BlackBox

Lightweight Security Monitoring for COTS Binaries

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Why Security Monitoring?

Motivation #1: Exploits occur frequently.

- Thousands of vulnerabilities reported in 2015.
- Millions of new malware released every year.
- Over 90% of attacks target 10+ year old bugs.
- Windows XP still claims over 10% market share!

Why Security Monitoring?

Motivation #2: Exploit recovery requires information.

- Identify which machines were affected:
  - Repair corrupted files.
  - Restore failed or crippled services.
  - Remove persistent malware.
- Learn how the attacker gained control.
- Prevent recurrence of the same exploit.

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  - Legacy platforms maintain significant market share

Why Security Monitoring?

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- COTS rewriting approaches have been defeated.
- Recompilation required, but opportunity is limited:
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  - Legacy platforms maintain significant market share
- Is it possible to build security into the compiler?

Exploit Example: Buffer Overflow

Parse the argument by copying up to the space into the buffer.

```
$ foobar limit 3
2.83749
```

l	i	m	i	t		3	∕

buffer:

l	i	m	i	t	∕		

```c
static const char *
parse_option(const char *input, option_t **option_out)
{
    char buffer[8];

    for (int i = 0; input[i] != '\0'; i++) {
        if (input[i] != ' ') {
            buffer[i] = input[i];
        } else {
            ...
        }
    }
```

Exploit Example: Buffer Overflow

User input can change the return address of this function!

```
$ foobar option-wit
Segmentation fault
```

o	p	t	i	o	n	-	w	i	t	h	-	i	n	v	a

buffer: <base pointer>

o	p	t	i	o	n	-	w	i	t	h	-	i	n	v	a

```
static const char *
parse_option(const char *input, option_t **option_out)
{
    char buffer[8];

    for (int i = 0; ...) {
        ...
    }
}
```

0x00007fffffffd418	arg #2:	**option_out
0x00007fffffffdae7	arg #1:	*input
0x0000000100000000	local #2:	i
0x772d6e6f6974706f	local #1:	buffer
0x61766e692d687469	<previous stack frame base>	
0x756c61762d64696c	<return address>	

Adversary controls the program!

Automated Security

Defense concept:

- Identify vulnerable program instructions

```
0x00007fffffffd418   arg #2:     **option_out
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Adversary controls the program!

Automated Security

Defense concept:

- Identify vulnerable program instructions
- Detect adversarial manipulation of instruction operands

```
0x00007fffffffd418   arg #2:     **option_out
0x00007fffffffdae7   arg #1:     *input
0x0000000100000000   local #2:   i
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0x 61766e692d687469   <previous stack frame base>
0x 756c61762d64696c   <return address>
```

Adversary controls the program!

Automated Security

Defense problem:

- How to distinguish adversarial influence?

```
0x00007fffffffd418   arg #2:     **option_out
0x00007fffffffdae7   arg #1:     *input
0x0000000100000000   local #2:   i
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Adversary controls the program!

Automated Security

Defense proposal:

- Detect unintended data flows...

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Adversary controls the program!

Automated Security

Defense proposal:

- ~~Detect unintended data flows…~~
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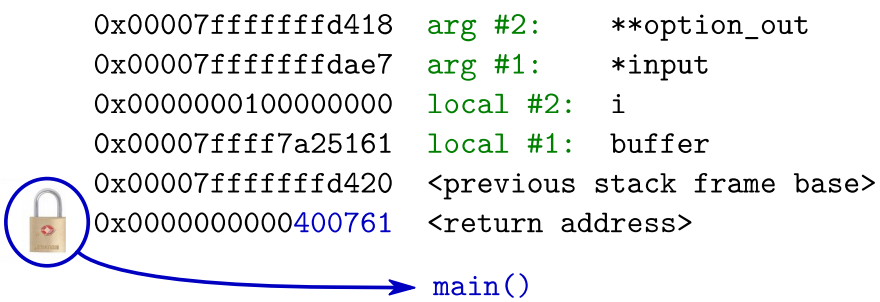
- Calculate intended operand values
  - e.g. legitimate return addresses



Automated Security

Defense proposal:

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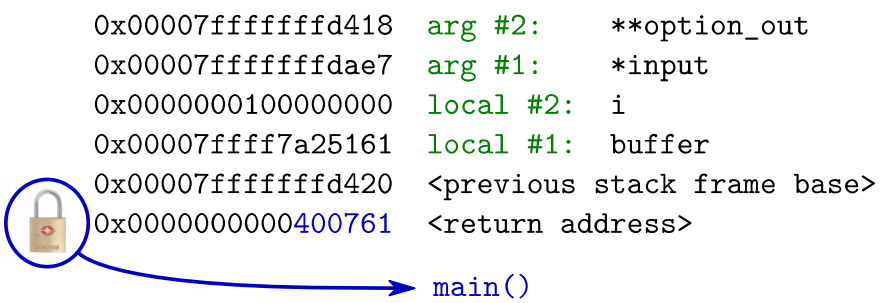
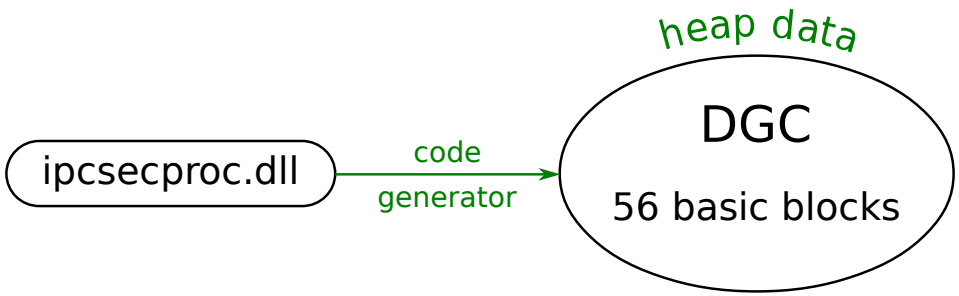
  - Counter example: Microsoft media licensing



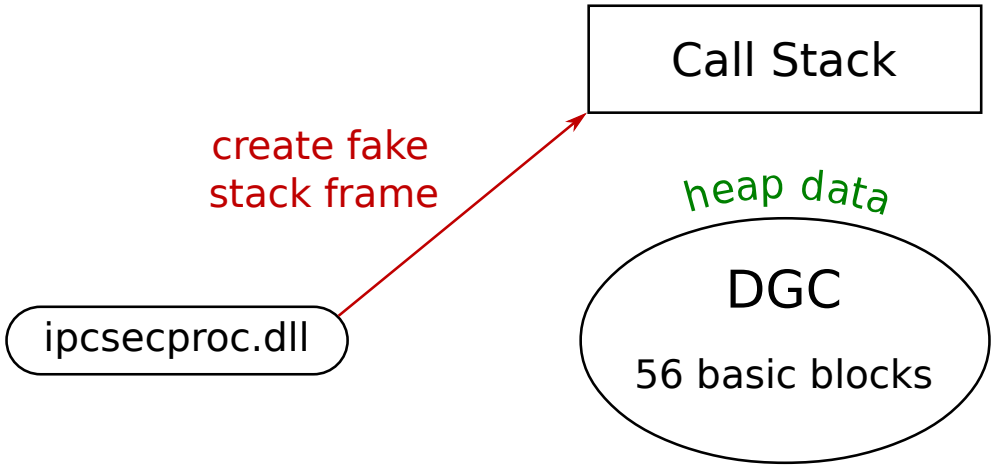
Automated Security Limitations

At startup of Microsoft Word, a media license module dynamically generates a small routine on the heap:



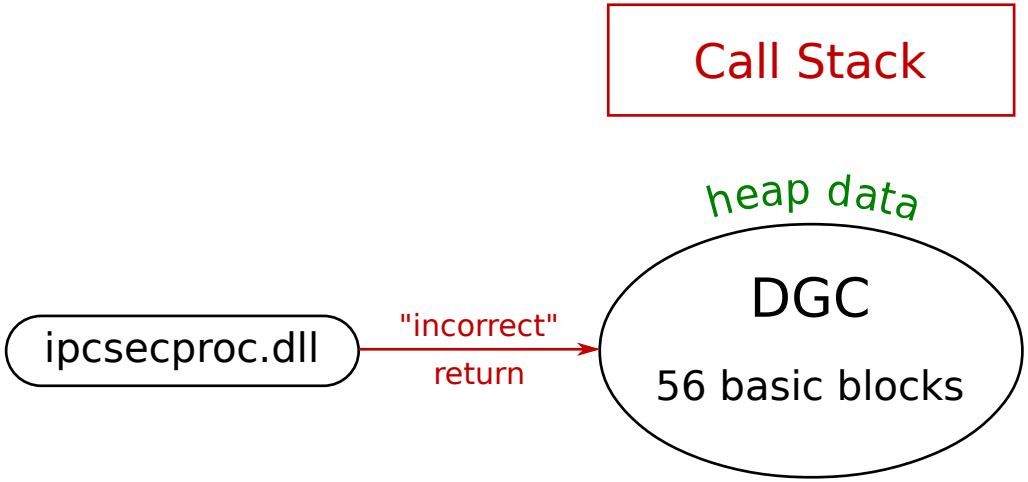
Automated Security Limitations

It pushes a placeholder on the call stack...



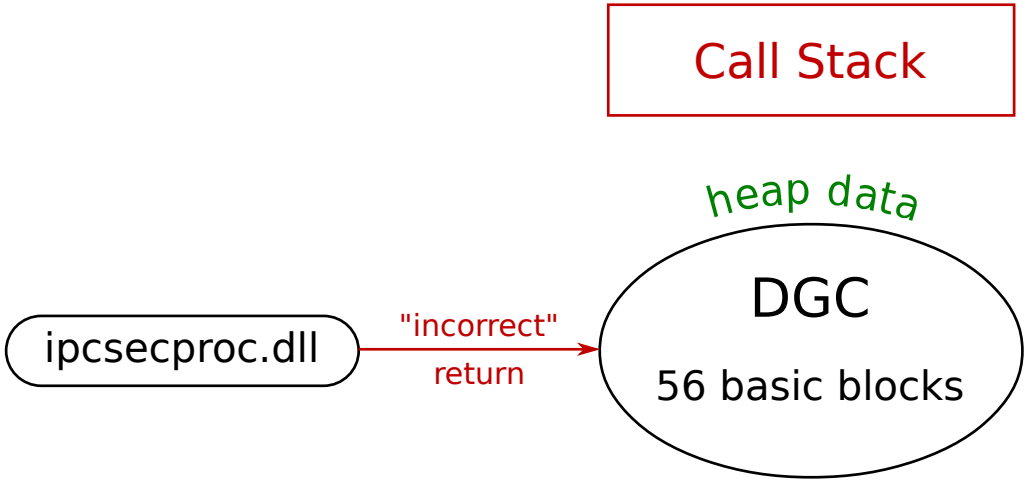
Automated Security Limitations

...followed by a non-conventional “return” to enter the DGC.



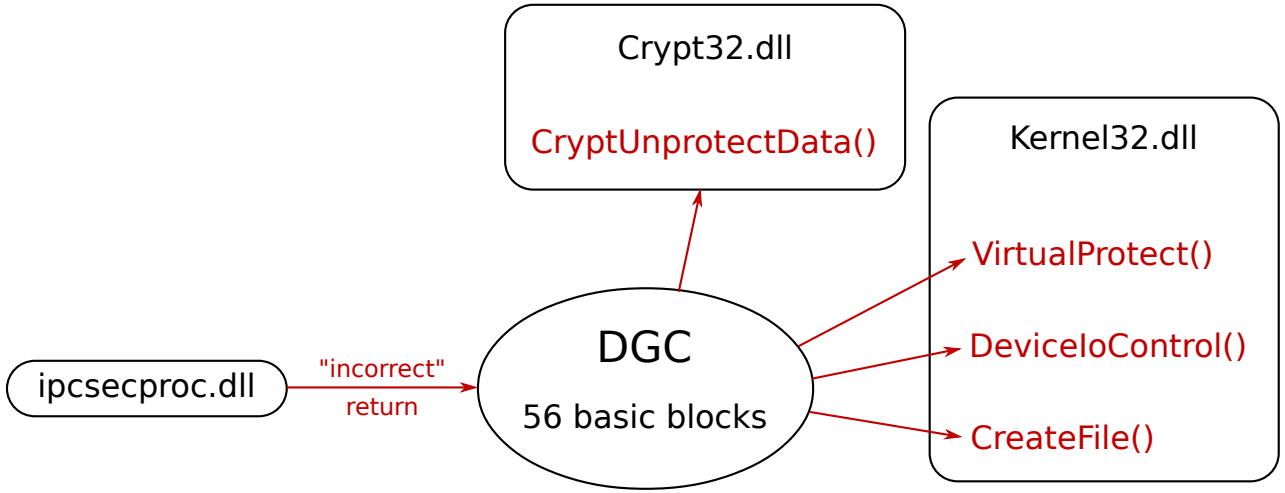
Automated Security Limitations

Calculating this return address requires calculating heap states.



Automated Security Limitations

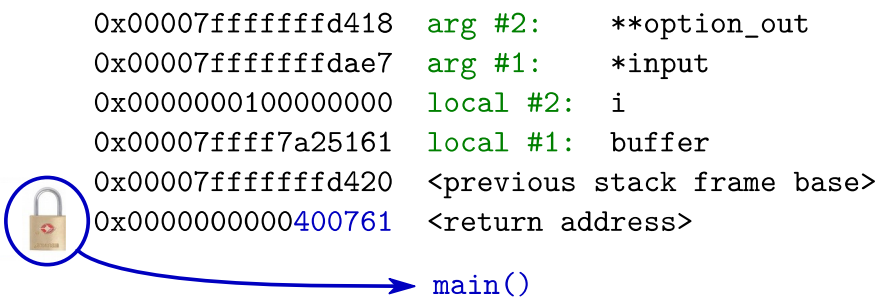
The DGC routine calls several security-sensitive functions.



Automated Security Limitations

Defense proposal:

- ~~Detect unintended data flows…~~
  - Intended data flows can be exploited!
- ~~Calculate intended operand values~~
  - ~~e.g. legitimate return addresses~~
  - Counter example: Microsoft media licensing
  - Counter example: Windows thread injection



Automated Security Limitations

```
DWORD yourAppProcessId = GetProcessByName("YourApp.exe");
```

Automated Security Limitations

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DWORD yourAppProcessId = GetProcessByName("YourApp.exe");

HANDLE yourAppProcess = OpenProcess(PROCESS_ALL_ACCESS, yourAppProcessId);
```

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DWORD yourAppProcessId = GetProcessByName("YourApp.exe");

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HMODULE kernel32 = GetModuleHandle("kernel32.dll");
```

Automated Security Limitations

```
DWORD yourAppProcessId = GetProcessByName("YourApp.exe");

HANDLE yourAppProcess = OpenProcess(PROCESS_ALL_ACCESS, yourAppProcessId);

HMODULE kernel32 = GetModuleHandle("kernel32.dll");

LPTHREAD_START_ROUTINE loadLibrary = GetProcAddress(kernel32, "LoadLibraryA");
```

Automated Security Limitations

```
DWORD yourAppProcessId = GetProcessByName("YourApp.exe");

HANDLE yourAppProcess = OpenProcess(PROCESS_ALL_ACCESS, yourAppProcessId);

HMODULE kernel32 = GetModuleHandle("kernel32.dll");

LPTHREAD_START_ROUTINE loadLibrary = GetProcAddress(kernel32, "LoadLibraryA");

HANDLE hThread = CreateRemoteThread(yourAppProcess, loadLibrary, myMalwareDllPath);
```

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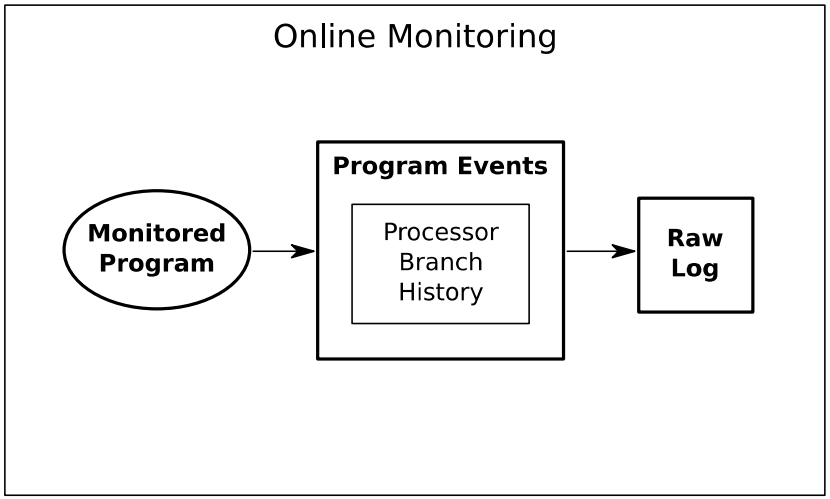
Motivation #3: Automated security may never be feasible.

- COTS rewriting approaches have been defeated.
- Recompilation required, but opportunity is limited:
  - Slow adoption of security tools
  - Legacy platforms maintain significant market share
- Indirect branch targets may be difficult to calculate:
  - Microsoft media licensing
  - Windows thread injection

Goals of BlackBox

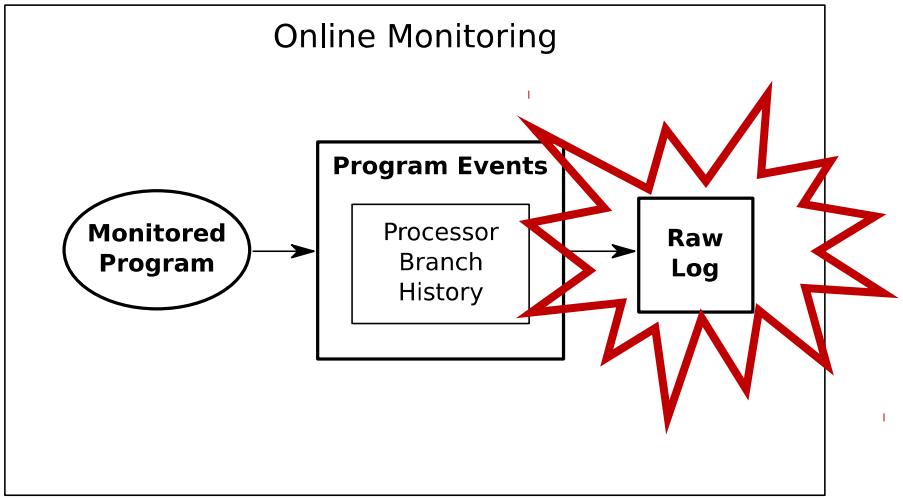
- Log malicious and abnormal program activity
- Minimize logging of ordinary control flow
- Block known exploits and protect known vulnerabilities

Naïve Application Monitoring



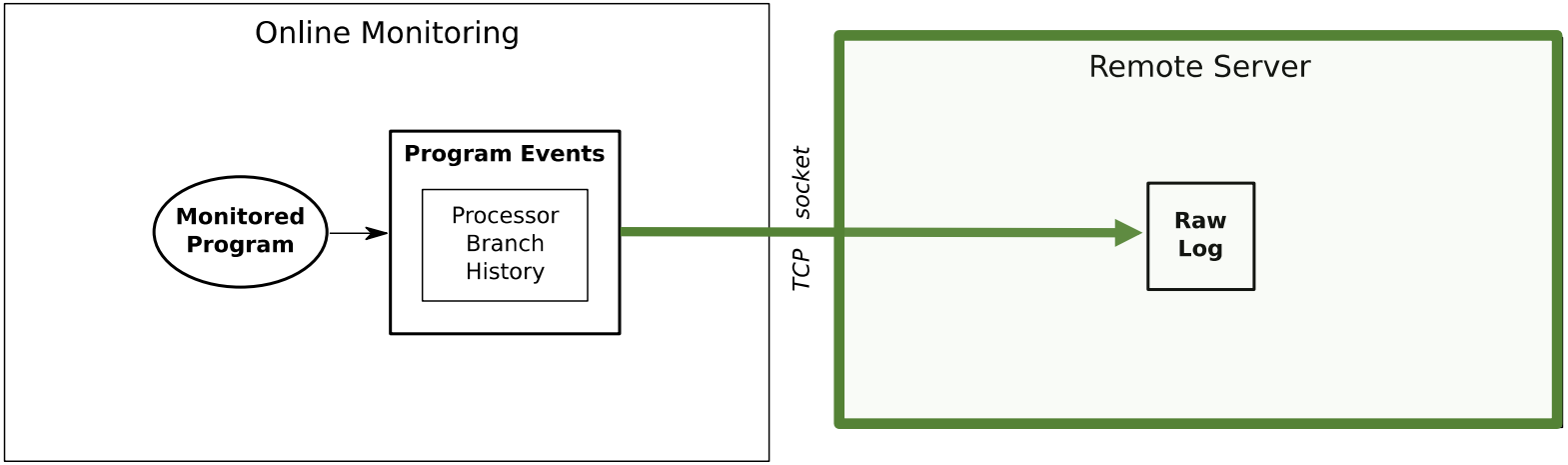
Log all branches executed by the monitored program.

Naïve Application Monitoring



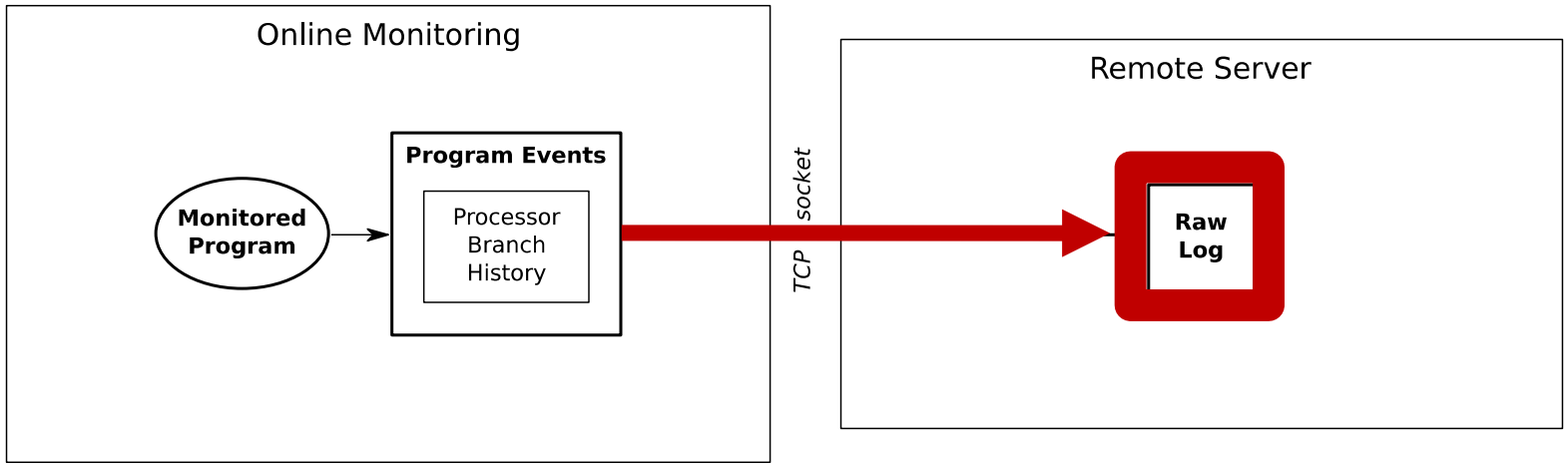
Problem: Adversary can hide evidence after a successful exploit.

Component: Remote Logging



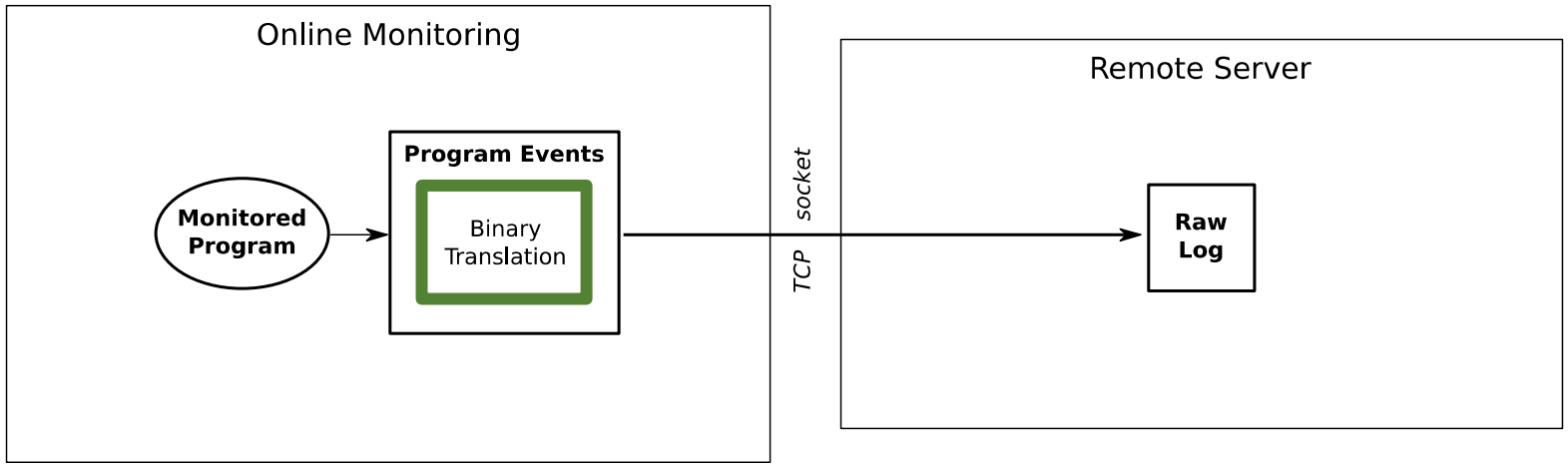
Write logs over a TCP socket to a remote server.

Component: Remote Logging

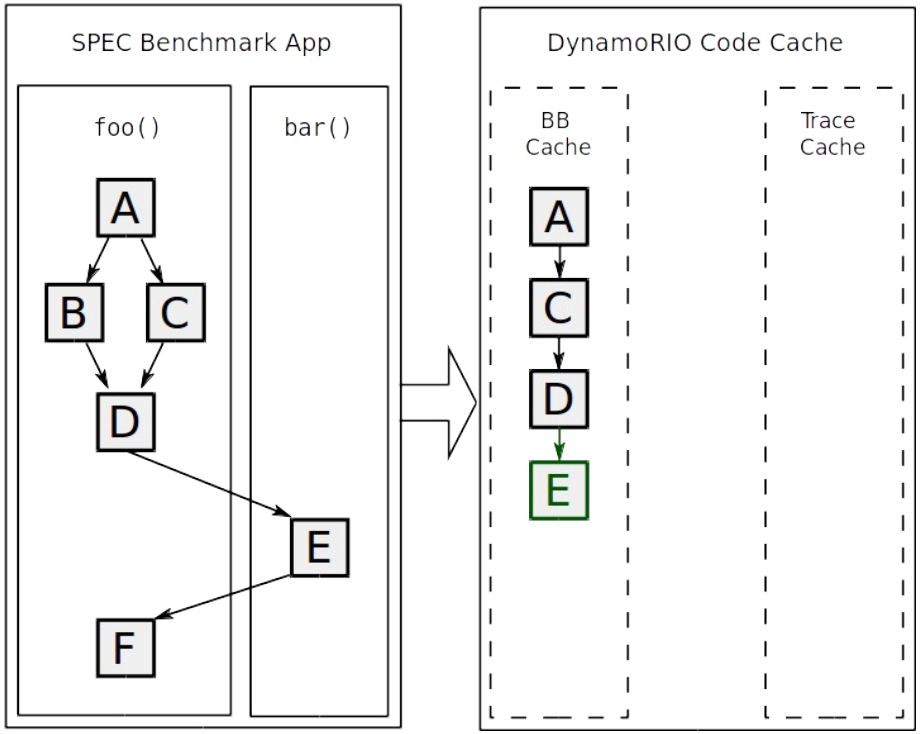


Problem: Billions of branch history events per hour.

Component: Binary Translation

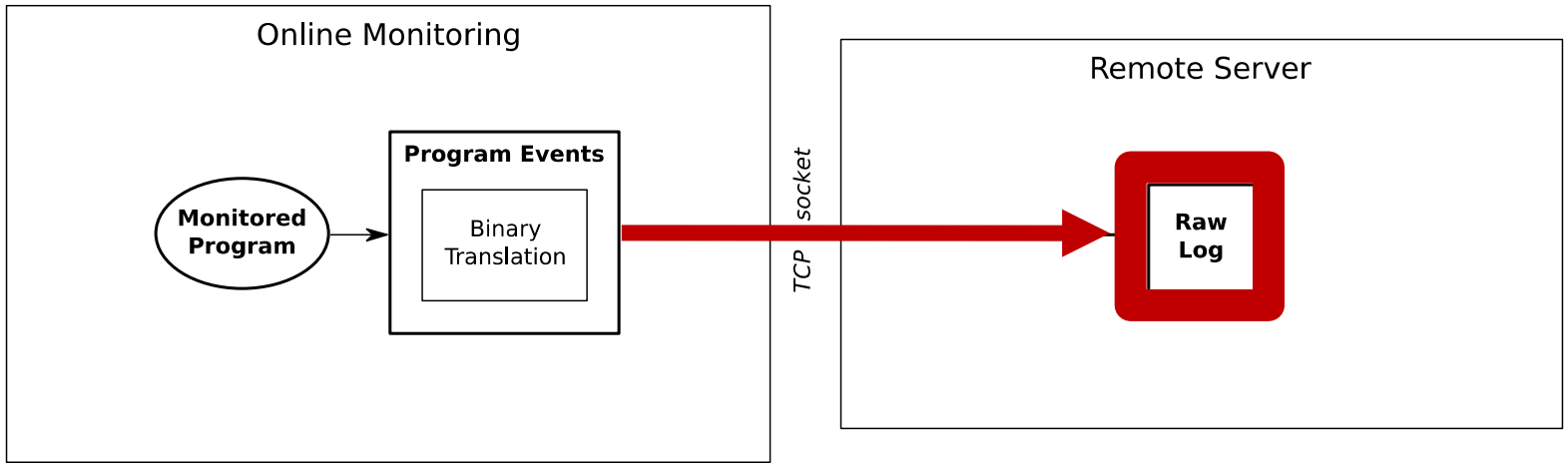


Execute code from a cached copy, logging each CFG edge once.



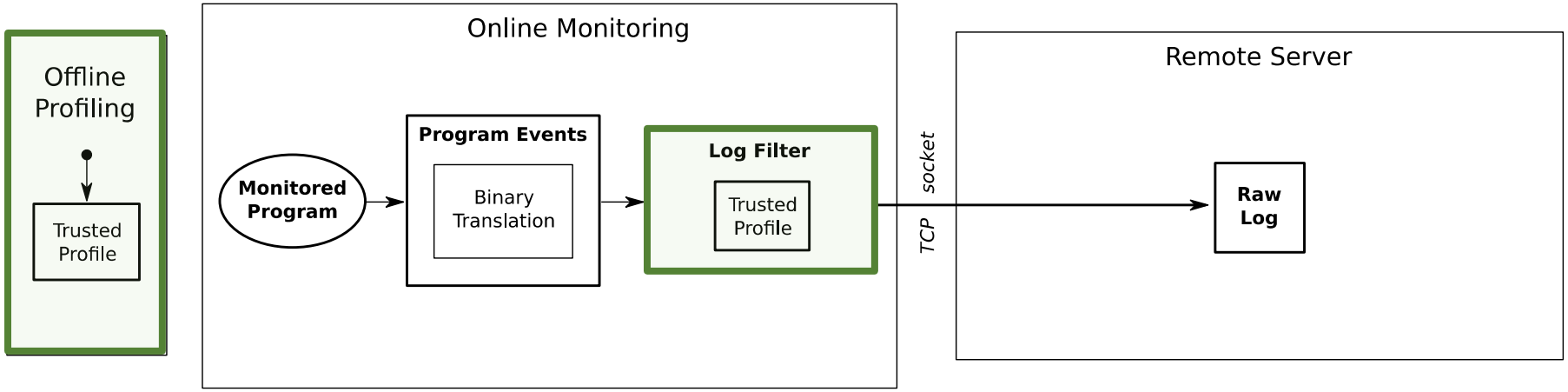
Next call to foo() will not log A → C → D → E again.

Component: Binary Translation



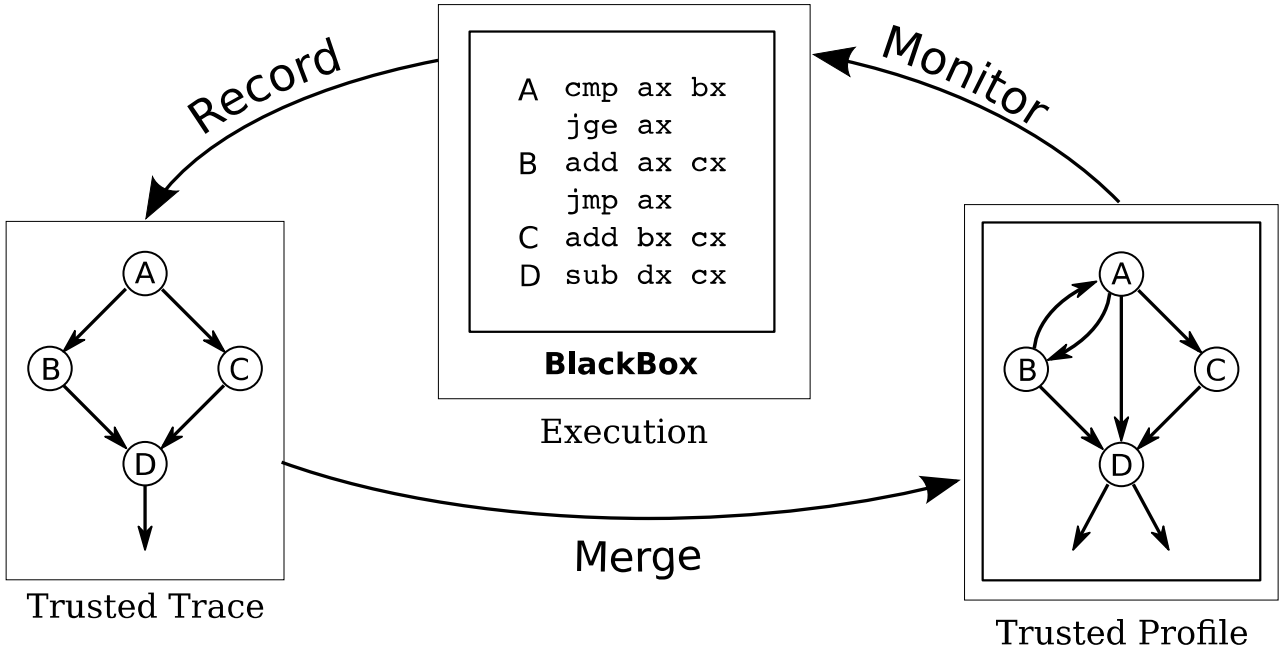
Problem: Still up to millions of CFG edges per hour.

Component: Trusted Profile

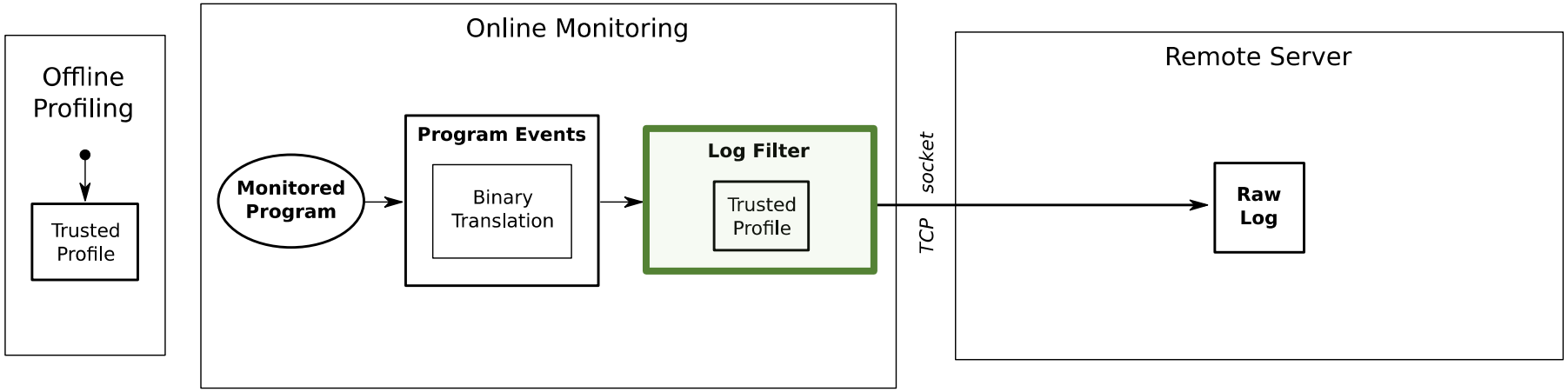


Learn normal program behavior during offline profiling.

Offline Profiling

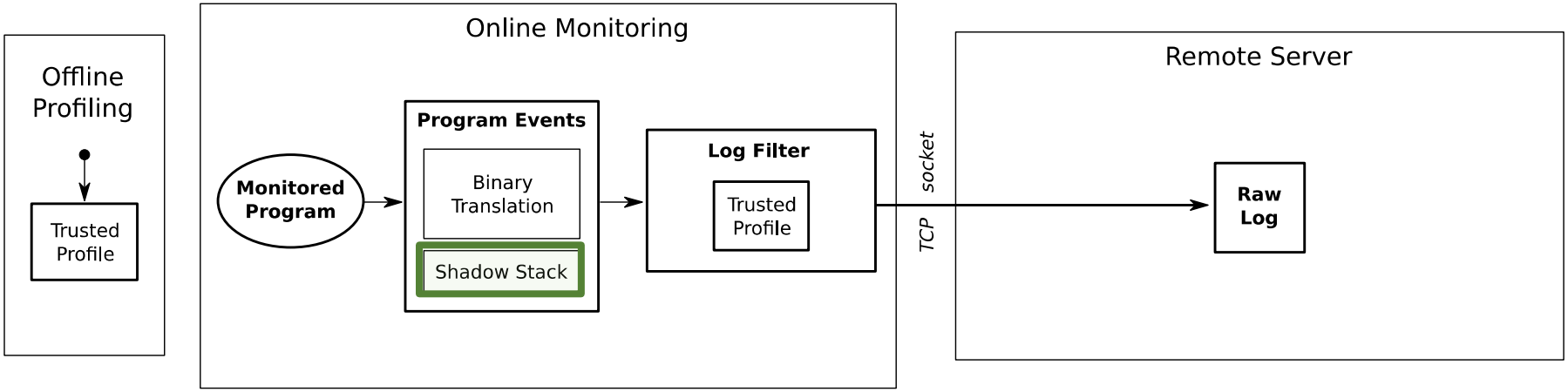


Component: Trusted Profile



Filter trusted CFG edges before logging.

Component: Trusted Profile



Shadow Stack: Always trust conventional return edges.

Trusting Dynamic Code

1. Large desktop applications typically use JIT engines:

Microsoft Office	JScript9
Adobe PDF Reader	JScript9, ShockwaveFlash
Chrome	V8, PepperFlash

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Microsoft Office	JScript9
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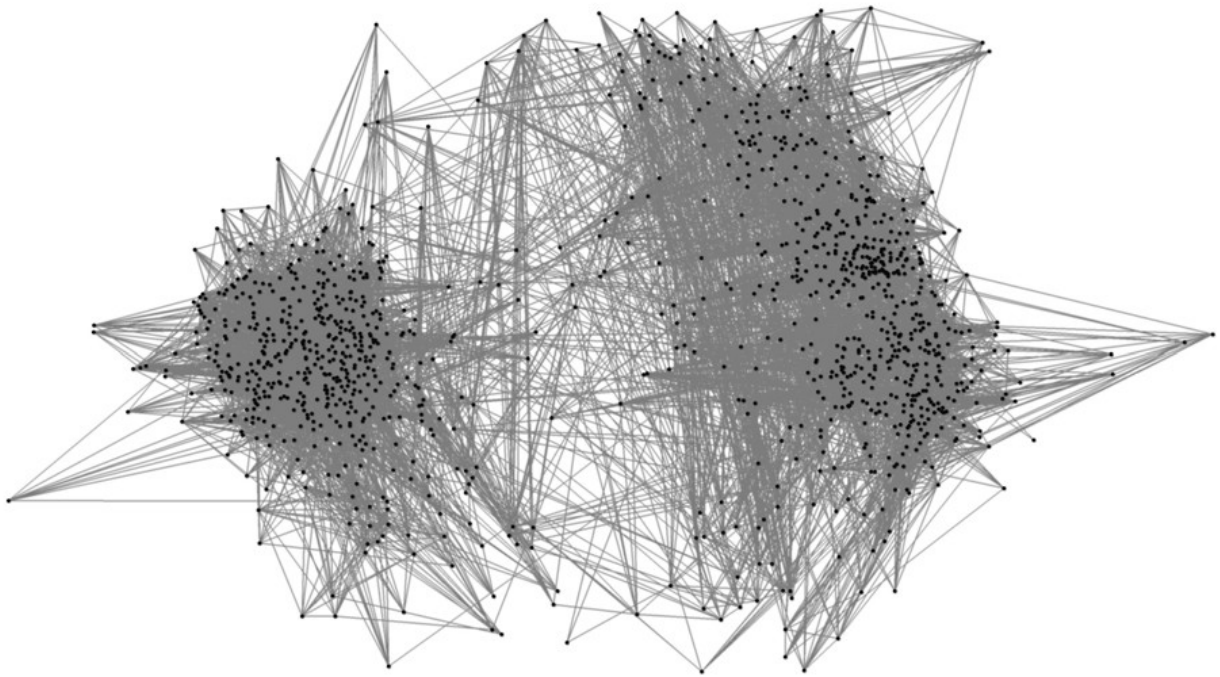
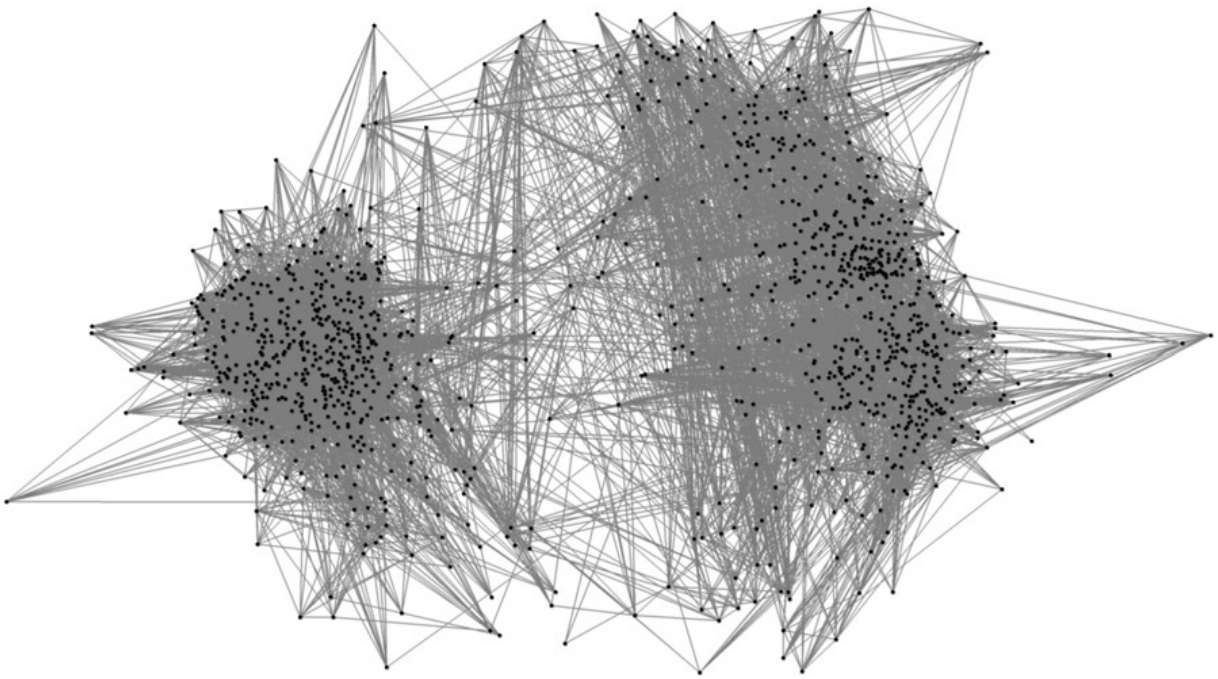
2. Observationally equivalent executions frequently exhibit low-level differences in generated code.

Component: Dynamic Code Abstraction



JIT engines may generate millions of basic blocks.

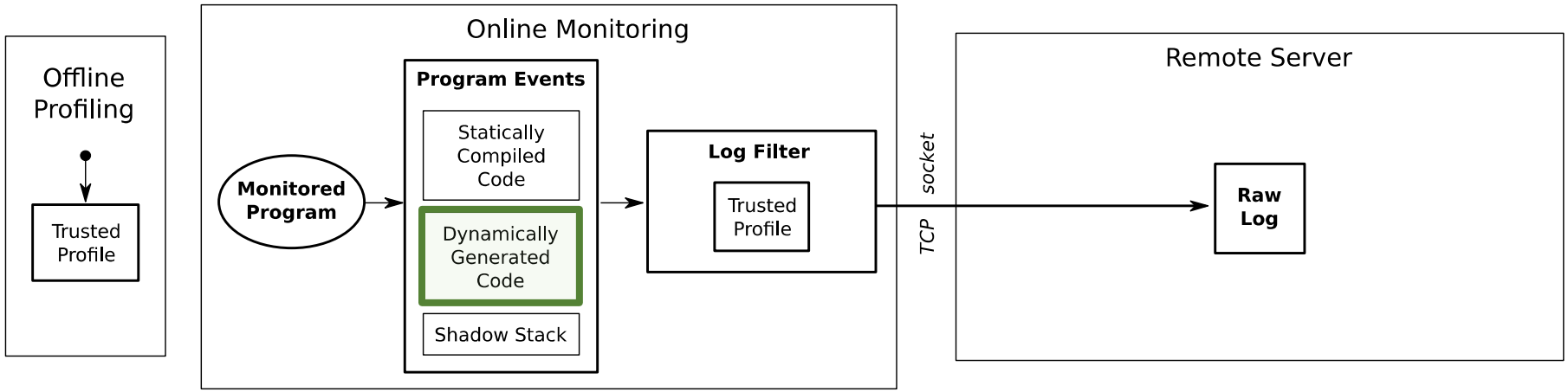
Component: Dynamic Code Abstraction



Random factors affect low-level code, e.g.:

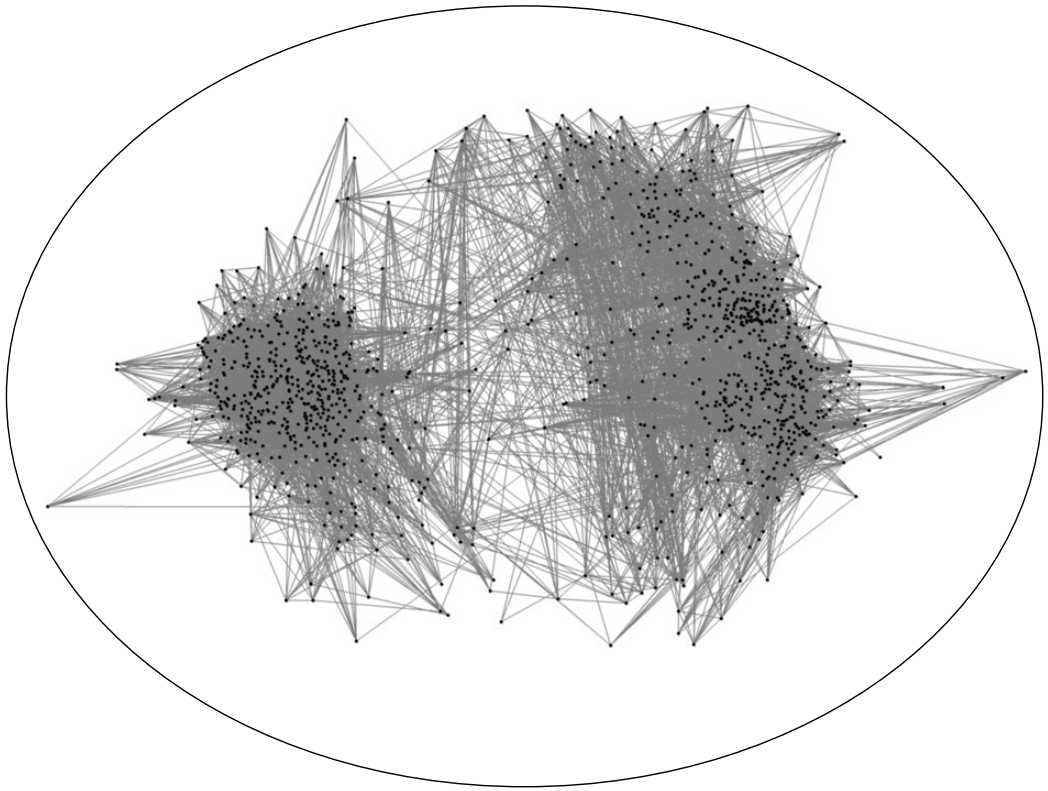
- OS thread scheduling
- Webserver response time
- Internal timers

Component: Dynamic Code Abstraction



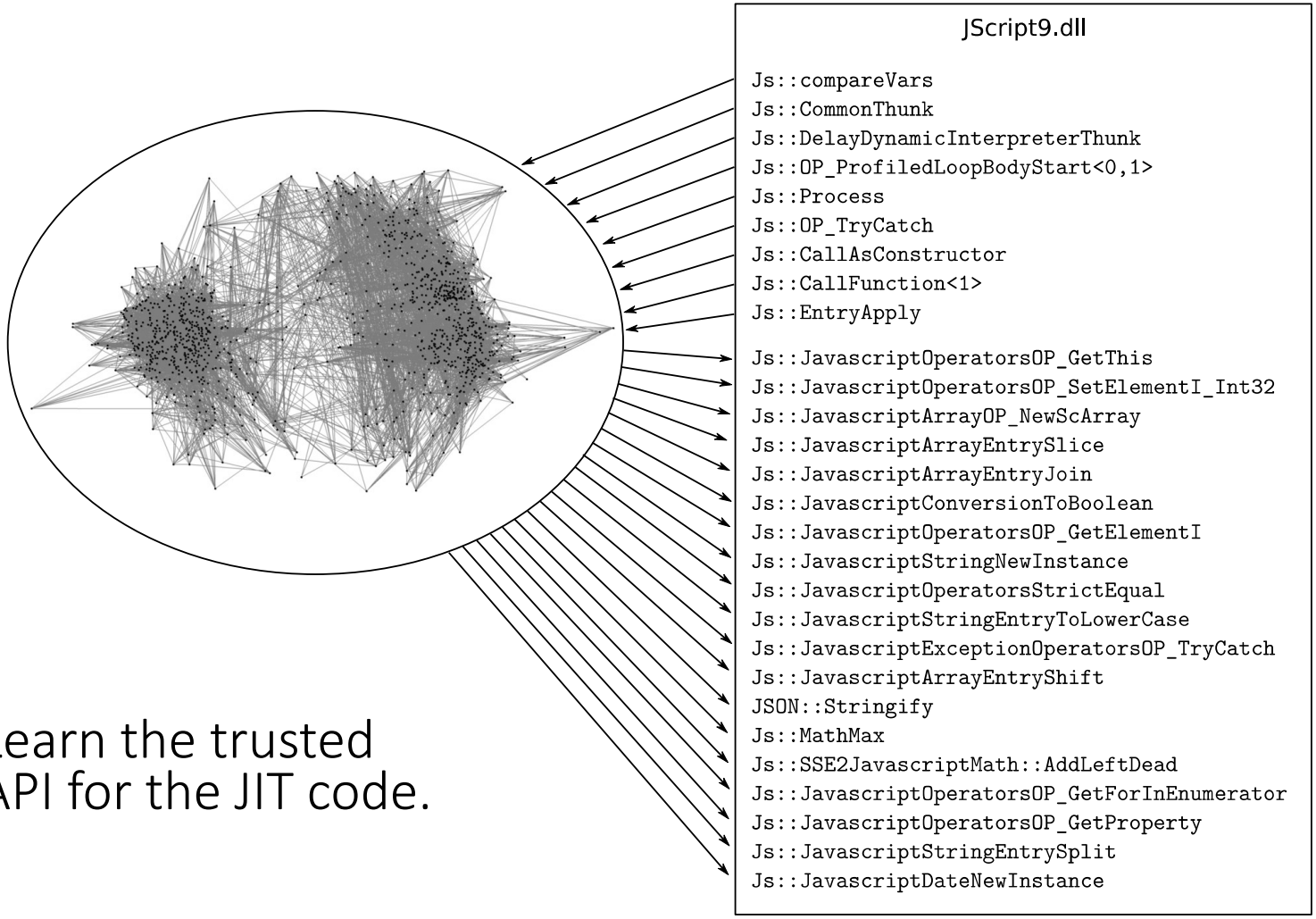
JIT Profile: Learn trusted entry and exit points (API).

Component: Dynamic Code Abstraction



Encapsulate JIT code in a singleton CFG node.

Component: Dynamic Code Abstraction



Learn the trusted
API for the JIT code.

Improve System Call Visibility

- Exploits rely on system calls to carry out malicious actions such as creating or deleting files.

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- System calls are usually invoked from trampolines in core system libraries like ntdll:

```
[syscall 0x52]
ntdll!ZwCreateFile()
KERNELBASE!CreateFileW()
kernel32!CreateFileWImplementation()
DWrite!File::File()
DWrite!LocalFileLoader::FontFileStream()
DWrite!LocalFileLoader::CreateFontFileStream()
```

← trampoline →

```
[syscall 0x52]
ntdll!ZwCreateFile()
KERNELBASE!CreateFileW()
KERNELBASE!BasepLoadLibraryAsDataFileInternal()
KERNELBASE!BasepLoadLibraryAsDataFile()
KERNELBASE!LoadLibraryExW()
KERNELBASE!ConvertTimeZoneMuiString()
```

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```

Execution of a trusted trampoline does not always imply execution of a trusted system call.

Improve System Call Visibility

The ZwCreateFile trampoline is trusted—what can go wrong?

Load fonts from a system table:

```
[syscall 0x52]
ntdll!ZwCreateFile()
KERNELBASE!CreateFileW()
kernel32!CreateFileWImplementation()
DWrite!File::File()
DWrite!LocalFileLoader::FontFileStream()
DWrite!LocalFileLoader::CreateFontFileStream()
DWrite!LocalFileLoader::CreateStreamFromKey()
DWrite!FontFileReference::GetStreamInternal()
DWrite!FontFragmentPtr<unsigned char>()
DWrite!FontFileReference::ReadIntoBuffer()
DWrite!OpenTypeTableDirectory::GetTableCount()
```

Load the timezone library:

```
[syscall 0x52]
ntdll!ZwCreateFile()
KERNELBASE!CreateFileW()
KERNELBASE!BasepLoadLibraryAsDataFileInternal()
KERNELBASE!BasepLoadLibraryAsDataFile()
KERNELBASE!LoadLibraryExW()
KERNELBASE!ConvertTimeZoneMuiString()
```

Change the indirect call target!

A malicious font could cause a malware library to be loaded!

Improve System Call Visibility

The ZwCreateFile trampoline is trusted—what can go wrong?

	`[syscall 0x52]`
trusted?	`ntdll!ZwCreateFile()`
trusted?	`KERNELBASE!CreateFileW()`
trusted?	`KERNELBASE!BasepLoadLibraryAsDataFileInternal()`
trusted?	`KERNELBASE!BasepLoadLibraryAsDataFile()`
trusted?	`KERNELBASE!LoadLibraryExW()`
untrusted!	`DWrite!FontFileReference::GetStreamInternal()`
trusted	`DWrite!FontFragmentPtr<unsigned char>()`
trusted	`DWrite!FontFileReference::ReadIntoBuffer()`
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Component: Stack Spy

Suspicious syscall: influenced by an untrusted branch.

suspicious	[syscall 0x52]
suspicious	ntdll!ZwCreateFile()
suspicious	KERNELBASE!CreateFileW()
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untrusted!	KERNELBASE!LoadLibraryExW()
trusted	DWrite!FontFileReference::GetStreamInternal()
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untrusted!	KERNELBASE!LoadLibraryExW()
trusted	DWrite!FontFileReference::GetStreamInternal()
trusted	DWrite!FontFragmentPtr<unsigned char>()
trusted	DWrite!FontFileReference::ReadIntoBuffer()
	DWrite!OpenTypeTableDirectory::GetTableCount()

Log this syscall 0x52 as suspicious,

along with the untrusted branch.

BlackBox Log

What’s in the log file?

BlackBox Log

Log sample of Adrenalin Media Player:

```
Rank Event
 900 Suspicious syscall #36 NtSetInformationFile
     adrenalinx.dll(0xf160a -> 0x97ac0) raised suspicion
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     adrenalinx.dll(0xf160a -> 0x97ac0) raised suspicion
 300 Structural indirect  mp3dmod!CMpgaDecoder::DecodeFrame(0x76) -> qasf!<callback>
 300 Structural indirect  quartz!CFilterGraph::AddFilterInternal(0x91) -> addicted!<callback>
 300 Structural indirect  mp3dmod!CMpgaDecoder::DecodeFrame(0x76) ->  mp3dmod!CBitStream::Reset()
 300 Structural indirect  mp3dmod!CMP3DecoderDMO::DoFlush(0x16) -> qasf!<callback>
 295 Structural indirect  qasf!CMediaWrapperFilter::JoinFilterGraph(0x68) -> quartz!<callback>
 295 Structural indirect  qasf!ImediaSeeking::`vcall'{40}' -> quartz!<callback>
 295 Structural indirect  qasf!CMediaWrapperFilter::DeliverInputSample(0x47) -> quartz!<callback>
```

Suspicious syscalls occur where the player handles a media format not covered in the Trusted Profile.

BlackBox Log

Log sample of an ROP exploit on Adrenalin Player:

```
Rank Event
 999 Suspicious entry into DGC
     adrenalinx.dll(0x16f313) -> DGC(0x3bfffb) raised suspicion
 999 Incorrect return adrenalinx.dll(0x16f313) -> DGC(0x3bfffb)
 999 Untrusted module calc.exe-1db1446a00060001
 999 Suspicious indirect shlwapi!QISearch -> comctl32!<callback>
 999 Suspicious indirect ntdll!LdrEnumerateLoadedModules(0x86) -> kernel32!<callback>
 999 Untrusted module gdiplus.dll-1db146c800060001
 999 Suspicious indirect kernel32!BaseThreadInitThunk(0xc) -> calc!<callback>
 998 DGC standalone owned by adrenalinx.dll-300010001 (4 nodes)
 900 Suspicious syscall #25 ZwSetInformationProcess
     ntdll!memcpy(0x33 -> 0x170) raised suspicion
 900 Suspicious syscall #82 ZwCreateFile
     ntdll!memcpy(0x5c -> 0x128) raised suspicion
 900 Suspicious syscall #79 ZwResumeThread
     kernelbase!CreateRemoteThreadEx(0x2dd) -> ntdll!NtResumeThread() raised suspicion
 900 Suspicious syscall #26 ZwCreateKey
     user32.dll(0x16d88) -> ntdll!RtlDeactivateActivationContextUnsafeFast() raised suspicion
 900 Suspicious syscall #77 ZwProtectVirtualMemory
     apphelp!SeiIatPatch(0x86) -> ntdll!RtlDeactivateActivationContextUnsafeFast() raised suspicion
 900 Suspicious syscall #165 ZwCreateThreadEx
     kernelbase!CreateRemoteThreadEx(0x102) -> ntdll!NtCreateThreadEx() raised suspicion
```

BlackBox Log

How can this exploit be prevented?

```
Rank Event
 999 Suspicious entry into DGC
     adrenalinx.dll(0x16f313) -> DGC(0x3bfffb) raised suspicion
 999 Incorrect return adrenalinx.dll(0x16f313) -> DGC(0x3bfffb)
 999 Untrusted module calc.exe-1db1446a00060001
 999 Suspicious indirect shlwapi!QISearch -> comctl32!<callback>
 999 Suspicious indirect ntdll!LdrEnumerateLoadedModules(0x86) -> kernel32!<callback>
 999 Untrusted module gdiplus.dll-1db146c800060001
 999 Suspicious indirect kernel32!BaseThreadInitThunk(0xc) -> calc!<callback>
 998 DGC standalone owned by adrenalinx.dll-300010001 (4 nodes)
 900 Suspicious syscall #25 ZwSetInformationProcess
     ntdll!memcpy(0x33 -> 0x170) raised suspicion
 900 Suspicious syscall #82 ZwCreateFile
     ntdll!memcpy(0x5c -> 0x128) raised suspicion
 900 Suspicious syscall #79 ZwResumeThread
     kernelbase!CreateRemoteThreadEx(0x2dd) -> ntdll!NtResumeThread() raised suspicion
 900 Suspicious syscall #26 ZwCreateKey
     user32.dll(0x16d88) -> ntdll!RtlDeactivateActivationContextUnsafeFast() raised suspicion
 900 Suspicious syscall #77 ZwProtectVirtualMemory
     apphelp!SeiIatPatch(0x86) -> ntdll!RtlDeactivateActivationContextUnsafeFast() raised suspicion
 900 Suspicious syscall #165 ZwCreateThreadEx
     kernelbase!CreateRemoteThreadEx(0x102) -> ntdll!NtCreateThreadEx() raised suspicion
```

Blacklist

Log entries can be converted into blacklist entries:

```
Rank Event
 999 Suspicious entry into DGC
     adrenalinx.dll(0x16f313) -> DGC(0x3bfffb) raised suspicion
 999 Incorrect return adrenalinx.dll(0x16f313) -> DGC(0x3bfffb)
 999 Untrusted module calc.exe-1db1446a00060001
 999 Suspicious indirect shlwapi!QISearch -> comctl32!<callback>
 999 Suspicious indirect ntdll!LdrEnumerateLoadedModules(0x86) -> kernel32!<callback>
```

This blacklist prohibits the exploited basic block from ever making an entry into dynamic code:

```
edge adrenalinx.dll 0x16f313 <export> 0x3bfffb658587ad92
```

Blacklist

Prohibit the exploited basic block from entering DGC:

```
edge adrenalinx.dll 0x16f313 <export> 0x3bfffb658587ad92
```

Blacklist

Prohibit abnormal return sites in an entire module:

```
node adrenalinx.dll <abnormal-return>
```

Blacklist

Prohibit abnormal return sites in the whole program:

```
node * <abnormal-return>
```

Blacklist

Prohibit abnormal return sites in the whole program:

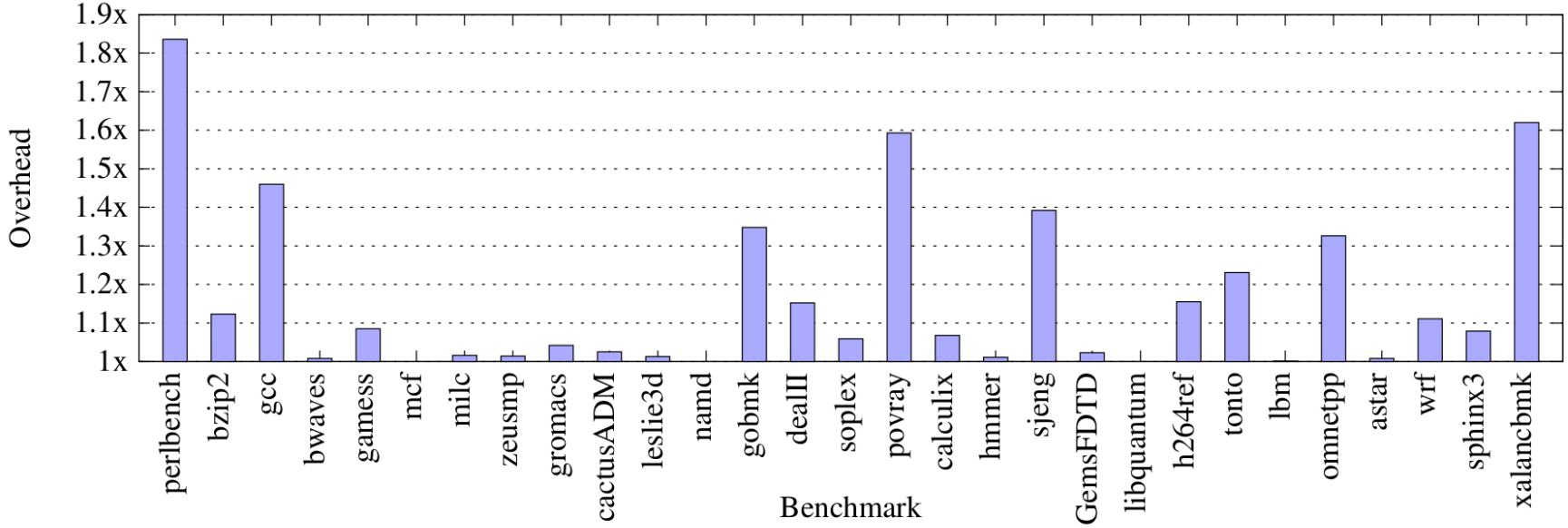
```
node * <abnormal-return>
```

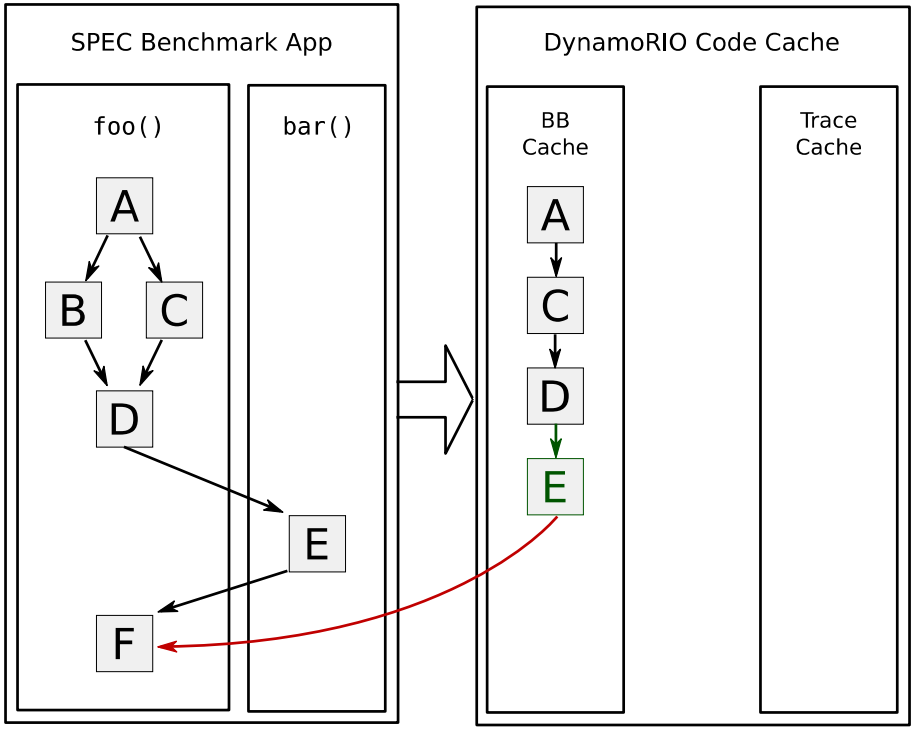
Not viable for all programs!

- Adobe PDF Reader plugins contain abnormal returns

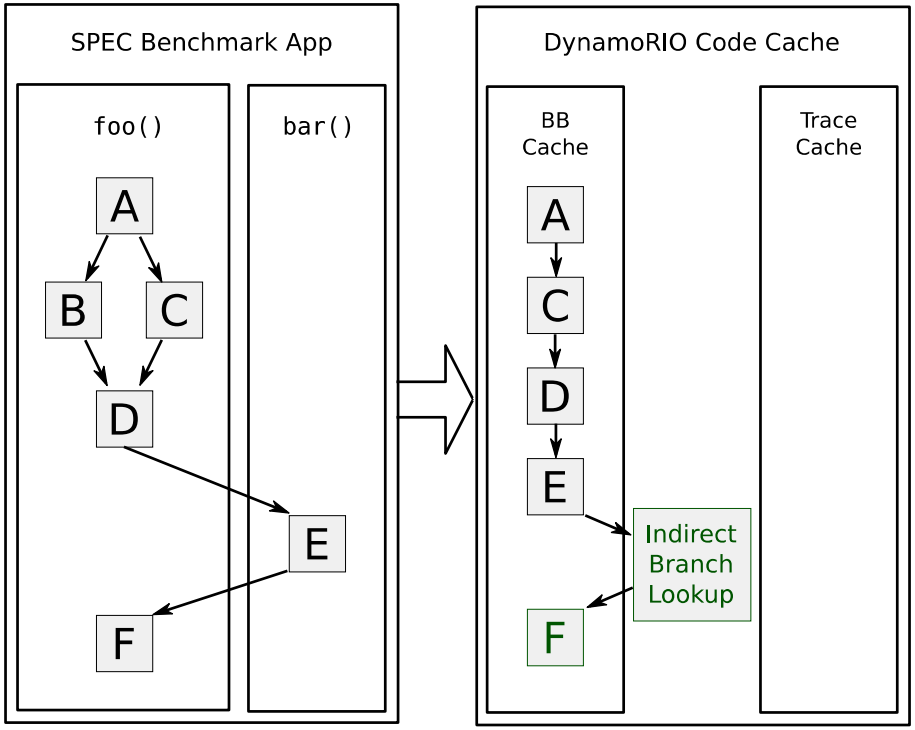
Benchmark: SPEC CPU 2006

Geometric Mean: 14.5%

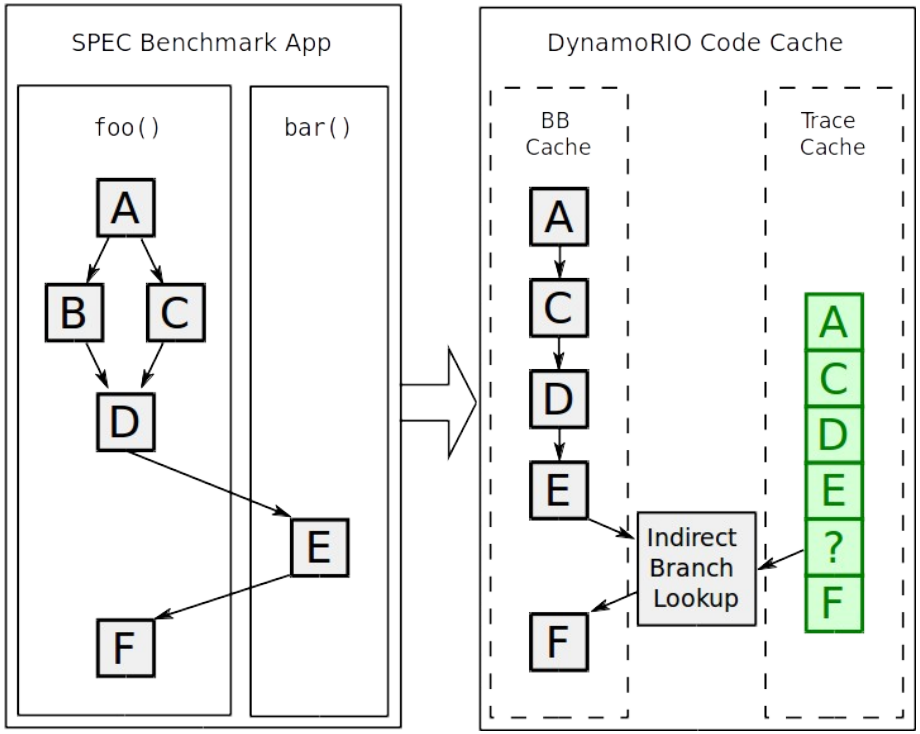




Problem: Return address points to F on the left.

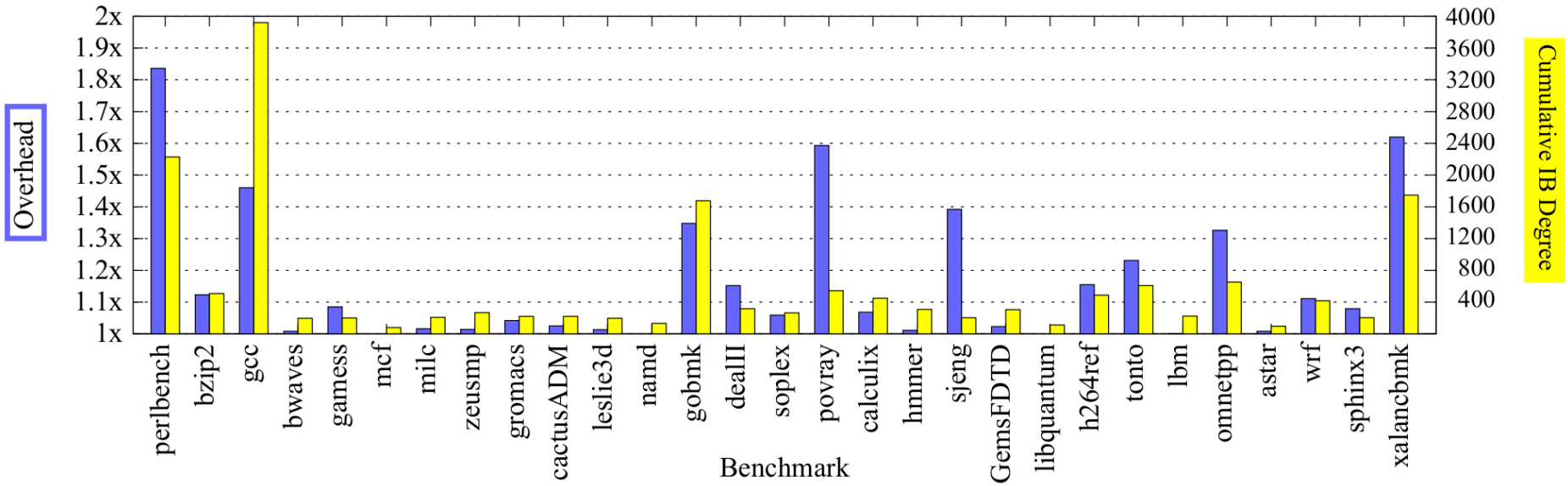


Correlate indirect branch targets via hashtable.



Hot paths are compiled into traces (10% speedup).

Benchmark: SPEC CPU 2006



Overhead corresponds roughly to cumulative indirect branch degree.

Log Reduction

Program	All Branches	Binary Translation	Trusted Profile
Chrome	485,251,278,660	6,137,106	7
Adobe PDF	34,075,711,128	2,292,342	4
Word	603,491,452,236	580,655	24
PowerPoint	251,845,377,624	1,335,817	50
Excel	198,427,776,372	561,401	28
Outlook	547,678,615,056	615,708	4
SciTE	61,325,719,872	124,013	33
pldflatex	23,504,352,560	64,290	43
Notepad++	129,695,545,404	589,155	24
Adrenalin	48,881,533,212	791,847	603
mp3info	2,080,031,200	4,339,200	3

Total log entries in one hour of normal program use.

Related Work: Other Defenses

- Code Pointer Integrity, *Kuznetsov et al*, USENIX '14
- SafeDispatch, *Jang et al*, NDSS '14
- Inference of Peak Density of Indirect Branches, *Tymburiba et al*, CGO '16
- Automated Software Diversity, *Larsen et al*, S&P '14
  - Librando, *Homescu et al*, CCS '13
- Mining Sandboxes, *Jamrozik et al*, ICSE '16

Related Work: CFI

- Control-Flow Integrity, *Abadi et al*, CCS '05
- Control Data Isolation, *Arthur et al*, CGO '15
- Context-Sensitive CFI, *van der Veen et al*, CCS '15
- Cryptographic CFI, *Mashtizadeh et al*, CCS '15
- Opaque CFI, *Mohan et al*, NDSS '15
- RockJIT, *Niu et al*, CCS '14

Related Work: Other Defenses

- Code Pointer Integrity, *Kuznetsov et al*, USENIX '14
- SafeDispatch, *Jang et al*, NDSS '14
- Inference of Peak Density of Indirect Branches, *Tymburiba et al*, CGO '16
- Automated Software Diversity, *Larsen et al*, S&P '14
  - Librando, *Homescu et al*, CCS '13
- Mining Sandboxes, *Jamrozik et al*, ICSE '16

Related Work: Attacks

- Control Flow Bending, *Carlini et al*, USENIX '15
- Control Flow Jujutsu, *Evans et al*, CCS '15
- Counterfeit Object Oriented Programming, *Schuster et al*, S&P '15
- Losing Control, *Conti et al*, CCS '15

Conclusion

- Software exploits are an ongoing problem.
- Automated security continues to face challenges.
- BlackBox provides an effective alternative to both automated security and anti-virus:
  - Isolates the pivotal actions of exploits.
  - Prevents repeated and foreseen exploits.