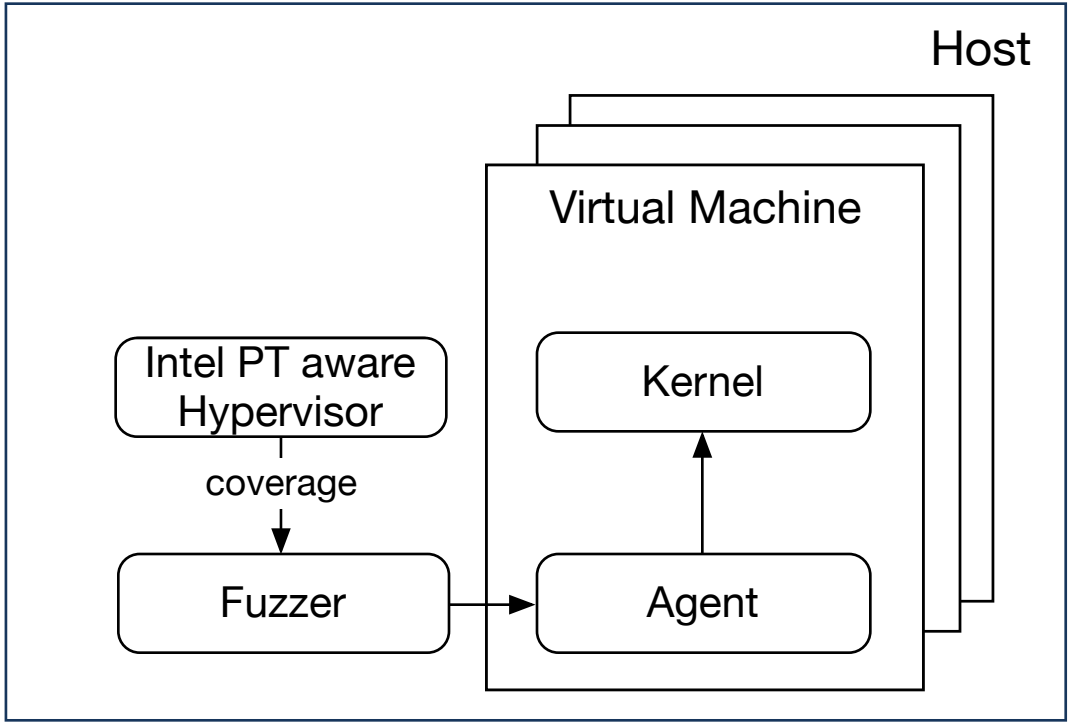
Trace Filtering

Filter-Mechanisms:

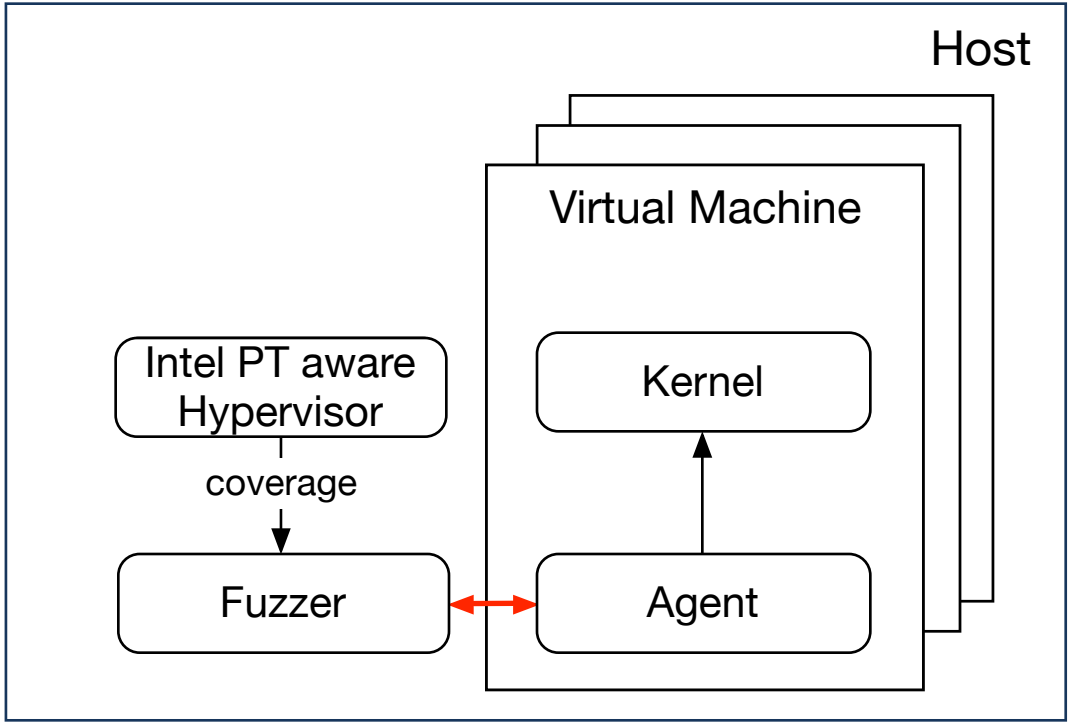
- ✓ vCPU
- ✓ Supervisor
- ✓ CR3
- ✓ IP-Range



Inter-VM Communication

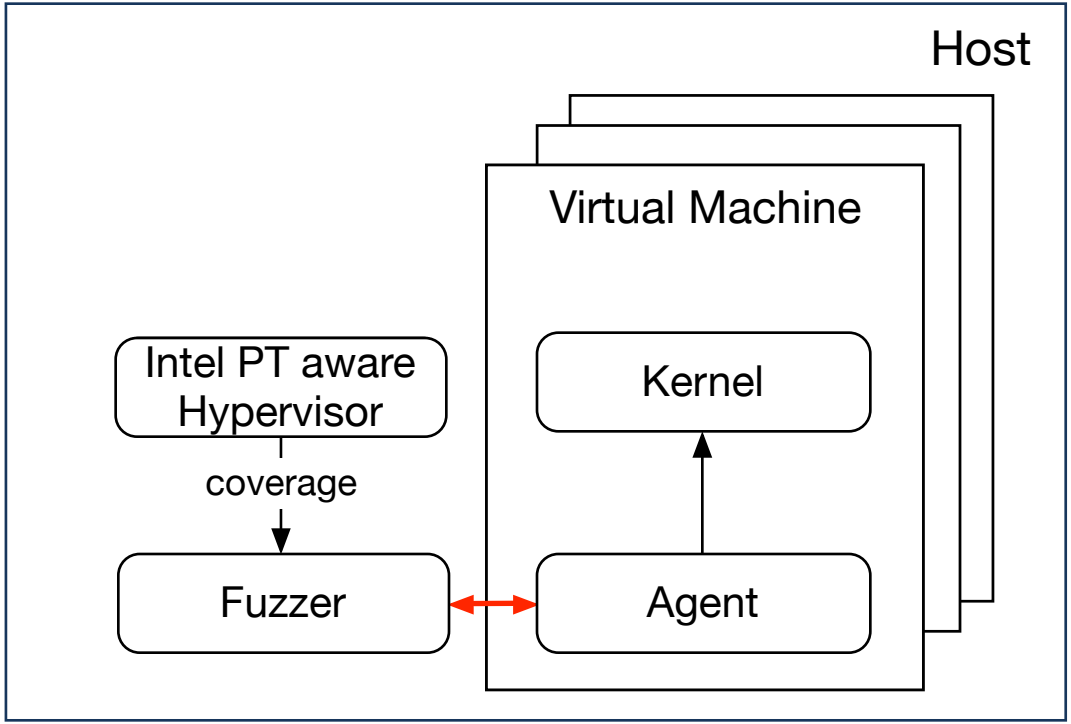


Inter-VM Communication



Inter-VM Communication

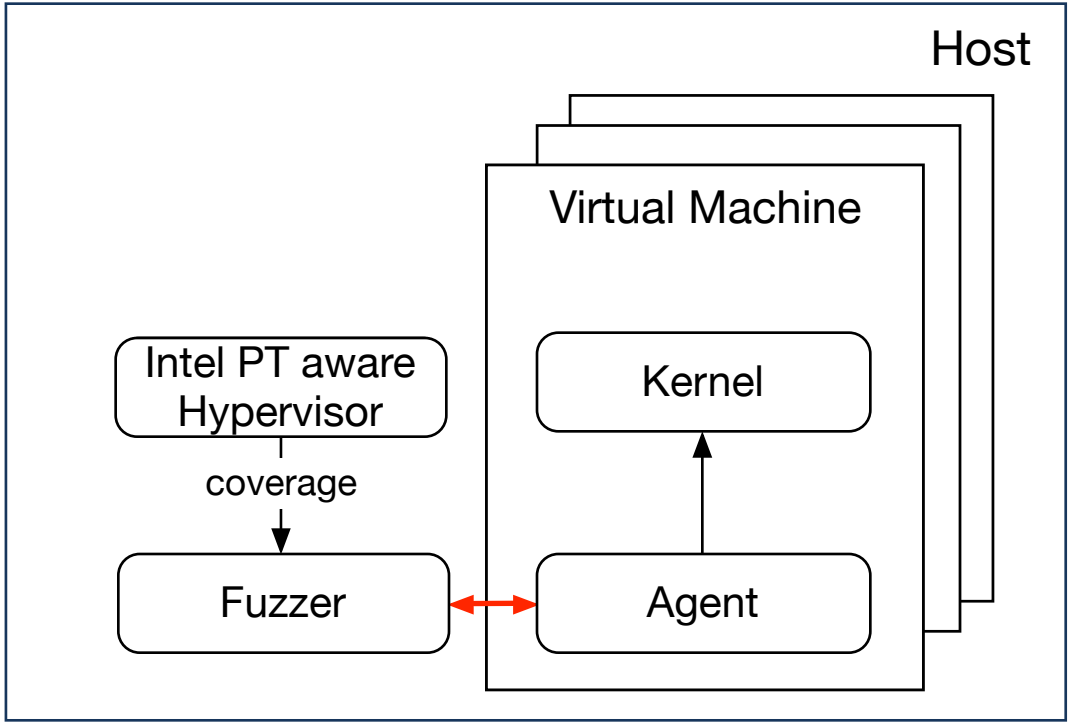
Guest to Host:



Inter-VM Communication

Guest to Host:

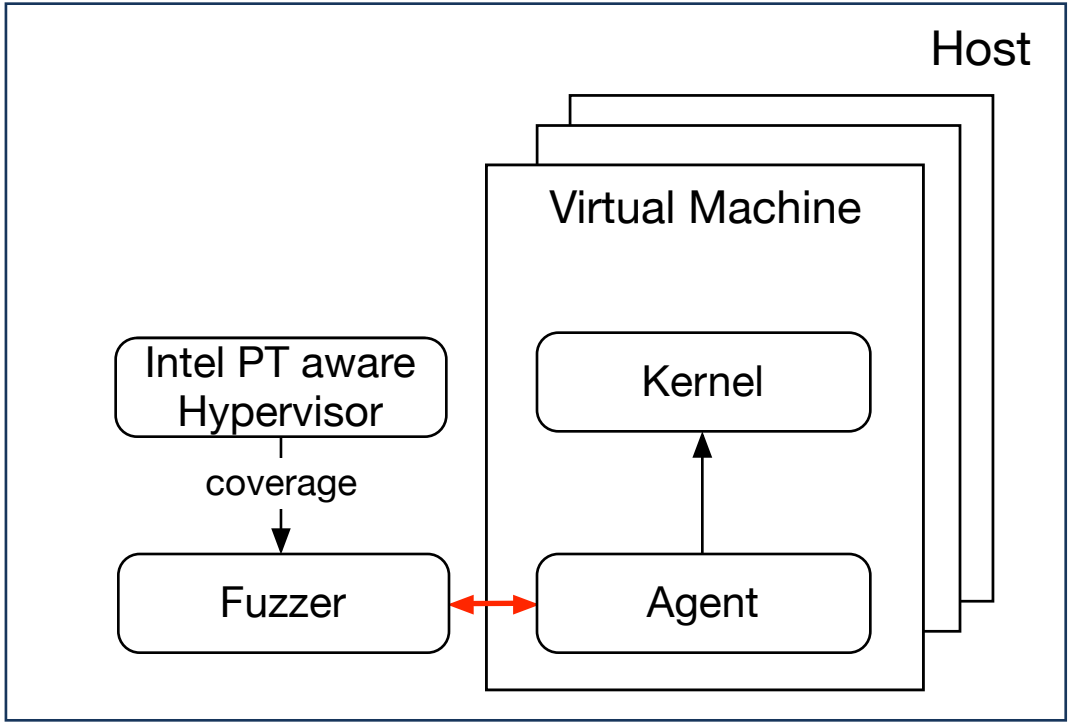
- Synchronization



Inter-VM Communication

Guest to Host:

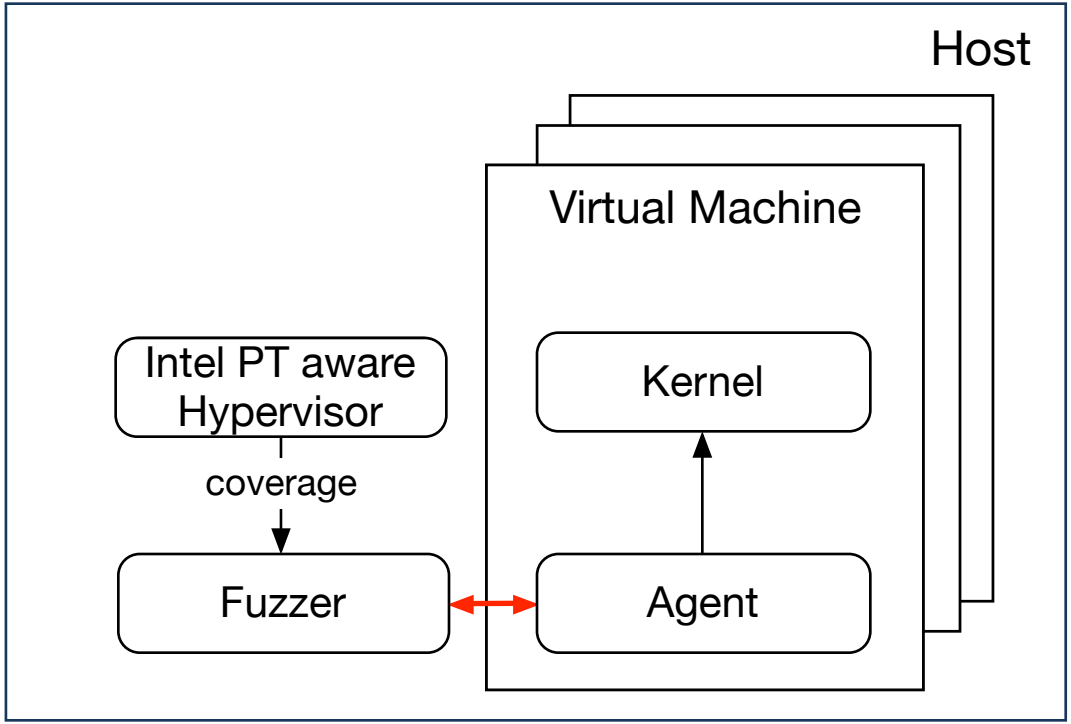
- Synchronization
- Next payload



Inter-VM Communication

Guest to Host:

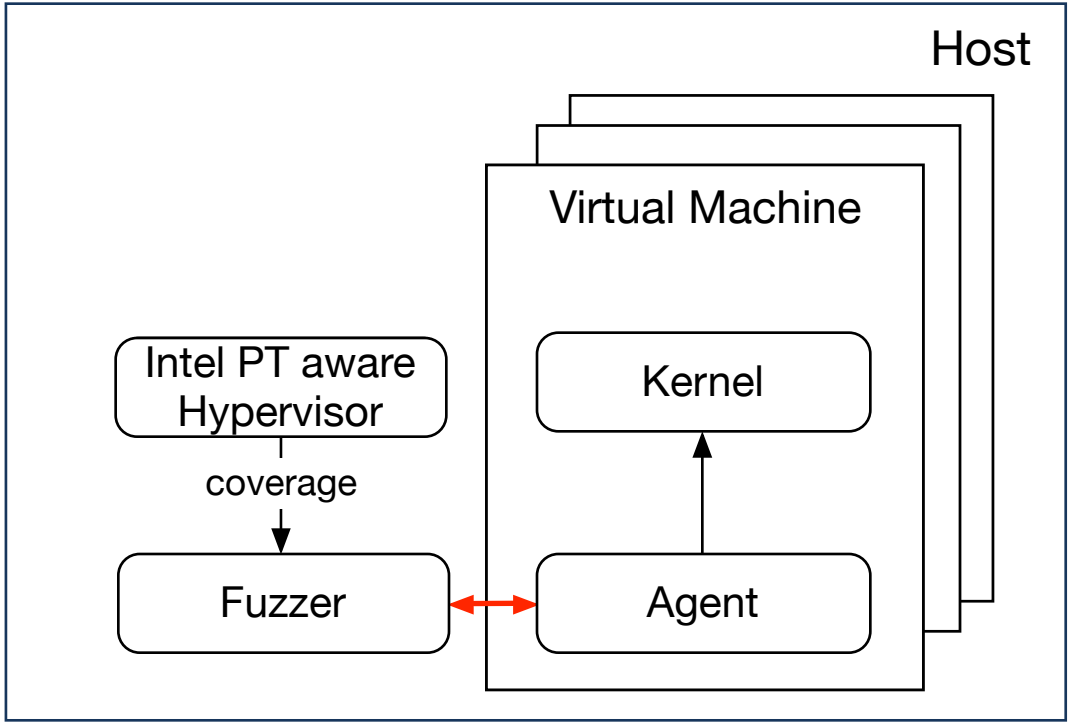
- Synchronization
- Next payload
- Disclose CR3 value



Inter-VM Communication

Guest to Host:

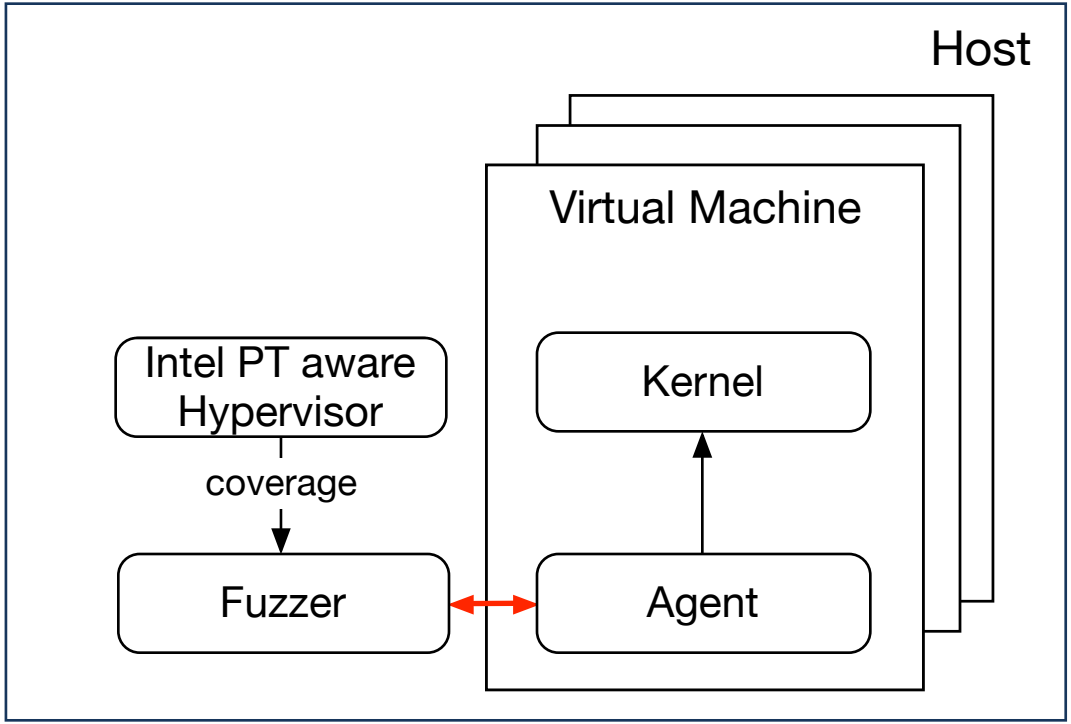
- Synchronization
- Next payload
- Disclose CR3 value
- Panic handler address



Inter-VM Communication

Guest to Host:

- Synchronization
- Next payload
- Disclose CR3 value
- Panic handler address
- Signal kernel panic

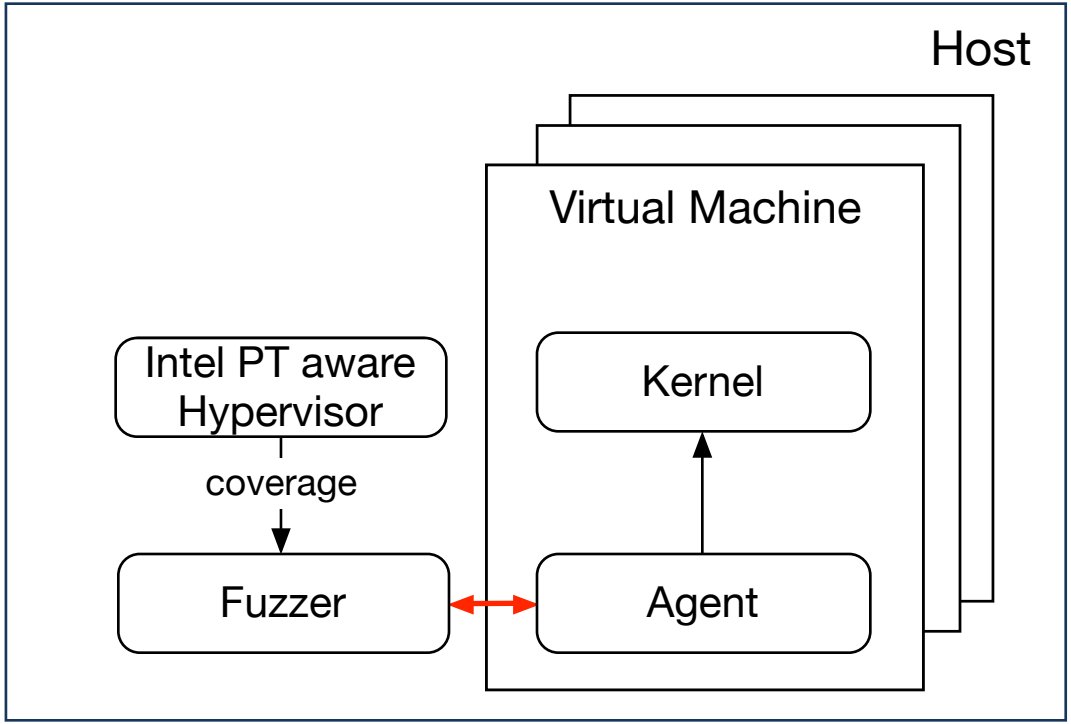


Inter-VM Communication

Guest to Host:

- Synchronization
- Next payload
- Disclose CR3 value
- Panic handler address
- Signal kernel panic

Host to Guest:



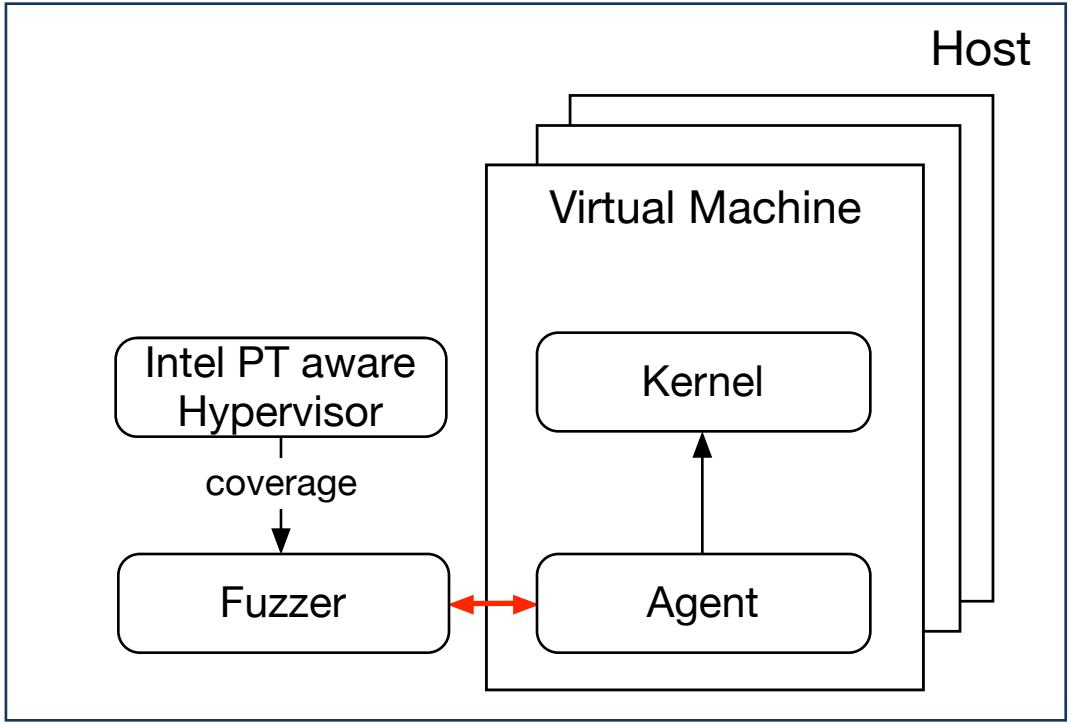
Inter-VM Communication

Guest to Host:

- Synchronization
- Next payload
- Disclose CR3 value
- Panic handler address
- Signal kernel panic

Host to Guest:

- Agent



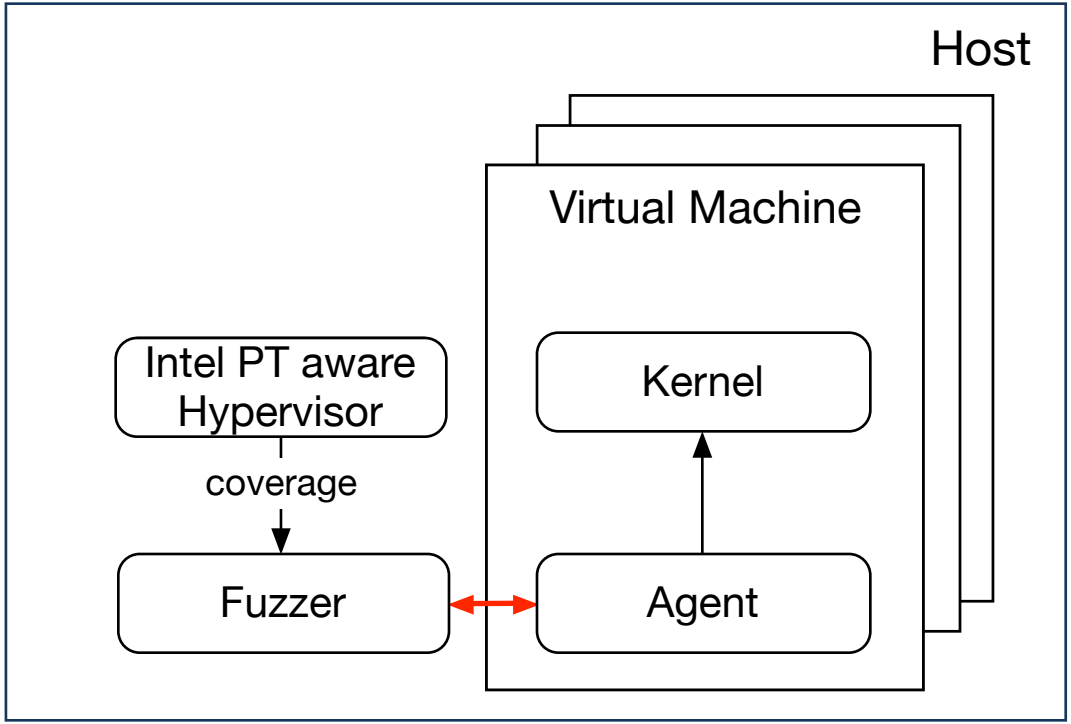
Inter-VM Communication

Guest to Host:

- Synchronization
- Next payload
- Disclose CR3 value
- Panic handler address
- Signal kernel panic

Host to Guest:

- Agent
- Payloads



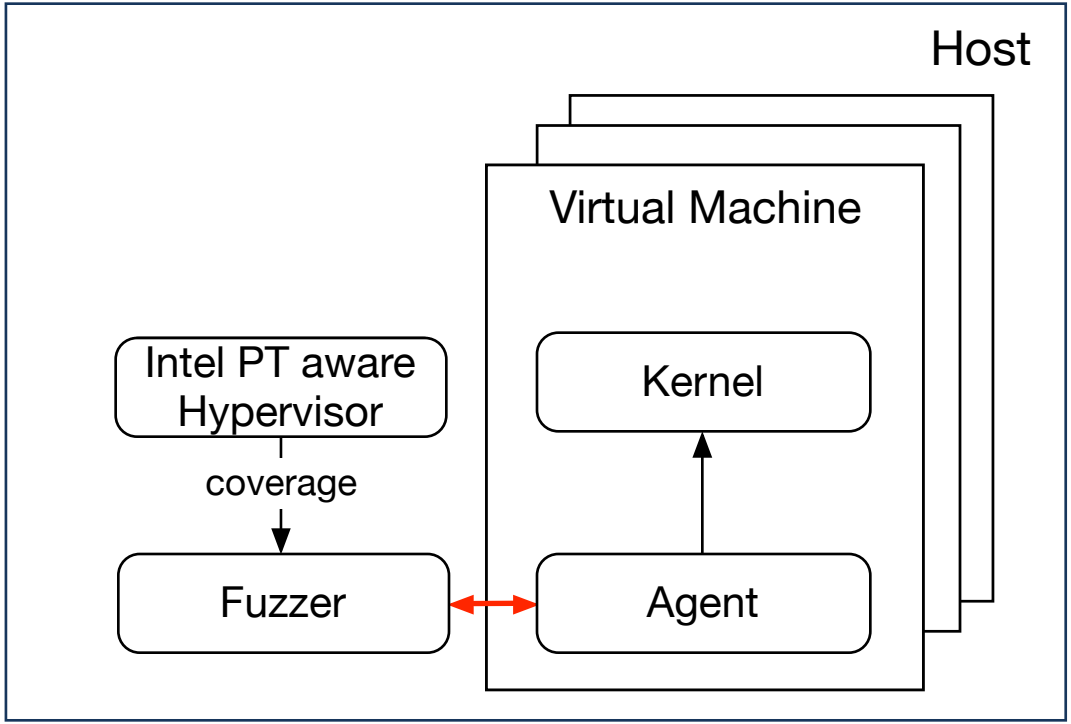
Inter-VM Communication

Guest to Host:

- Synchronization
- Next payload
- Disclose CR3 value
- Panic handler address
- Signal kernel panic

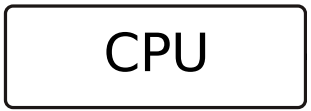
Host to Guest:

- Agent
- Payloads
- Overwrite panic handler



Implementation

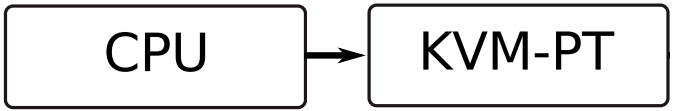
Implementation



CPU:

- generates raw Intel-PT data
- writes data to main memory

Implementation



KVM-PT:

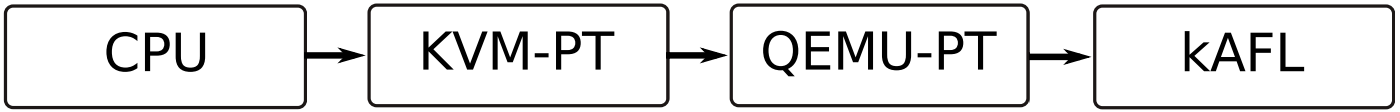
- configures Intel PT via MSRs
- enables tracing during VM-Entry transition
- disables tracing during VM-Exit transition

Implementation

QEMU-PT:

- usermode counterpart
- decodes Intel PT data on-the-fly

Implementation



kAFL Fuzzer:

- generates new fuzz payloads
- detects new behavior

Evaluation

New Vulnerabilities

Windows:

- NTFS (DoS)

macOS:

- HFS (DoS, Memory Corruption)
- APFS (Memory Corruption)

Linux:

- EXT4 (DoS, Memory Corruption)
- Keyctl (Nullpointer Dereference)

Evaluation Driver

```
1  jsmn_parser parser;
2  jsmntok_t tokens[5];
3  jsmn_init(&parser);
4
5  int res=jsmn_parse(&parser, input, size, tokens, 5);
6  if(res >= 2){
7      if(tokens[0].type == JSMN_STRING){
8          int json_len = tokens[0].end - tokens[0].
               start;
9          int s = tokens[0].start;
10         if(json_len > 0 && input[s+0] == 'K'){
11         if(json_len > 1 && input[s+1] == 'A'){
12         if(json_len > 2 && input[s+2] == 'F'){
13         if(json_len > 3 && input[s+3] == 'L'){
14             panic(KERN_INFO "KAFL...\n");
15     }}}}}
16 }
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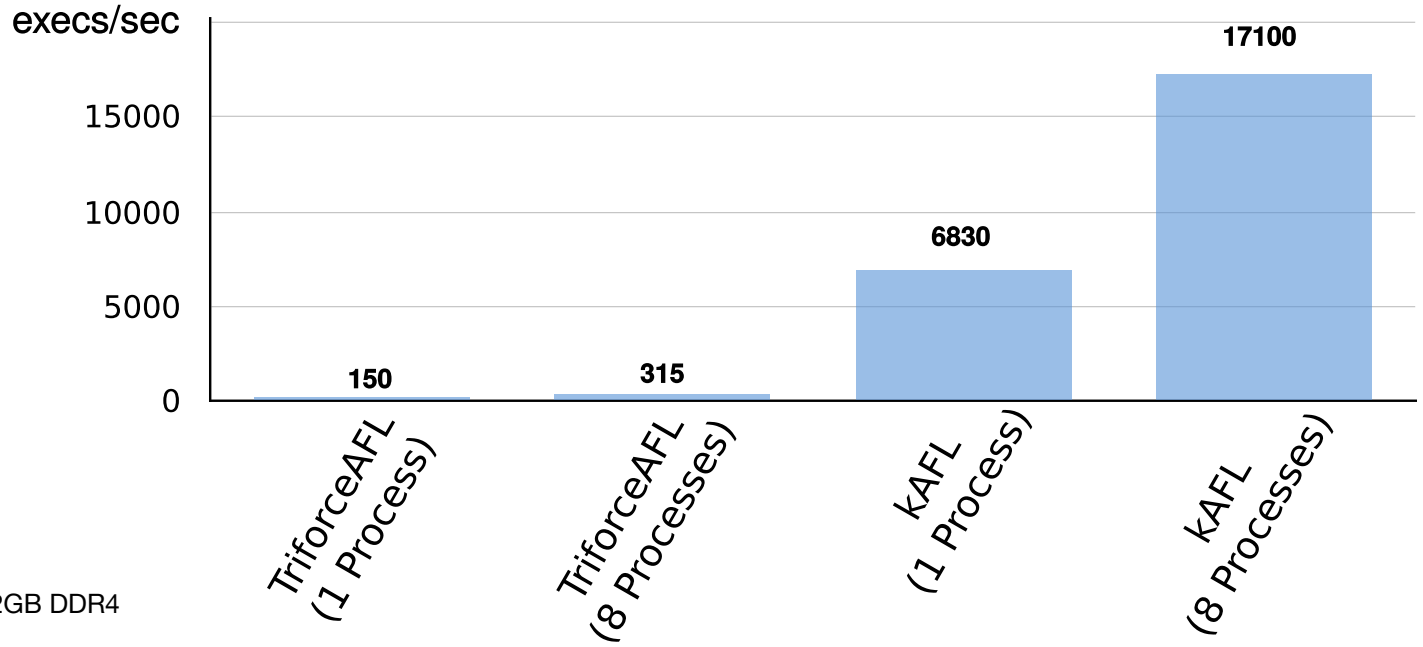
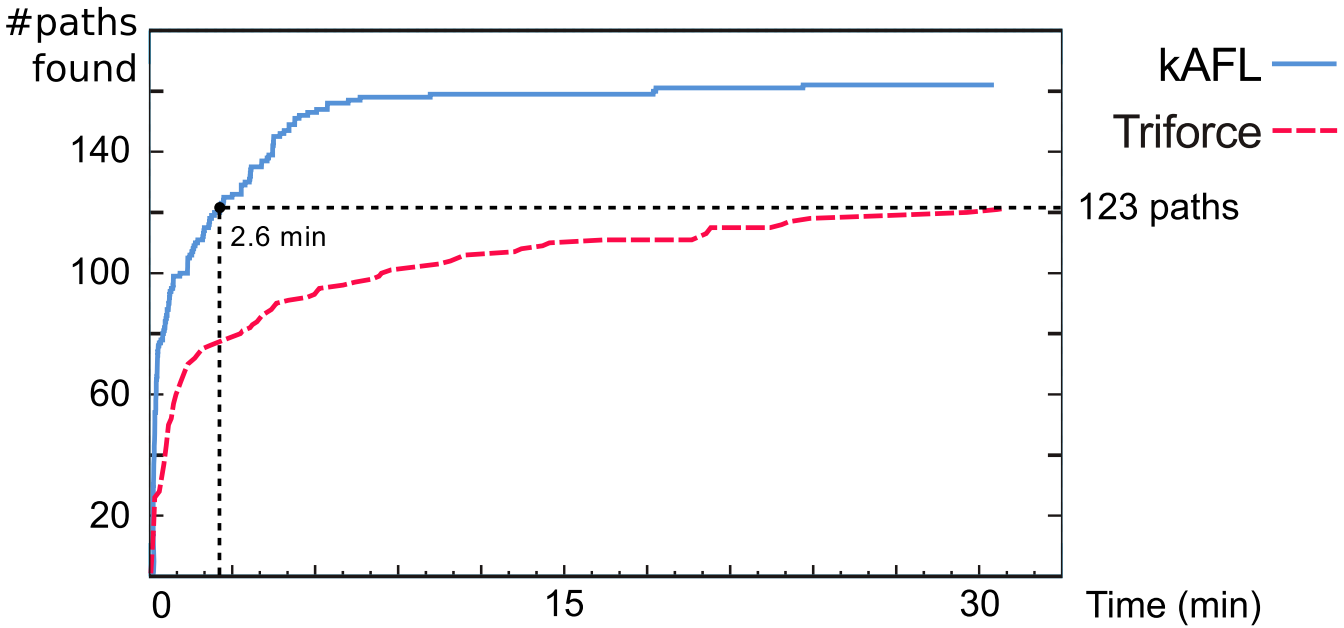
Performance



Intel i7-6700 / 32GB DDR4

Coverage



Intel i7-6700 / 32GB DDR4

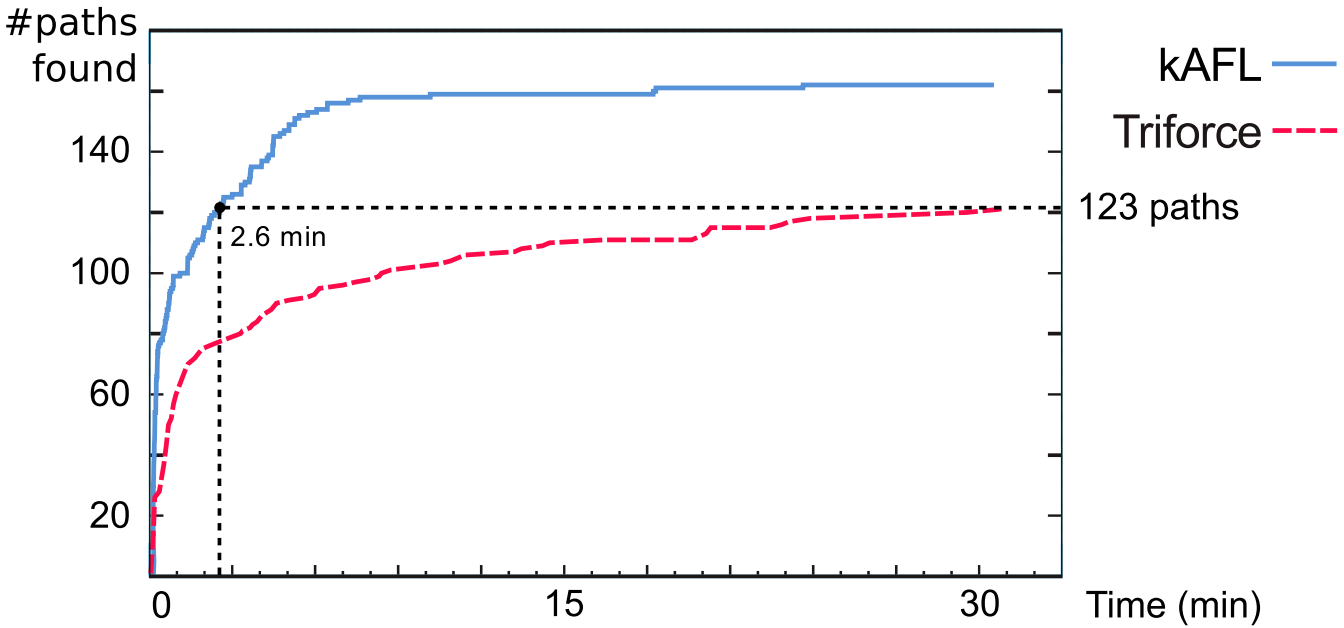
Coverage

kAFL:

- 5-7 minutes

TriforceAFL:

- ~2 hours



Intel i7-6700 / 32GB DDR4

Conclusion

- Intel PT and virtualization for feedback fuzzing
  - Fast
  - OS independence (x86-64)
  - Reliable and long-term
  - Fully extensible
- High bug yield for kernel fuzzing
  - Opportunities for further fuzzing

https://github.com/RUB-SysSec/kAFL