DTrace: The Reverse Engineer's Swiss Army Knife

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What Is DTrace™?

DTRACE BACKGROUND

*Dtrace was created by Sun Microsystems, Inc. and released under the Common Development and Distribution License (CDDL), a free software license based on the Mozilla Public License (MPL).

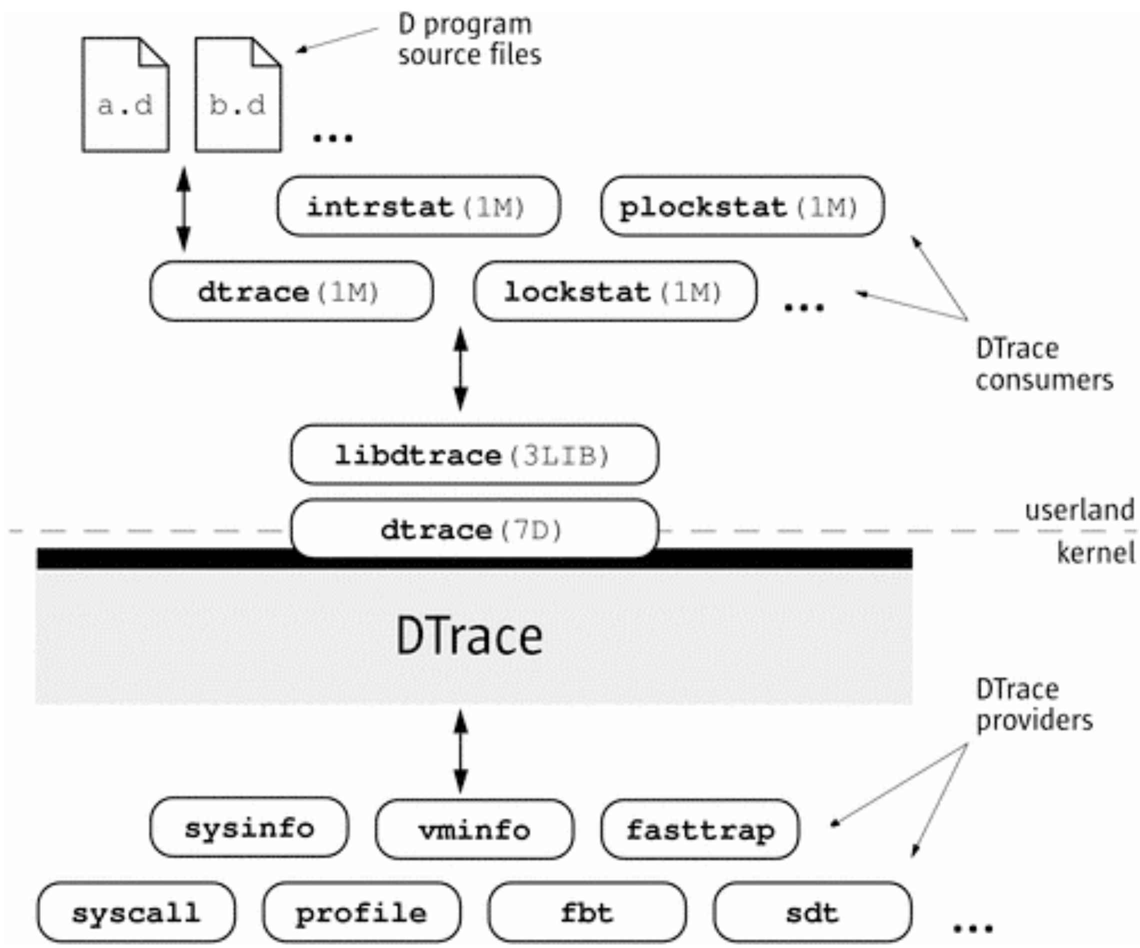
DTrace Background

- Kernel-based dynamic tracing framework
- Created by Sun Microsystems
- First released with Solaris™ 10 operating System
- Now included with Apple OS X Leopard, QNX
- Soon to be included with FreeBSD (John Birrell)
- OpenBSD, NetBSD, Linux?

DTrace Overview

- DTrace is a framework for performance observability and debugging in real time
- Tracing is made possible by thousands of “probes” placed “on the fly” throughout the system
- Probes are points of instrumentation in the kernel
- When a program execution passes one of these points, the probe that enabled it is said to have fired
- DTrace can bind a set of *actions* to each probe

DTrace Architecture



Source: Solaris Dynamic Tracing Guide

The D Language

- D is an interpreted, block-structured language
- D syntax is a subset of C
- D programs are compiled into intermediate form
- Intermediate form is validated for safety when your program is first examined by the DTrace kernel software
- The DTrace execution environment handles any runtime errors

The D Language

- D does not use control-flow constructs such as if statements and loops
- D program clauses are written as single, straight-line statement lists that trace an optional, fixed amount of data
- D can conditionally trace data and modify control flow using logical expressions called *predicates*
- *A predicate is tested at probe firing before executing any statements*

DTrace Performance

- DTrace is dynamic: probes are enabled only when you need them
- No code is present for inactive probes
- There is no performance degradation when you are not using DTrace
- When the `dtrace` command exits, all probes are disabled and instrumentation removed
- The system is returned to its original state

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DTrace Uses

- DTrace takes the power of multiple tools and unifies them with one programmatically accessible interface
- DTrace has features similar to the following:
  - `truss`: tracing system calls, user functions
  - `ptrace`: tracing library calls
  - `prex/tnf`*: tracing kernel functions
  - `lockstat`: profiling the kernel
  - `gdb`: access to kernel/user memory

DTrace Uses

- DTrace combines system performance statistics, debugging information, and execution analysis into one tight package
- A real “Swiss army knife” for reverse engineers
- DTrace probes can monitor every part of the system, giving “the big picture” or zooming in for a closer look
- Can debug “transient” processes that other debuggers cannot

Creating DTrace Scripts

- Dozens of ready-to-use scripts are included with Sun's DTraceToolkit; they can be used as templates
- These scripts provide functions such as syscalls by process, reads and writes by process, file access, stack size, CPU time, memory r/w and statistics
- Complex problems can often be diagnosed by a single "one-liner" DTrace script

Example: Syscall Count

- System calls count by application:

dtrace -n 'syscall:::entry{@[execname] = count();}'.

Matched 427 probes	
Syslogd	1
DirectoryService	2
Finder	3
TextMate	3
Cupsd	4
Ruby	4309
vmware-vmx	6899

Example: File Open Snoop

```
#!/usr/sbin/dtrace -s

syscall::open*:entry {
  printf("%s %s\n",
          execname,
          copyinstr(arg0));
}
```

Example: File Snoop Output

vmware-vmx	/dev/urandom
Finder	/Library/Preferences/SystemConfiguration/com.apple.smb.server.plist
iChat	/Library/Preferences/SystemConfiguration/com.apple.smb.server.plist
Microsoft Power	/Library/Preferences/SystemConfiguration/com.apple.smb.server.plist
nmblookup	/System/Library/PrivateFrameworks/ByteRange ... ByteRangeLocking
nmblookup	/dev/dtracehelper
nmblookup	/dev/urandom
nmblookup	/dev/autofs_nowait
Nmblookup	/System/Library/PrivateFrameworks/ByteRange... ByteRangeLocking

DTrace Lingo

- Probes are points of instrumentation
- Providers are logically grouped sets of probes
- Examples of providers include syscall, lockstat, fbt, io, mib
- Predicates allow actions to be taken only when certain conditions are met
- Actions are taken when a probe fires

DTrace Syntax

Generic D Script

<u>Probe</u>: provider:module:function:name

<u>Predicate</u>: /some condition that needs to happen/

{

<u>Action</u>: action1;

action2; (ex: printf();)

}

How Can We Use DTrace?

DTRACE AND REVERSE ENGINEERING (RE)

DTrace for RE

- DTrace is extremely versatile and has many applications for RE
- It is very useful for understanding the way a process works and interacts with the rest of the system
- DTrace probes work in a manner very similar to debugger “hooks”
- DTrace probes are useful because they can be described generically and focused later

DTrace for RE

- Think of DTrace as a rapid development framework for RE tasks and tools
- One of DTrace's greatest assets is speed
- DTrace can instrument any process on the system without starting or stopping it
- Complex operations can be understood with a succinct one-line script
- You can refine your script as the process continues to run

Helpful Features

DTrace gives us some valuable features for free:

- Control flow indicators
- Symbol resolution
- Call stack trace
- Function parameter values
- CPU register values
- Both in kernel space and user space!

Control Flow

```
1    -> -[AIContentController finishSendContentObject:]
1      -> -[AIAdium notificationCenter]
1      <- -[AIAdium notificationCenter]
1      -> -[AIContentController processAndSendContentObject:]
1        -> -[AIContentController handleFileSendsForContentMessage:]
1        <- -[AIContentController handleFileSendsForContentMessage:]
1        -> -[AdiumOTREncryption willSendContentMessage:]
1          -> policy_cb
1            -> contactFromInfo
1              -> -[AIAdium contactController]
1              <- -[AIAdium contactController]
1              -> accountFromAccountID
```

Symbol and Stack Trace

```
dyld`strcmp
  dyld`ImageLoaderMachO::findExportedSymbol(char
  dyld`ImageLoaderMachO::resolveUndefined(...
  dyld`ImageLoaderMachO::doBindLazySymbol(unsigned
  dyld`dyld::bindLazySymbol(mach_header const*, ...
  dyld`stub_binding_helper_interface2+0x15
  Ftpd`yylex+0x48
  Ftpd`yyparse+0x1d5
  ftpd`ftp_loop+0x7c
  ftpd`main+0xe46
```

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Function Parameters

DTrace's copyin* functions allow you to copy data from the process space:

```
printf("arg0=%s", copyinstr( arg0 ))
```

Output:

```
1  -> strcmp     arg0=_isspecial_l
```

CPU Register Values

Uregs array allows access to reading CPU registers

```
printf("EIP:%x", uregs[R_EIP]);
```

Example:

```
EIP: 0xdeadbeef
EAX: 0xffffeae6
EBP: 0xdefacedd
ESP: 0x183f6000
```

Destructive Examples

```
#!/usr/sbin/dtrace -w -s
syscall::uname:entry { self->a = arg0; }

syscall::uname:return{
        copyoutstr(“Windows”, self->a, 257);
        copyoutstr(“PowerPC”, self->a+257, 257);
        copyoutstr(“2010.b17”, self->a+(257*2), 257);
        copyoutstr(“fud:2010-10-31”, self->a+(257*3), 257);
        copyoutstr(“PPC”, self->addr+(257*4), 257);
}
```

Adapted from: Jon Haslam, http://blogs.sun.com/jonh/date/20050321

Snooping

```
syscall::write: entry {
   self->a = arg0;
}
syscall::write: return {
   printf("write: %s",
   copyinstr(self->a);
}
```

Got Ideas?

Using DTrace:

- Monitor stack overflows
- Code coverage
- Fuzzer feedback
- Monitor heap overflows

DTrace vs. Debuggers

- Don’t think of DTrace as a DBG.
- User mode and kernel mode debuggers allow you to control execution and inspect process information
- DTrace can instrument both the kernel and user land applications <u>at the same time</u>
- To trace execution, debuggers use instructions to pause and resume execution
- DTrace carries out parallel actions in the kernel when a probe is hit

DTrace vs. Debuggers

- Traditional debuggers also affect the target process's memory layout. DTrace doesn't
- DTrace does not directly perform exception handling
- DTrace can halt process and transfer control to external debugger
- Currently DTrace is not susceptible to traditional anti-debugging techniques (isdebuggerpresent())
- However, Apple has implemented probe blocking with use of the PT_ATTACH_DENY

DTrace vs. Tracers

- Truss, ltrace, and strace operate one process at a time, with no system-wide capability
- Truss reduces application performance
- Truss stops threads through procfs, records the arguments for the system call, and then restarts the thread
- Valgrind™ is limited to a single process and only runs on Linux
- Ptrace is much more efficient at instruction level tracing but it is crippled on OS X

*Valgrind is Open Source/Free Software and is freely available under the GNU General Public License.

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DTrace Limitations

- The D language does not have conditionals or loops
- The output of many functions is to stdout (i.e., stack(), unstack())
- Lack of loops and use of stdout means DTrace is not ideal for processing data
- We can fix this

RE:Trace

Reverse Engineering with Ruby and DTrace

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RE:Trace

- RE:Trace combines Ruby with DTrace
- Ruby gives us the power of OOP, text processing, iteration
- RE:Trace utilizes Ruby libdtrace bindings, written by Chris Andrews
- Can be the glue which combines the power of several existing Ruby RE frameworks (idarub, librub, metasm, MSF3)
- RE:Trace is similar to programmatic debuggers (pyDBG, knoxDBG, immDBG)

IdaRub

- Wraps IDA interface
- Ruby code is the client
- Server is IDA plugin
- Ruby glues it all together
- IdaRub was released by Spoonm at REcon 2006

```
ida.set_item_color(eip, 3000)
```

More info:
http://www.metasploit.com/users/spoonm/idarub/

RE:Trace and Exploit Dev

- Vulnerability analysis times of conventional debuggers can be dramatically reduced with RE:Trace
- DTrace probes allow you to track data input flow throughout a process to understand where and why memory corruption took place
- Methods that cause stack and heap corruption can be pinpointed using IDARub to integrate IDA's static analysis features

RE:Trace and Code Coverage

- DTrace can “hook” every function in a process
- This makes it perfect for implementing a “code coverage aware” fuzzer
- Code coverage is useful for understanding what areas are being fuzzed
- Current RE code coverage monitors are mostly block based (PaiMei)
- We can use IDA to obtain block information or check code coverage at the function or instruction level

Writing a Stack Overflow Monitor

MONITORING THE STACK

Stack Overflow Monitoring

Programmatic control at EIP overflow time allows you to:

- Pinpoint the vulnerable function
- Reconstruct the function call trace
- Halt the process before damage occurs (HIDS)
- Dump and search process memory
- Send feedback to fuzzer
- Attach debugger

Overflow Detection in One Probe

```
#/usr/sbin/dtrace -w -s

pid$target:::return
   / uregs[R_EIP] == 0x41414141 / {
   printf("Don't tase me bro!!!");
          stop()
          ...
}
```

Cautionaries

A few issues to be aware of:

- DTrace drops probes by design
- Tune options, narrow trace scope to improve performance
- Some libraries and functions behave badly
- Stack overflows can cause violations before function return

First Approach

- Store RETURN value at function entry
- uregs[R_SP], NOT uregs[R_ESP]
- Compare EIP to saved RETURN value at function return
- If different, there was an overflow

Simple enough, but false positives from:

- Tail call optimizations
- Functions without return probes

DTrace and Tail Calls

- Certain compiler optimizations mess with the standard call/return control flow
- Tail calls are an example of such an optimization
- Two functions use the same stack frame, saves resources, less instruction
- DTrace reports tail calls as a return then a call, even though the return never happens
- EIP on return is not in the original calling function, it is the entry to second
- Screws up simple stack monitor if not aware of it

New Approach

- Store RETURN value at function entry
- At function return, compare saved RETURN value with CURRENT value
- Requires saving both the original return value and its address in memory
- Fires when saved RETURN ! = current RETURN and EIP = current RETURN

But Missing Return Probes???

Still trouble with functions that “never return”

- Some functions misbehave
- DTrace does not like function jump tables (dyld_stub_*)
- Entry probe but no exit probe

Determining Missing Returns

Using DTrace – l flag

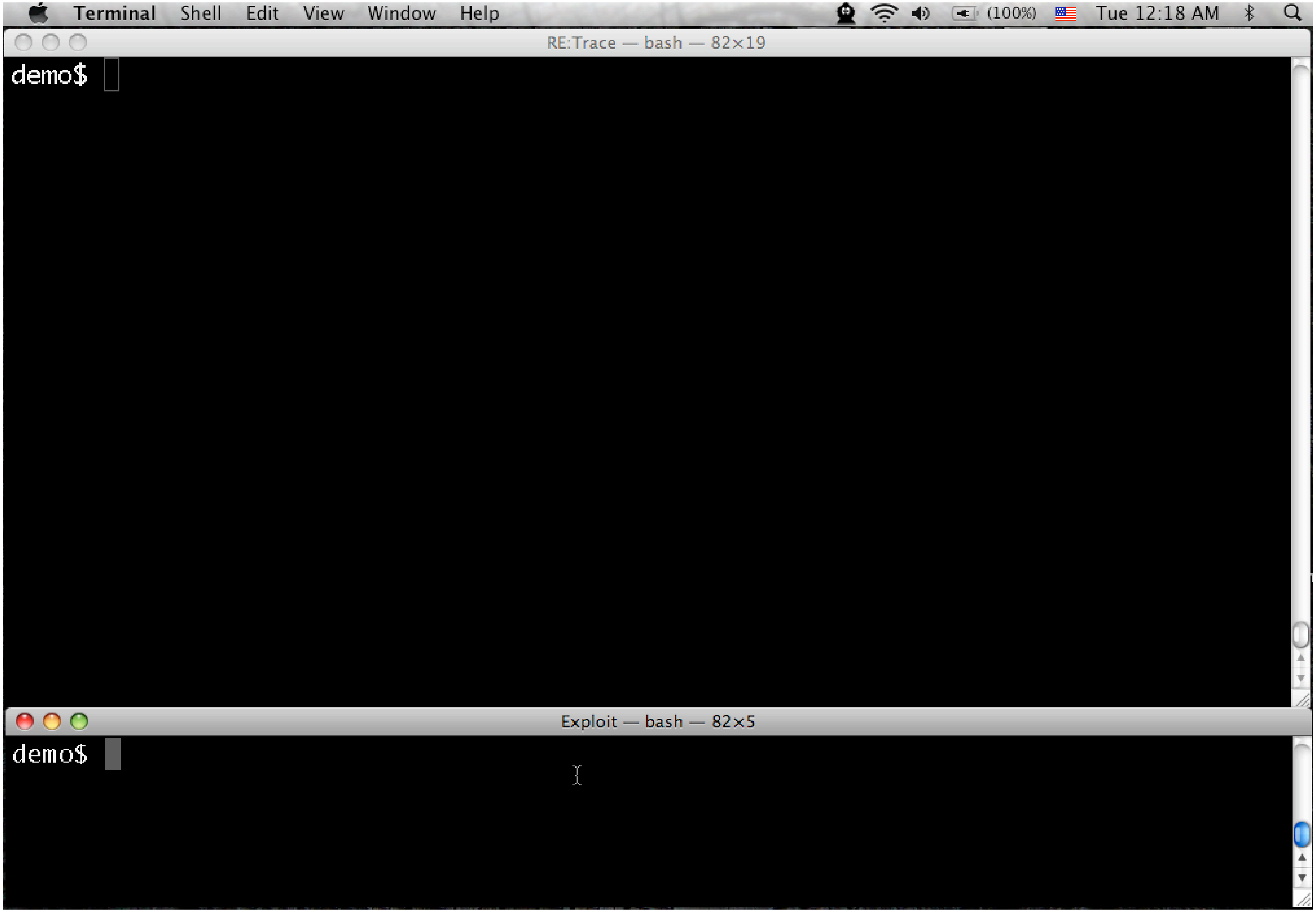
- List entry/exit probes for all functions
- Find functions with entry but no exit probe

Using DTrace aggregates

- Run application
- Aggregate on function entries and exits
- Look for mismatches

Exclude these functions with predicates

- / probefunc ! = “everybodyJump” /


Terminal
Shell
Edit
View
Window
Help
(100%)
Tue 12:18 AM
RE:Trace — bash — 82×19
demo$
Exploit — bash — 82×5
demo$

Advanced Tracing

Diving in deeper:

- Instruction-level tracing
- Code coverage with IDA Pro and IdaRub
- Profiling idle and GUI code
- Feedback to the fuzzer, smart/evolutionary fuzzing
- Conditional tracing based on function parameters (reaching vulnerable code paths)

Instruction Tracing

CODE COVERAGE

Code Coverage Approach

Approach

- Instruction-level tracing using DTrace
- Must properly scope tracing
- Use IdaRub to send commands to IDA
- IDA colors instructions and code blocks
- Can be done in real time, if you can keep up

Tracing Instructions

- The last field of a probe is the offset in the function
- Entry = offset 0
- Leave blank for every instruction
- Must map static global addresses to function offset addresses

Print address of every instruction:

pid$target:a.out:: { print(“%d”, uregs[R_EIP]); }

Tracing Instructions (cont.)

- DTrace to print instructions
- Ruby-Dtrace to combined DTrace with Ruby
- Idarub and rublib to combined Ruby with IDA

Tracing libraries

- When tracing libraries, must know memory layout of program
- `vmmap` on OS X will tell you
- Use offset to map runtime library EIPs to decompiled libraries

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Code Coverage with DTrace

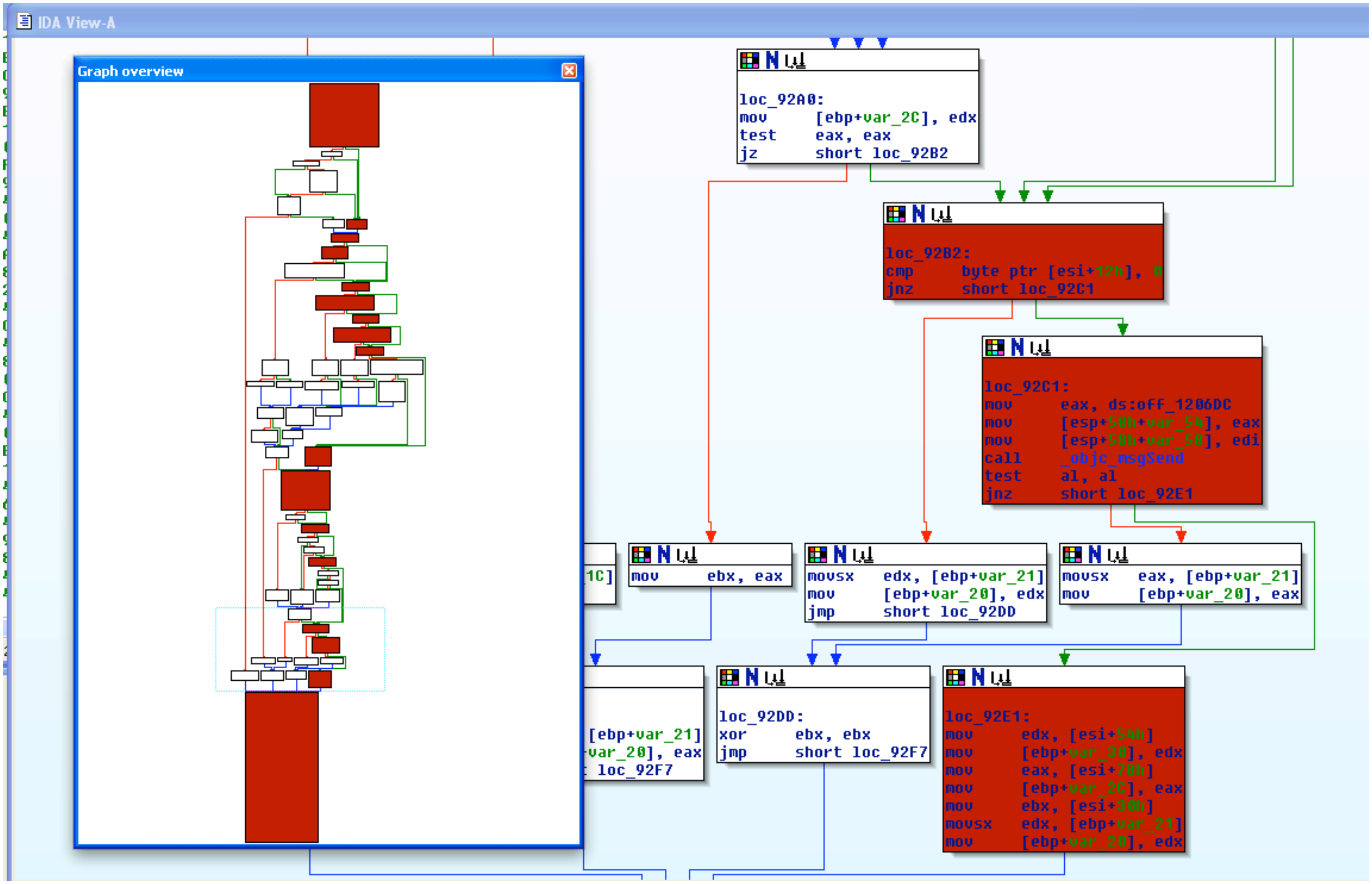
Capabilities:

- Associate fuzz runs with code hit
- Visualize code paths
- Record number of times blocks were hit
- Compare idle traces to other traces

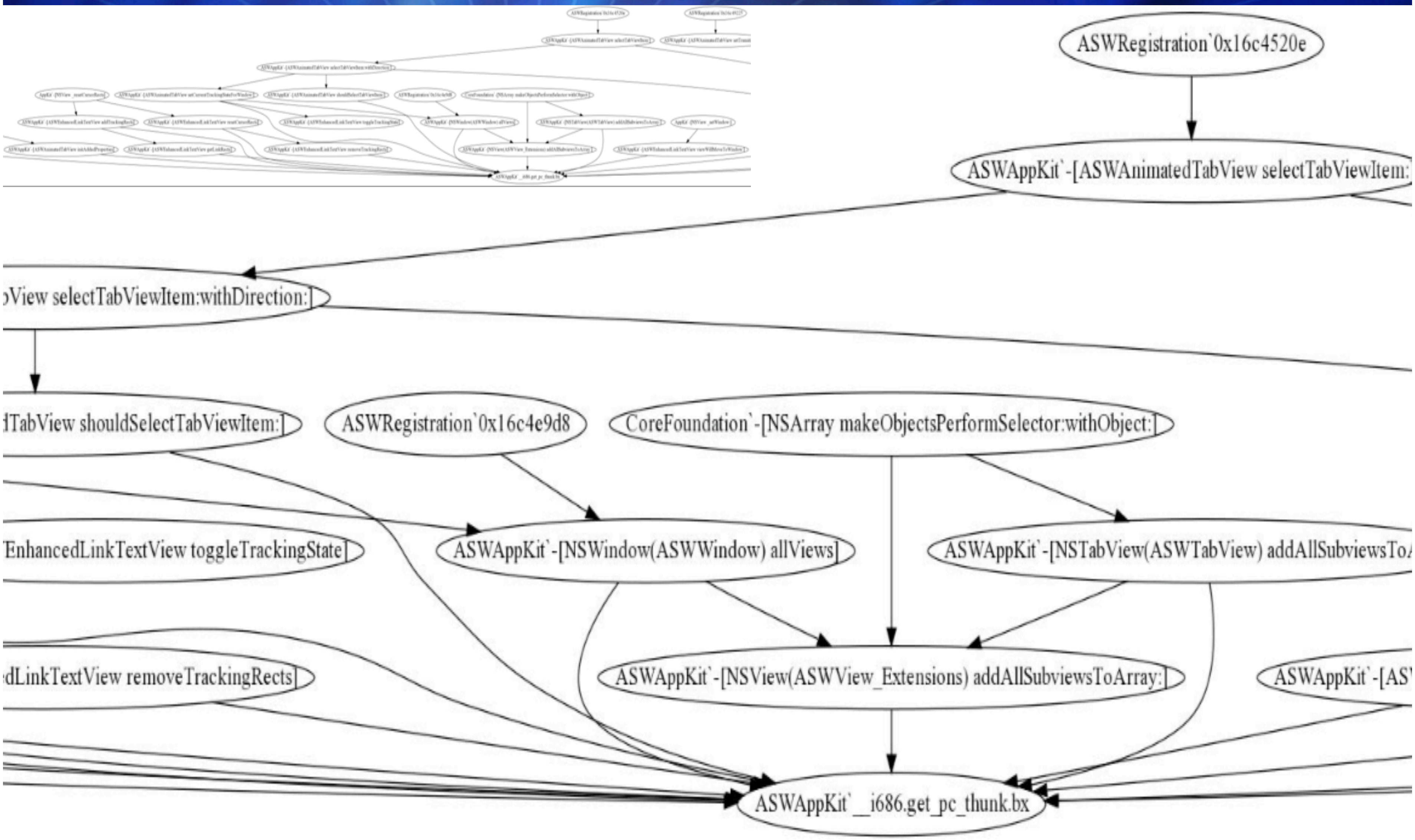
Limitations:

- Instruction tracing can be slow for some applications
- Again, tuning and limiting scope

Coverage Visualization



Runtime Call Graphs



Writing a Heap Overflow Monitor

MONITORING THE HEAP

Hackin' the Heap with RE:Trace

- The heap has become "the" major attack vector replacing stack-based buffer overflows
- Relatively common unlink() write4 primitives are no longer as "easy" to exploit on many platforms
- See Aitel and Waisman's excellent "Debugging with ID" presentation for more details
- As they point out, the key to the "new breed" of heap exploit is understanding the heap layout and allocation patterns
- ImmDBG can help you with this on Win32, and Gerrado Richarte's heap tracer can help you with visualization and double free() on Solaris and Linux

Hackin' the Heap with RE:Trace

- Many Different ways to use DTrace for heap exploits
- Standard double free(), double malloc(), Leak Detection
- Heap Visualization (Directed Graphs/OpenGL/Instruments)
- Pesky off by one errors
- Spot app specific function pointers to overwrite
- Find heap overflows/corruptions that might not be immediately dereferenced

OS X Heap Exploits

- ktrace = Bonds on the Pirates
- DTrace = Bonds on the Giants
- Older techniques such as overwriting initial_malloc_zones function pointers are dead
- You now have to overwrite app specific data
- DTrace already hooks functions to understand heap layout and allocation patterns (what, where, when)
- A slew of Heap Tools for OS X (vmmap, MallocScribble, MallocCheckHeap, leaks)
- DTrace is extensible and *quick* to use

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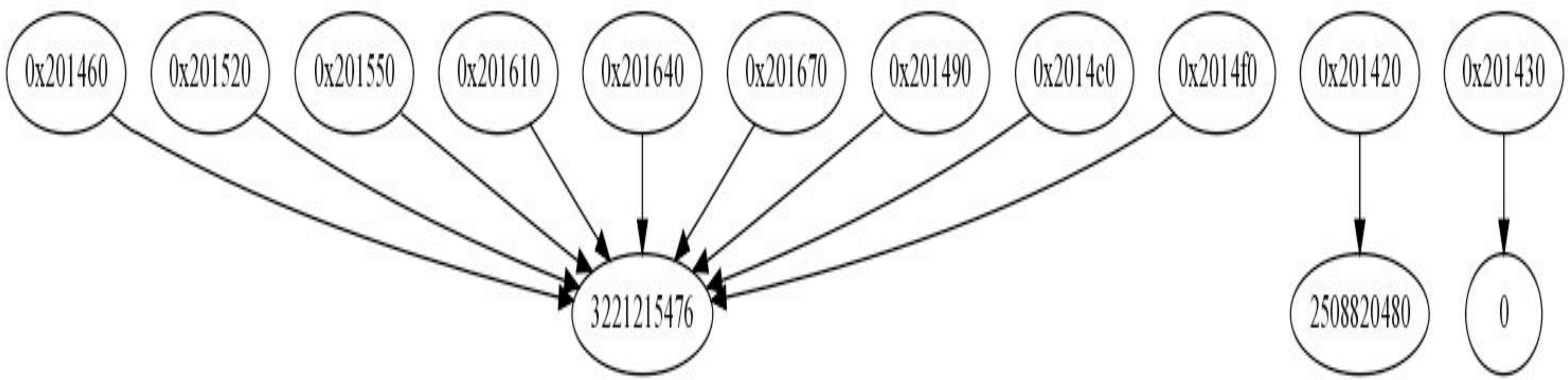
Heap Visualization

Directed Graph of Heap Allocation Sizes:



RE:Trace Heap Smasher()

Refresher:

- When you malloc() on OS X, you are actually calling the scalable zone allocator, which breaks allocations into different zones by size:

Zone Type	Zone Size	Allocation Size	Allocation Quantum
Tiny	2MB	< 992 Bytes	32 bytes
Small	8MB	993-15-369 bytes	1024 bytes
Large	-	15,360 – 16,773,120 bytes	1 page (4096 bytes)
Huge	-	16,773,121 bytes	1 page (4096 bytes)

Adapted from: *OS X Internals A System Approach*

RE:Trace Heap Smasher()

- In our heap smash detector, we must keep track of four different “heaps”
- We do this by hooking malloc() calls and storing them to ruby hashes with the pointer as the key and the size allocated as the value
- We break the hashes into tiny, small, large, and huge by allocation size
- We then hook all allocations and determine if the pointer falls in the range of the previous allocations. We can adjust the heap as memory is free()’d or realloc’d()

RE:Trace Heap Smasher()

- By hooking C functions (strncpy, memcpy, memmove, etc.) we can determine if they are over-allocating to locations in the heap by looking at the arguments and comparing to our heap records

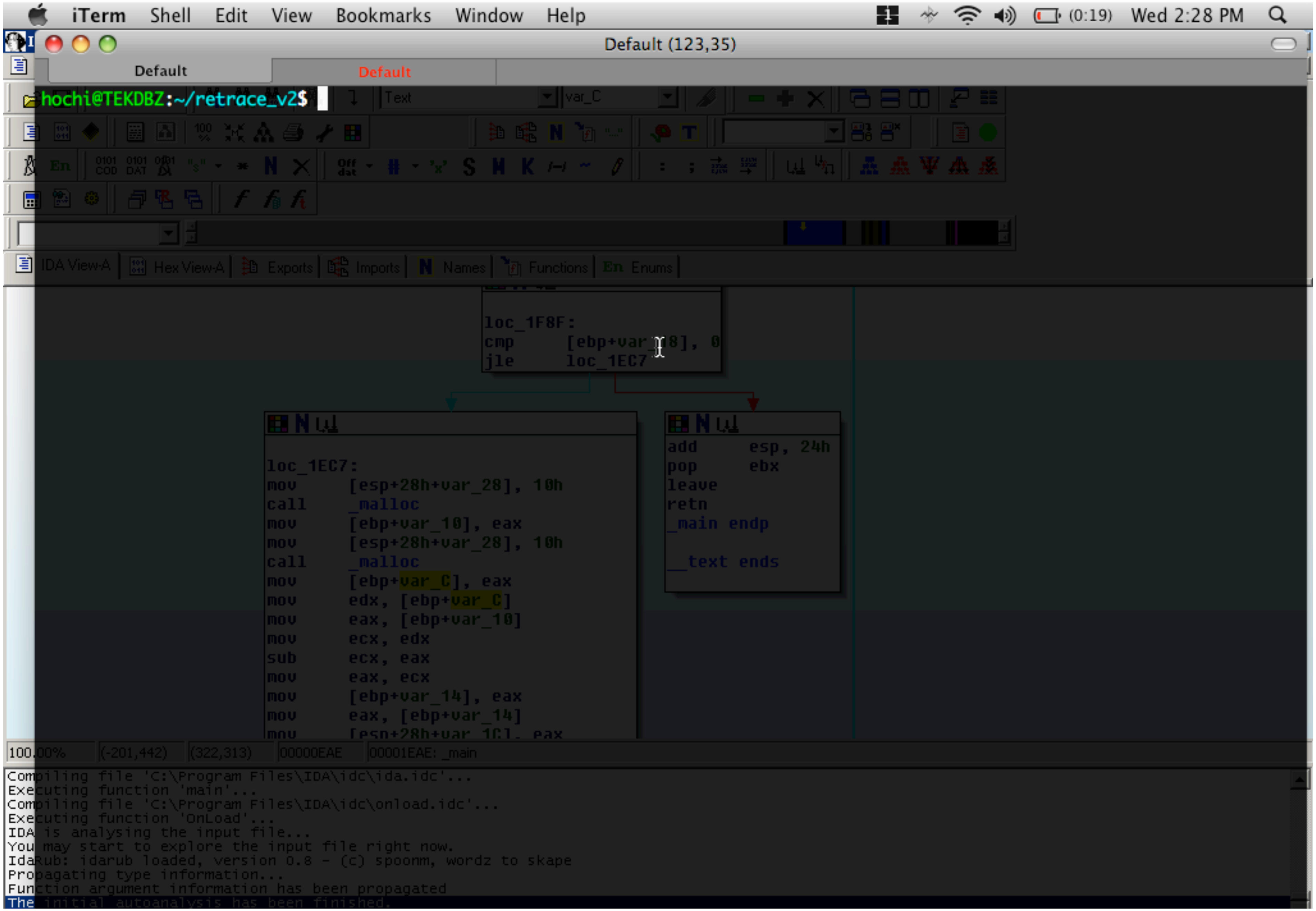
```
pid$target::strncpy:entry {
   self->sizer = arg2;
   printf("copyentry:dst=0x%p|src=0x%p;size=%i", arg0, arg1, arg2);
   self->sizer = 0;
}
```

RE:Trace Heap Smasher()

- We can check to see if the allocation happens in a range we know about (check the hash).
- If it does, we know the size allocation, and we can tell if a smash will occur
- Compared to our stack smash detector, we need very few probes. A few dozen probes will hook all the functions we need
- We can attach to a live process on and off without disturbing it

RE:Trace Heap Smasher()

- We also keep a hash with the stack frame, which is called the original malloc()
- When an overflow is detected, we know:
  - Who allocated it (stack frame)
  - Who used it (function hook)
  - Where the overflowed memory is
  - How large the overflow was
  - We can find out if its ever free()'d


iTerm Shell Edit View Bookmarks Window Help
(0:19) Wed 2:28 PM
Default (123,35)
Default
Default
hochi@TEKDBZ:~/retrace_v2$
IDA View-A Hex View-A Exports Imports Names Functions Enums
loc_1F8F:
cmp [ebp+var_18], 0
jle loc_1EC7
loc_1EC7:
mov [esp+28h+var_28], 10h
call _malloc
mov [ebp+var_10], eax
mov [esp+28h+var_28], 10h
call _malloc
mov [ebp+var_C], eax
mov edx, [ebp+var_C]
mov eax, [ebp+var_10]
mov ecx, edx
sub ecx, eax
mov eax, ecx
mov [ebp+var_14], eax
mov eax, [ebp+var_14]
mov [esp+28h+var_1C], eax
add esp, 24h
pop ebx
leave
retn
_main endp
__text ends
100.00% (-201,442) (322,313) 00000EAE 00001EAE: _main
Compiling file 'C:\Program Files\IDA\idc\ida.idc'...
Executing function 'main'...
Compiling file 'C:\Program Files\IDA\idc\onload.idc'...
Executing function 'OnLoad'...
IDA is analysing the input file...
You may start to explore the input file right now.
IdaRub: idarub loaded, version 0.8 - (c) spoonm, wordz to skape
Propagating type information...
Function argument information has been propagated
The initial autoanalysis has been finished.

RE:Trace Heap Smasher()

Future additions:

- Graphviz/OpenGL Graphs
- There is a new version of Firefox which has probes in the JavaScript library
- This would give us functionality similar to Alexander Soitorov's HeapLib (Heap Fung Shui) for heap manipulation generically
- Safari/DTrace should follow soon
- You tell me?

Using DTrace Defensively

DTRACE DEFENSE

Basic HIDS with DTrace

- Using Dtrace, you can profile your applications basic behavior
- You should then be able to trace for anomalies with predicates
- This is great for hacking up something to protect a custom application (monitor for return-to-libc)
- Easy to create a rails interface for monitoring with Ruby-DTrace

Basic HIDS with DTrace

- Problem: "I want to use QuickTime, but it's got a #@#$@# of holes"
- Solution: Make a DTrace script to call stop() when weird stuff happens
- QuickTime probably never needs to call /bin/sh or mprotect() on the stack to make it writable (Houston we have a problem)

Basic HIDS with DTrace

```
#!/usr/sbin/dtrace  -q -s

proc:::exec
     /execname == "QuickTime Player" &&
     args[0] == "/bin/sh"/
{
     printf("\n%s Has been p0wned! It tried
to  spawned %s\n", execname, args[0])
}
```

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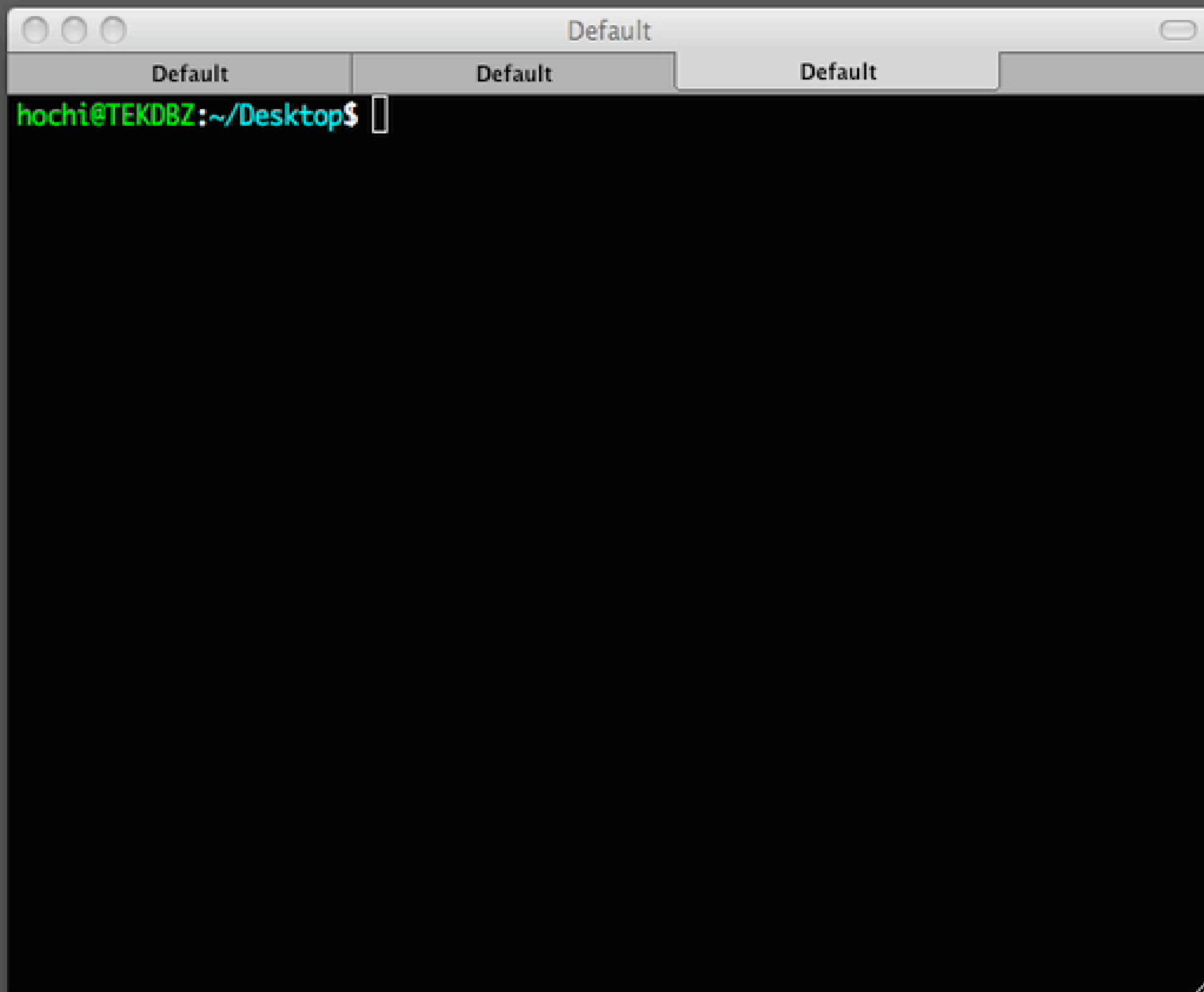
HIDS Video



DTrace and Rootkits

- Check out Archim's paper "B.D.S.M the Solaris 10 Way," from the CCC Conference
- He created the SInAr rootkit for Solaris 10
- Describes a method for hiding a rootkit from DTrace
- Only works on SPARC
- DTrace FBT (kernel) provider can spy on all active kernel modules
- Should have the ability to detect rootkits, which don't explicitly hide from DTrace (SInAr is the only one I could find)
- Expect more on this in the future

DTrace for Malware Analysis

- Very easy to hack up a script to analyze MalWare
- Example: Leopard DNS Changer (**OSX.RSPlug.A)**
- Why the heck is my video codec calling…

    /usr/sbin/scutil

    add ServerAddresses * $s1 $s2

    set State:/Network/Service/$PSID/DNS

- You can monitor file I/O and syscalls with just two lines
- Scripts to do this now included with OS X by default
- Malware not hiding from DTrace yet
- BUT Apple made that a feature (yayyy!)

Hiding from DTrace

- In Jan. Core DTrace developer Adam Leventhal discovered that Apple crippled DTrace for Leopard
- On OSX Your application can set the "PT_ATTACH_DENY" flag to hide from DTrace just like you can for GDB
- Leventhal used timing attacks to figure out they are hiding iTunes™ and QuickTime from DTrace
- Very easy to patch in memory or with kext
- Landon Fuller released a kext to do this

http://landonf.bikemonkey.org/code/macosx/Leopard_PT_DENY_ATTACH.20080122.html

Conclusion

DTrace can:

- Collect an unprecedented range of data
- Collect very specific measurements
- Scope can be **very broad** or **very precise**

Applied to Reverse Engineering:

- Allows researchers to pinpoint specific situation (overflows)
- Or to understand general behavior (heap growth)

Future Work

- Automated feedback and integration with fuzzers
- Kernel tracing
- Improved overflow monitoring
- Heap manipulation libraries (think a cross-platform, cross-browser implementation of Soitorov’s HeapLib)
- Utilizing application-specific probes (probes for JS in browsers, MySQL probes, ...)

Your own ideas!

Thank You!

See the RE:Trace framework for implementation:

http://re-tracer.blogspot.com/

Questions?

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