Revisiting iOS Kernel (In)Security: Attacking the Early Random PRNG

Tarjei Mandt
CanSecWest 2014
tm@azimuthsecurity.com
@kernelpool

About Me

- Senior Security Researcher at Azimuth Security
- Master's degree in Information Security
- Interested in operating system security and mitigation technology
- Recent focus on mobile device security
  - iOS 6 Kernel Security: A Hacker's Guide
- Occasionally blog on security topics
  - http://blog.azimuthsecurity.com

Introduction

- Several new kernel mitigations introduced in iOS 6 and OS X Mountain Lion
  - Stack and heap cookies
  - Memory layout randomization
  - Pointer obfuscation
- Require random (non-predictable) data generated at boot time
  - Introduced the early random PRNG

Early Random PRNG

- Boot time pseudorandom number generator
  - Intended for use before the kernel entropy pool is available
- Primarily designed to support kernel level mitigations
  - Also used to seed the Yarrow PRNG
- Platform dependent
  - Implemented differently in OS X and iOS

Robustness

- Strength of deployed mitigations depend on the robustness of the early random PRNG
  - Must provide sufficient entropy
  - Must produce non-predictable output
- iOS 6 implementation had some notable flaws
  - E.g. suffered from time correlation issues
- iOS 7 attempts to resolve these issues
  - Leverages an entirely new generator

Talk Outline

- Part 1: Early Random PRNG
  - iOS and OS X differences
  - Seed generation (iOS)
  - Improvements made in iOS 7
- Part 2: PRNG Analysis
  - Weaknesses
  - Attacks
  - Remedies

Recommended Reading

- Black-Box Assessment of Pseudorandom Algorithms
  - Derek Soeder et al., BH USA 2013
- PRNG: Pwning Random Number Generators
  - George Argyros, Aggelos Kiayias, BH USA 2012
- iOS 6 Kernel Security: A Hacker's Guide
  - Mark Dowd, Tarjei Mandt, HitB KL 2012

Early Random PRNG

Revisiting iOS Kernel (In)Security

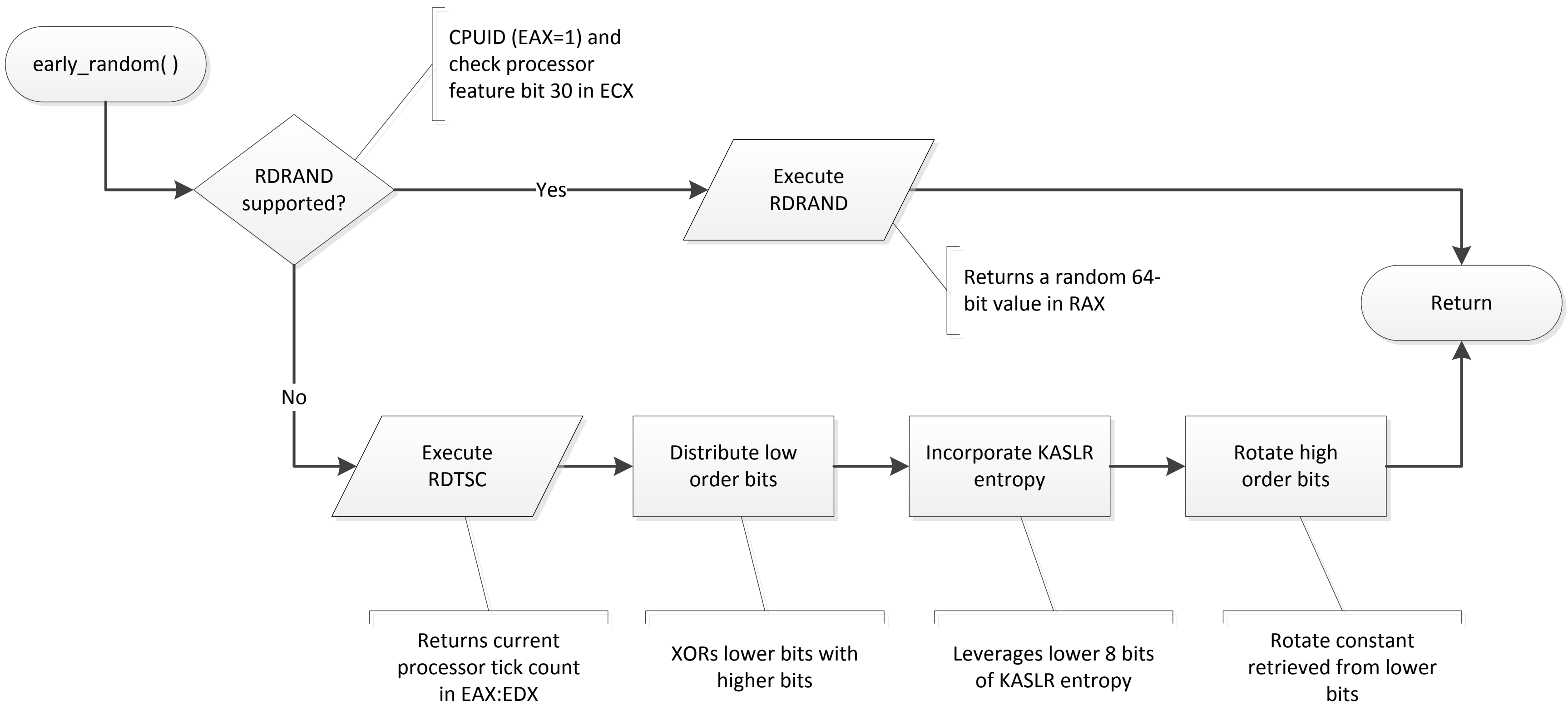
Early Random PRNG

- Two platform specific versions
  - Mac OS X (Intel)
  - iOS (ARM/ARM64)
- Primarily relies on entropy from low-level components
  - CPU clock information
  - Hardware embedded RNG

Early Random in OS X

- Returns the output from RDRAND if available
  - Intel Ivy Bridge and later
- Otherwise derives a value from the time stamp counter and KASLR entropy
  - Distributes the lower order bits (more random)
  - Successive outputs are well-correlated
- Provided in the XNU source
  - osfmk/x86_64/machine_routines_asm.s

Early Random in OS X



Early Random in iOS

- No hardware embedded RNG
  - Output derived from CPU clock counter
- Two different implementations
  - iOS 6: initial version
  - iOS 7: improved version
- Leverages a seed generated by iBoot
  - Provided to the kernel via the I/O device tree
  - IODeviceTree:/chosen/random-seed

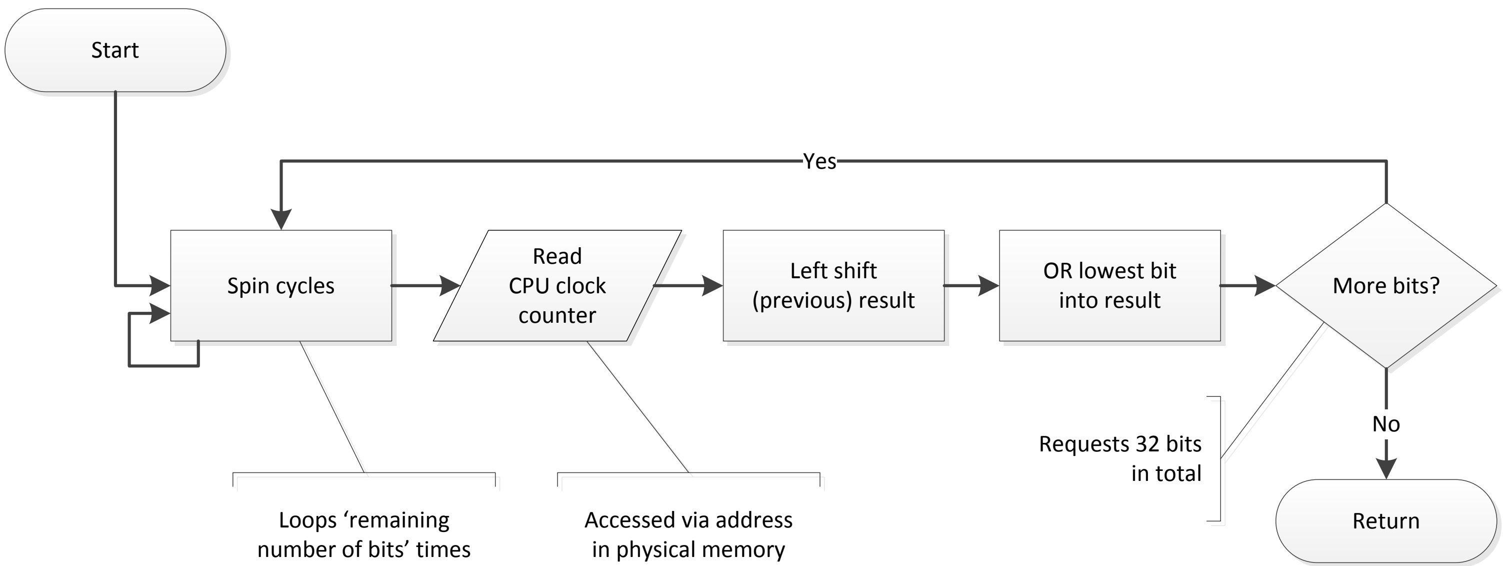
Seed Generation

- iBoot implements its own random data generator
  - Used to generate the early random seed
- Also used to support other tasks
  - Boot nonce generation
  - KASLR slide offset calculation
- Comprises two major components
  - Entropy accumulator
  - Output generator

Entropy Accumulator

- Gathers source entropy from CPU clock information
  - Reads clock counter in physical memory
  - E.g. 0x20E101020 on S5L8960X (Apple A7)
- Generates a 32-bit value
  - Reads lowest bit of clock value
  - Loops ‘remaining number of bits’ times between each read
  - Repeats until 32 bits read

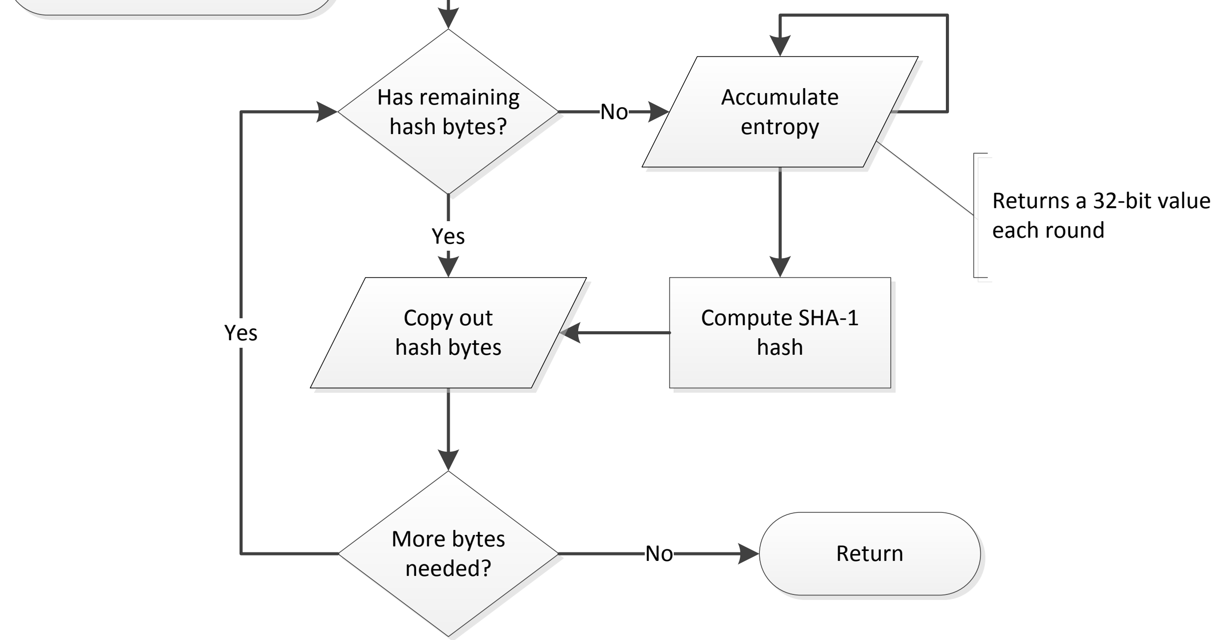
Entropy Accumulator



Output Generator

- Computes a SHA-1 hash over a stream of gathered entropy
  - 64-bit (e.g. iPhone 5S): 4000 bytes
  - 32-bit (e.g. iPhone 4): 9600 bytes
- Outputs the requested number of bytes from the hash itself
  - 20 bytes per hash
- Generates additional hashes if needed
  - Gathers new entropy and repeats the process

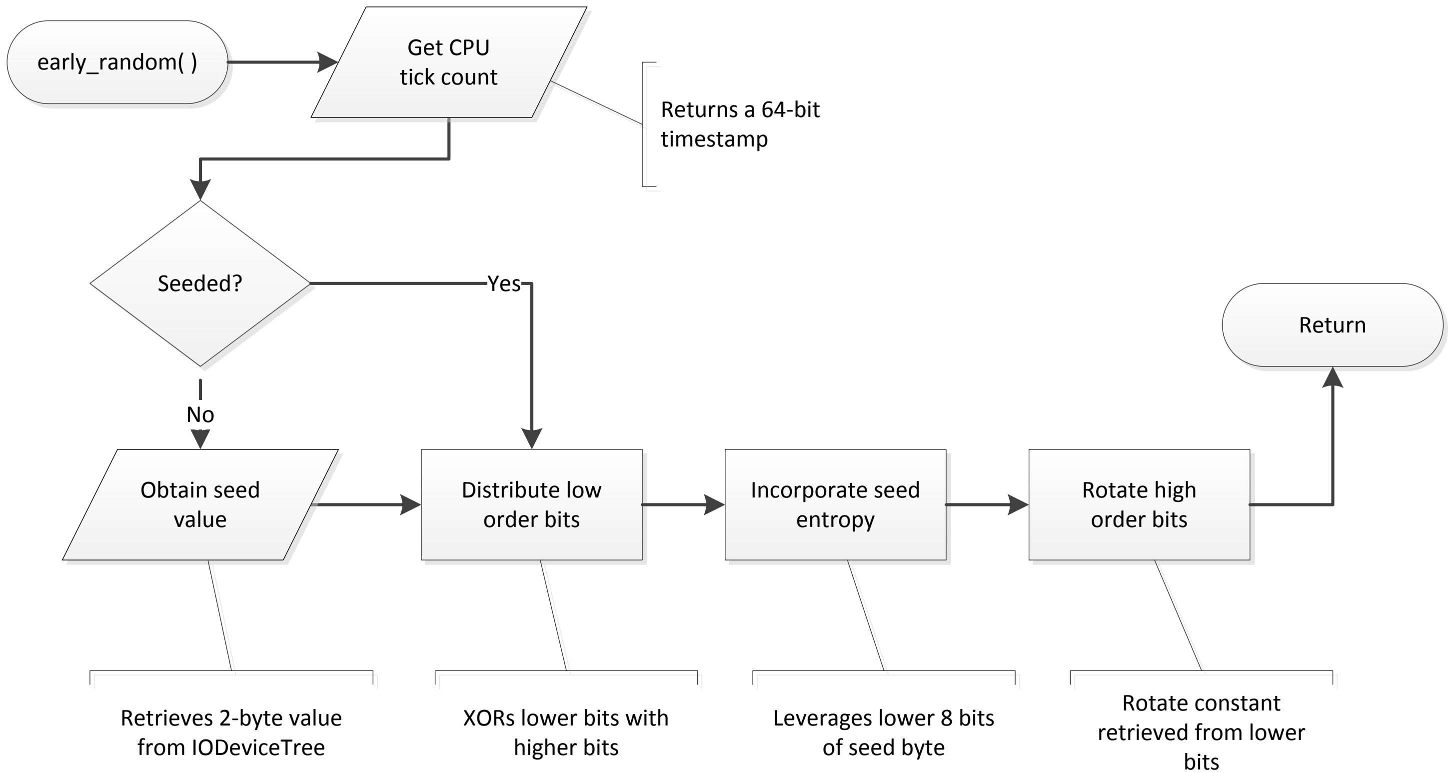
iBoot Random Data Generator



Early Random in iOS 6

- Similar to the OS X implementation
- Output derived from the current Mach absolute time
  - Platform dependent processor tick counter
- Attempts to address weak entropy in higher order bits
  - Mixes lower order (less predictable) with higher order bits
- Leverages a 2-byte seed

Early Random in iOS 6 – Overview



Early Random in iOS 6 – Issues

- Successive outputs are well-correlated
  - Poor entropy source
  - Highly sensitive to time of generation
- Poor use of seed data
  - Only one (lower) byte is used
  - Seed only affects higher 32 bits of output
  - E.g. rarely used on 32-bit devices

Early Random in iOS 6 – Issues

```
/*
 * Initialize backup pointer random cookie for poisoned elements
 * Try not to call early_random() back to back, it may return
 * the same value if mach_absolute_time doesn't have sufficient time
 * to tick over between calls.  <rdar://problem/11597395>
 * (This is only a problem on embedded devices)
 */
```

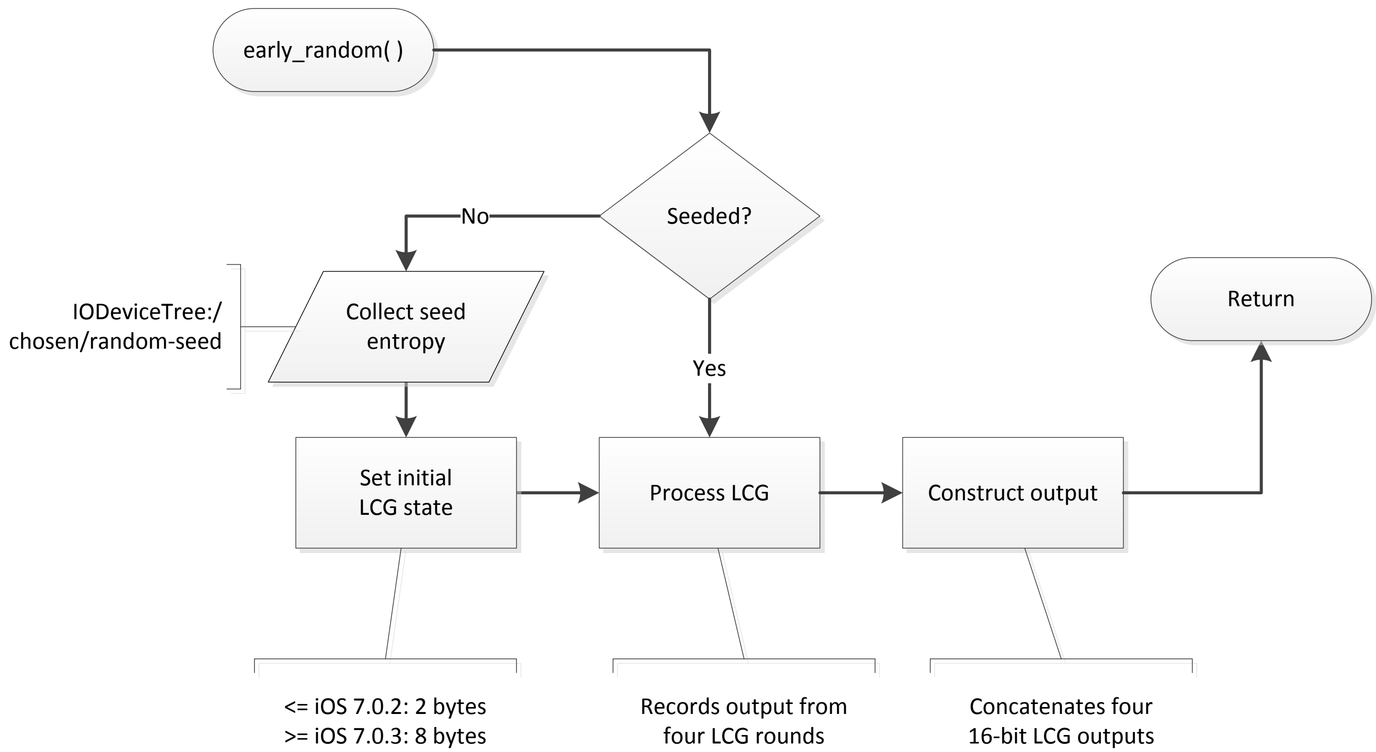
zp_init()
[*osfmk/kern/zalloc.c*]

```
#if MACH_ASSERT
    if (zp_poisoned_cookie == zp_nopoison_cookie)
        panic("early_random() is broken: %p and %p are not random\n",
              (void *) zp_poisoned_cookie, (void *) zp_nopoison_cookie);
#endif
```

Early Random in iOS 7

- Attempts to address the inherent weaknesses of early random in iOS 6
    - Avoids time-based correlation issues
- Output derived from the initial seed
    - Seed extended to 8 bytes in iOS 7.0.3 and later
- Leverages a *linear congruential generator*
    - Algorithm for generating a sequence of pseudorandom numbers

Early Random in iOS 7 – Overview



Linear Congruential Generator

- In an LCG, the next pseudorandom number is generated from the current one such that
  - $x_{n+1} = (ax_n + c) \mod m$
- Where x is the sequence of pseudorandom values, and
  - m = modulus and $m > 0$
  - a = the multiplier and $0 < a < m$
  - c = the increment and $0 <= c < m$
  - x_0 = the starting seed value and $0 <= x_0 < m$

Period

- An LCG's *period* is defined as the longest non-repeating sequence of output numbers
  - Should ideally be as large as possible
- When $c \neq 0$, the maximum period m is only possible if
  - 1. c and m are relatively prime
  - 2. $a - 1$ is divisible by all prime factors of m
  - 3. $a - 1$ is a multiple of 4 if m is a multiple of 4

LCG Parameters

- Early random in iOS 7 implements a *mixed* linear congruential generator
  - Non-zero increment
- LCG parameters are similar to ANSI C rand()
  - Multiplier (a): 1103515245
  - Increment (c): 12345
  - Modulus (m): 2^{64}
- Seed used as initial state x_o

Deriving Output

- Derives output by leveraging information from four successive states ($x_n \ldots x_{n+3}$)
- Each state produces 16 bits of the output
  - Discards the lower 3 bits of each state
  - Outputs the remaining lower 16 bits
- Full output (64-bit) generated by concatenating the retrieved outputs
  - $(x_{n-3} >> 3)$ & 0xffff || $(x_{n-2} >> 3)$ & 0xffff || $(x_{n-1} >> 3)$ & 0xffff || $(x_n >> 3)$ & 0xffff

Early Random in iOS 7

```
uint64_t
early_random( )
{
    uint32_t   i;
    uint64_t   StateArray[ 4 ];

    if ( !early_random_init )
    {
         early_random_init = 1;
         get_entropy_data( );
         ovbcopy( &entropy_data, &State, sizeof(uint64_t) );
    }

    for ( i = 0; i < 4; i++ )
    {
         State = StateArray[ i ] = ( State * 1103515245 ) + 12345;
    }

    return     (     StateArray[ 3 ] >> 3 & 0xffff ) |
               ( ( (StateArray[ 2 ] >> 3 ) << 16 ) & 0xffff0000 ) |
               ( ( (StateArray[ 1 ] >> 3 ) << 32 ) & 0xffff00000000 ) |
               ( ( (StateArray[ 0 ] >> 3 ) << 48 ) & 0xffff000000000000 )
}
```

Early Random PRNG Usage

Revisiting iOS Kernel (In)Security

Early Random PRNG Usage

- Primarily used to provide entropy to various kernel exploit mitigations
  - Physical map randomization
  - Stack check guard
  - Zone cookies and factor
  - Kernel map randomization
  - Pointer obfuscation
- Also used to seed the Yarrow generator

Physical Map Randomization

- Kernel maps a copy of physical memory in its address space
  - Used to support copy operations between virtual and physical addresses
- Base randomization applied to physical map
  - Retrieves a byte from the early random PRNG
  - Byte used as page directory pointer index to map base
  - 0xFFFFFE8000000000 + (0x40000000 * byte)

Physical Map Randomization

```
static void
physmap_init(void)
{
    pt_entry_t *physmapL3 = ALLOCPAGES(1);
    struct {
        pt_entry_t entries[PTE_PER_PAGE];
    } * physmapL2 = ALLOCPAGES(NPHYSMAP);

    uint64_t i;
    uint8_t phys_random_L3 = ml_early_random() & 0xFF;

    …

    physmap_base = KVADDR(KERNEL_PHYSMAP_PML4_INDEX, phys_random_L3, 0, 0);
    physmap_max = physmap_base + NPHYSMAP * GB;
}
```

physmap_init()
[*/osfmk/i386/i386_init.c*]

Stack Check Guard

- Stack cookie used to mitigate exploitation of return pointer overwrites
  - Function prologue places cookie on stack
  - Function epilogue verifies the stack cookie
- System-wide kernel stack cookie created on boot
  - Pointer-wide value generated by early random
  - Second byte zeroed to prevent recreating cookie using null-terminated strings

Stack Check Guard

ARM64

```
__TEXT:__text:FFFFFF8016E1CDDC          BL              _early_random
__TEXT:__text:FFFFFF8016E1CDE0          AND             X8, X0, #0xFFFFFFFFFFFF00FF
__TEXT:__text:FFFFFF8016E1CDE4          ADRP            X9, #___stack_chk_guard@PAGE
__TEXT:__text:FFFFFF8016E1CDE8          ADD             X9, X9, #___stack_chk_guard@PAGEOFF
__TEXT:__text:FFFFFF8016E1CDEC          STR             X8, [X9]
```

```
__TEXT:__text:80017C5C      MOV      R0, #(stack_cookie_ptr - 0x80017C68) ; stack_cookie_ptr
__TEXT:__text:80017C64      ADD      R0, PC ; stack_cookie_ptr
__TEXT:__text:80017C66      LDR      R4, [R0]
__TEXT:__text:80017C68      BL       _early_random ; get random value
__TEXT:__text:80017C6C      BIC.W    R0, R0, #0xFF00
__TEXT:__text:80017C70      STR      R0, [R4] ; stack cookie
```

ARMv7

Zone Cookies

- Attempt to mitigate exploitation of zone free list pointer overwrites
  - Encoded free list pointer stored at chunk end
  - Verified on allocation
- Early random PRNG generates two cookies
  - zp_poisoned_cookie
  - zp_nopoisoned_cookie
- Poisoned cookie used whenever chunk content is poisoned (filled with *0xdeadbeef*) on free

Zone Cookies

```
  /* Initialize backup pointer random cookie for poisoned elements */
  zp_poisoned_cookie = (uintptr_t) early_random();

  /* Initialize backup pointer random cookie for unpoisoned elements */
  zp_nopoison_cookie = (uintptr_t) early_random();

  zp_poisoned_cookie |=   (uintptr_t)0x1ULL;
  zp_nopoison_cookie &= ~((uintptr_t)0x1ULL);

#if defined(__LP64__)
  zp_poisoned_cookie &= 0x000000FFFFFFFFFF;
  zp_poisoned_cookie |= 0x0535210000000000; /* 0xFACADE */

  zp_nopoison_cookie &= 0x000000FFFFFFFFFF;
  zp_nopoison_cookie |= 0x3f00110000000000; /* 0xC0FFEE */
#endif
```

zp_init()
[*/osfmk/kern/zalloc.c*]

Zone Poison Factor

- Determines how frequently larger zone blocks are poisoned
  - Defaults to 16 in iOS 7
- Early random PRNG generates a bias value
  - 3 lower bits of output
- Zone poison factor adjusted by bias
  - Increments/decrements by 1 or remains at original value
  - Ensures less predictable poisoning pattern

Zone Poison Factor

```
zp_factor = ZP_DEFAULT_SAMPLING_FACTOR;

//TODO: Bigger permutation?
/*
 * Permute the default factor +/- 1 to make it less predictable
 * This adds or subtracts ~4 poisoned objects per 1000 frees.
 */
if (zp_factor != 0) {
    uint32_t rand_bits = early_random() & 0x3;

    if (rand_bits == 0x1)
          zp_factor += 1;
    else if (rand_bits == 0x2)
          zp_factor -= 1;
    /* if 0x0 or 0x3, leave it alone */
}
```

zp_init()
[*/osfmk/kern/zalloc.c*]

Kernel Map Randomization

- Task memory divided into maps and sub-maps
  - Kernel space defined by kernel_map
- Allocations from maps are generally made from the lowest possible address
  - Early allocations may fall at predictable offsets
- Kernel triggers a randomly sized allocation on boot
  - First allocation made in the kernel map
  - Size determined by 9 bits from early random
  - Randomizes the offset of subsequent heap, stack, and zone addresses

Kernel Map Randomization

```
/*
 * Eat a random amount of kernel_map to fuzz subsequent heap, zone and
 * stack addresses. (With a 4K page and 9 bits of randomness, this
 * eats at most 2M of VA from the map.)
 */
if (!PE_parse_boot_argn("kmapoff", &kmapoff_pgcnt,
    sizeof (kmapoff_pgcnt)))
    kmapoff_pgcnt = early_random() & 0x1ff; /* 9 bits */

if (kmapoff_pgcnt > 0 &&
    vm_allocate(kernel_map, &kmapoff_kaddr,
    kmapoff_pgcnt * PAGE_SIZE_64, VM_FLAGS_ANYWHERE) != KERN_SUCCESS)
    panic("cannot vm_allocate %u kernel_map pages", kmapoff_pgcnt);
```

vm_mem_bootstrap()
[*/osfmk/vm/vm_init.c*]

Yarrow Seed

- iOS and OS X provide a cryptographically secure pseudorandom number generator
  - Leverages the SHA-1 version of Yarrow
  - Designed by Counterpane, Inc.
- Accessible through two character devices
  - /dev/(u)random
- Kernel requests a 64-bit value from early random to seed the Yarrow PRNG

Yarrow Seed

```
uint64_t tt;
char buffer [16];

/* get a little non-deterministic data as an initial seed. */
/* On OSX, securityd will add much more entropy as soon as it */
/* comes up.  On iOS, entropy is added with each system interrupt. */
tt = early_random();

perr = prngInput(gPrngRef, &tt, sizeof (tt), SYSTEM_SOURCE, 8);
if (perr != 0) {
    /* an error, complain */
    printf ("Couldn't seed Yarrow.\n");
    goto function_exit;
}
```

PreliminarySetup()
[*/bsd/dev/random/randomdev.c*]

Permutation Values

- Many APIs traditionally exposed kernel pointers to user mode (e.g. as tokens)
  - Now obfuscated using permutation values
- Two permutation values generated by early random at boot time
  - vm_kernel_addrperm
  - buf_kernel_addrperm
- Least significant bit is always set
  - Ensures that obfuscated value never becomes null

Permutation Values

```
/*
 * Initialize the global used for permuting kernel
 * addresses that may be exported to userland as tokens
 * using VM_KERNEL_ADDRPERM(). Force the random number
 * to be odd to avoid mapping a non-zero
 * word-aligned address to zero via addition.
 */
vm_kernel_addrperm = (vm_offset_t)early_random() | 1;
buf_kernel_addrperm = (vm_offset_t)early_random() | 1;
```

```
#define   VM_KERNEL_ADDRPERM(_v)                    \
          (((vm_offset_t)(_v) == 0) ?               \
               (vm_offset_t)(0) :                   \
               (vm_offset_t)(_v) + vm_kernel_addrperm)
```

kernel_bootstrap_thread()
[*/osfmk/kern/startup.c*]

Summary

Name	Variable	Initialization	Notes
Physical Map Offset	phys_random_l3	physmap_init()	OS X only
Stack Check Guard	stack_chk_guard	arm_init() / vstart()	Second byte zeroed
Zone Poison Cookie	zp_poisoned_cookie	zp_init()	Lower bit set
Zone Factor	zp_factor	zp_init()	Only lower two bits
Zone No Poison Cookie	zp_nopoison_cookie	zp_init()	Lower bit cleared
Kernel Map Offset	kmapoff_pgcnt	vm_mem_bootstrap()	No. pages (4K)
Yarrow Seed	n/a (stack variable)	PreliminarySetup()	
VM Permutation Value	vm_kernel_addrperm	kernel_bootstrap_thread()	Lower bit set
I/O Buffer Permutation Value	buf_kernel_addrperm	kernel_bootstrap_thread()	Lower bit set

PRNG Analysis (iOS 7)

Revisiting iOS Kernel (In)Security

Requirements

- Likely that an attacker may recover a single PRNG output or parts of it
  - Stack cookie disclosure (e.g. via memory leak)
  - Permutation value disclosure (e.g. using method presented by Stefan Esser at SyScan 2013)
- At minimum, the PRNG should
  - Resist backtracking of compromised output
  - Resist direct cryptoanalysis of outputs

LCG Problems

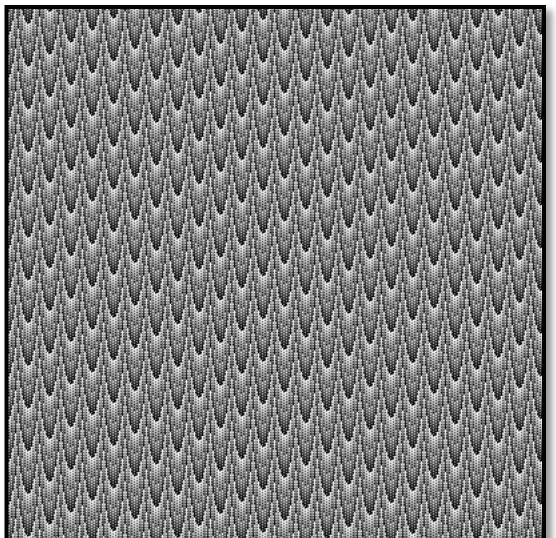
- Several well-known problems with linear congruential generators
  - Serial correlation between successive outputs
  - Weak low order bits
  - Output period is often much lower than possible output space
- Susceptible to brute-force attacks
  - May allow recovery of the internal PRNG state
  - Usually only requires a small number of outputs

Weak Bits

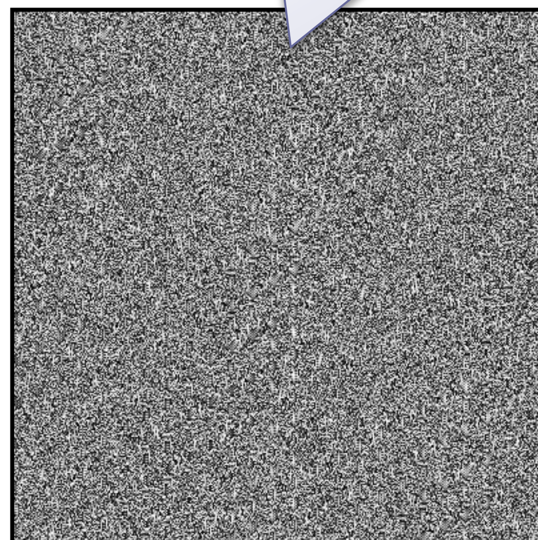
- LCGs with a modulus to a power of 2 typically discard the lower bits from the output
  - Lower bits go through very short cycles
  - Lower 16 or 32 bits usually discarded
- The early random PRNG only discards 3 bits from each LCG round
  - Weak bits still present in the output
  - Allows an attacker to predict lower bits

Weak Bits

Lower byte of each output represented as pixel value (0-255)



Low-order byte in output fragment



High-order byte in output fragment

Output Period

- Typically much lower than the output space
  - Weak bits discarded from output
  - Multiple states mapped to a single output
- The early random PRNG constructs a 64-bit output from four successive states
  - State modulus: 2^{64}
  - Discard divisor: 2^{3} (discards lower 3 bits)
  - Output modulus: 2^{16} (outputs remaining 16 bits)

Output Period

- State modulus (2^{64}) is divisible by the output modulus (2^{16}) times discard divisor (2^3)
  - Only lower 19 bits of a given state affect the output
  - Effective state modulus: $2^{16} \times 2^3 = 2^{19}$
- Number of concatenated outputs (4) is not relatively prime to the effective state modulus
  - Output period reduced to 17 bits
  - Longest unique sequence of PRNG outputs: 131072 (!)

State Seeking

- Past and future states can be computed if the internal state is known
  - No external re-seeding of internal state
- Backtrack using multiplication inverse of the LCG's multiplication term for modulus 2^{64}
  - E.g. using Euclid's extended algorithm
  - Possible as multiplier (a) and modulus (m) are relatively prime, i.e. GCD(m,a) == 1

Output Recovery

- An attacker can recover arbitrary outputs if the lower 19 bits of the internal state is known
  - 16 bits are reflected in output (known)
  - 3 bits are discarded (unknown)
- Trivial to brute-force discarded bits using information from two successive states
  - Four states held by each 64-bit PRNG output
  - Requires at most 2^3 tries

Recovering Discarded Bits

```
uint8_t get_weaker_bits( uint64_t output )
{
    uint64_t state_4, state_3;
    uint8_t bits;

    for ( bits = 0; bits < 8; bits++ )
    {
        state_4 = ( ( output & 0xffff ) << 3 ) | bits;

        // Compute previous state using modular multiplicative inverse (for mod 2^19)
        state_3 = ( ( state_4 - 12345 ) * 125797 );

        // Check if the bits of previous state correspond with the bits in the PRNG output
        if ( ( state_3 >> 3 & 0xffff ) == ( output >> 16 & 0xffff ) )
        {
            return bits;
        }
    }

    return -1;
}
```

Seed Recovery

- Seed is used as the initial PRNG state
  - Generated by iBoot
- Seed recovery may provide information on the generating component
  - In this case, a SHA-1 hash generated by iBoot
  - Same hash used for computing KASLR slide

Seed Recovery (iOS < 7.0.3)

- Prior to iOS 7.0.3, early random only leveraged a 2-byte seed
  - Provides 16 bits of entropy
- Attacker can recover the whole seed via backtracking
  - E.g. via partial internal state recovery

Seed Recovery (iOS >= 7.0.3)

- Since iOS 7.0.3, early random leverages an 8-byte seed
- Entropy is still very limited due to algorithm constraints
  - Only lower 19 bits of the seed is used
- Attacker can recover the lower part of the seed via backtracking

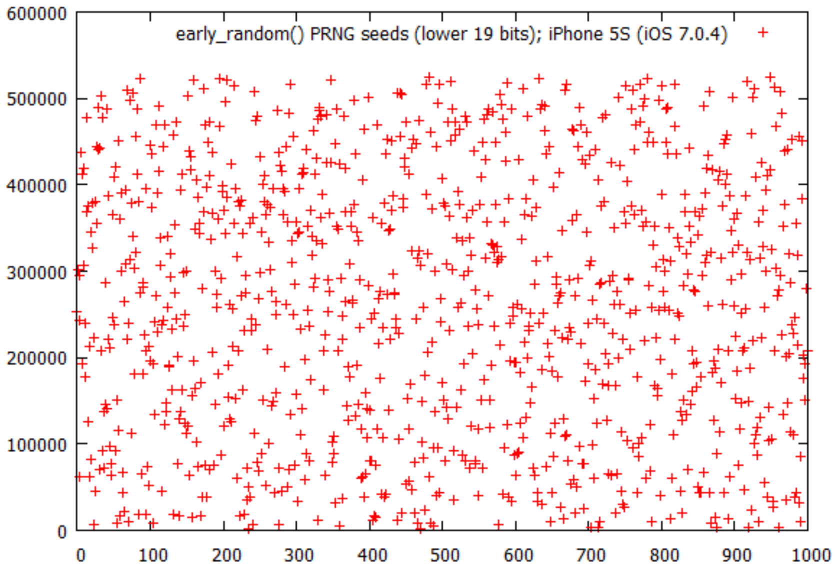
Seed Entropy

- Seed should provide sufficient entropy
  - Outputs derived directly from it
- Expected to be random
  - Should not exhibit bias
  - Bits should be evenly distributed
  - Must remain non-predictable

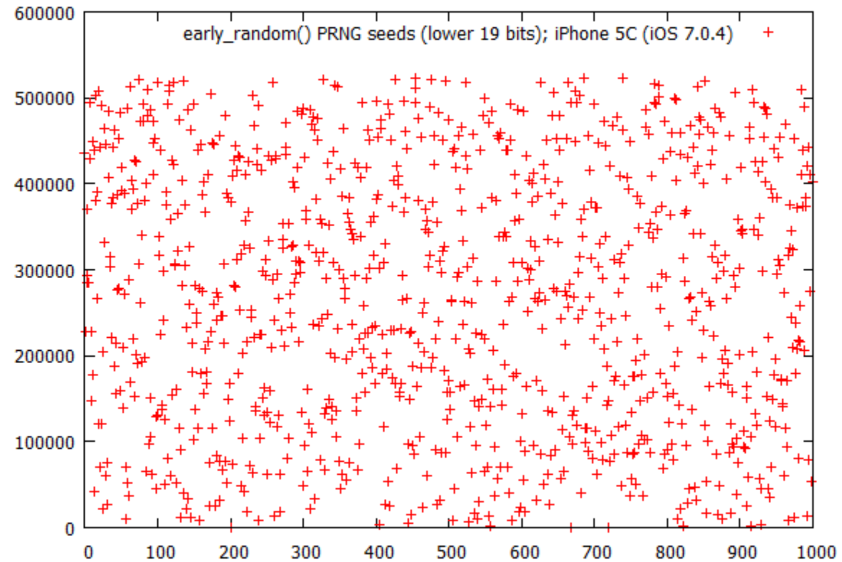
Seed Analysis

- Recorded seeds from 1000 boots from various devices
  - Appears to be evenly distributed
  - No noticeable bias in collected sets
- Ideally require a lot more seeds to perform proper statistical analyses
  - Time consuming as these results are hard to simulate

Seed Analysis: iPhone 5S/5C



iPhone 5S (iOS 7.0.4)



iPhone 5C (iOS 7.0.4)

Case Study: Arbitrary Output Recovery

Revisiting iOS Kernel (In)Security

Assumptions

- Attacker has no particular knowledge about the kernel address space
- Attacker is not assisted by additional vulnerabilities or information leaks
- Attacker is unprivileged and restricted by an application sandbox

Attack Objectives

- Recover (parts of) a PRNG output
  - Should reveal information from at least 2 states
- Recover the lower 19 bits of the internal PRNG state for the recovered output
  - E.g. via brute-force
- Win ☺

Recovering PRNG Output

- Raw output not exposed directly to user
  - However, we can obtain obfuscated values
- Many ways to obtain obfuscated pointers
  - E.g. query the inode number of a pipe via fstat()
- Possible to deduce output bits from an obfuscated pointer
  - Memory/pointer alignment
  - Static address bits

Known Address Bits

- Lower bits are recoverable given that we know the object's relative memory position
  - E.g. intra-zone page locality
  - Note: lowest bit is always set
- In 64-bit builds of iOS, the higher 32 bits of kernel pointers are always fixed
  - 0xffffff80xxxxxxxx
  - We can recover these bits via simple subtraction!

Recovering Discarded Bits

- The higher 32 bits are derived from two successive PRNG states
  - Can be used to brute-force the discarded bits (2^3)
  - Need to consider possible carry bit (into high 32 bits) caused by the obfuscation (2^1)
  - Brute-force space: 2^4
- Once the discarded bits are found, the remaining states can be computed
  - Recovers the full output

Attack Summary

- Query obfuscated pipe object pointer
- Recover high 32 bits of obfuscated pointer
  - Subtract known address bits
- Brute force discarded bits of the internal state
- Seek to target state
- Compute output

Demo

- Arbitrary output recovery on iPhone 5S

Improvements

Revisiting iOS Kernel (In)Security

Reduce State Information

- Hard to defend against an attacker who can monitor PRNG outputs
  - Even when the internal LCG parameters are unknown
- Less state generations per output may make attacks less practical
  - Prevent brute-force of internal state using single output
  - May also improve PRNG period

Weak Bits and Correlation

- Avoid weak bits
  - Use a higher output discard divisor
- Pass output through a temper function
  - Reduces serial correlation between outputs
  - E.g. used by Mersenne Twister
- Alternatively, choose a PRNG with less correlation
  - E.g. an LFG operating over boot loader seed data
  - Similar strategy as Windows 8/8.1

Mitigation Hardening

- Severity of PRNG output recovery can be reduced by hardening mitigations
  - XOR stack cookies with address of stack frame
  - XOR zone list pointers with address of zone allocation
- Should limit the number of known address bits exposed by obfuscated pointers
  - Higher 32 bits are always static (0xffffff80)
  - Can be replaced by a sentinel value or truncated

Conclusion

Revisiting iOS Kernel (In)Security

Conclusion

- Exploit mitigations are only as strong as the weakest link
- Early random in iOS 7 is surprisingly weak
  - Exhibits a high degree of determinism
  - Trivial to brute force
- Avoid single point of compromise
  - Leverage additional entropy when possible
  - E.g. combine cookies with address information

Thanks!

- Questions?
  - @kernelpool
  - kernelpool@gmail.com
  - tm@azimuthsecurity.com
- White paper
  - http://blog.azimuthsecurity.com