Analysis of the Linux random number generator

(Presentation based on article of Z. Gutterman, B. Pinkas, and T. Reinman)

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Article outline

- Random number generator in Linux – unique combination of TRNG and PRNG
    - A part of a Linux kernel
    - About 2500 lines of code
        - Poorly documented
        - Hundreds of (undocumented) patches
- Reverse engineering used for generator analysis
    - One bug in code itself
    - The problem with forward security
    - Several other design flaws
- Fundamentals of random number generation
    - Terminology issue (jargon in this field): term "entropy" instead of "data with entropy"

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Random number generation

- Truly random data (samples) generated by TRNG
  - Hardware-based TRNG
    - Exact timing of keystrokes or exact movements of mouse
  - Software-based TRNG
    - Process, network, or I/O completion statistics
  - Difficulty of collecting sufficient amount truly random data => the need of pseudo-random data
- Pseudorandom data generated by PRNG
  - PRNG is deterministic finite state machine => at any point of time it is in a certain internal state
    - PRNG state is secret (PRNG output must be unpredictable)
    - PRNG (whole) state is repeatedly updated (PRNG must produce different outputs)
- The problem of state compromitting => need of recovering from state compromise => periodic state refreshing => pooling

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Linux (pseudo)random number generator (LRNG)

- Access to the LRNG through two device drivers
  - `/dev/random` and `/dev/urandom`
- Both devices let users read pseudorandom bits
  - Difference – the level of security and resulting delay
  - Blocked `/dev/random` and non-blocked `/dev/urandom`
- Basic structure of the LRNG – three asynchronous components:
  - 1^{st} translates system events into bits
  - 2^{nd} adds these bits to the LFSR-based generator pool
  - 3^{rd} applies three consecutive SHA-1 operations to generate the output (feedback also entered back into the pool)
- Each sample of "randomness" (from system events) collected as two 32-bit words
  - The first word: measures the time of the event
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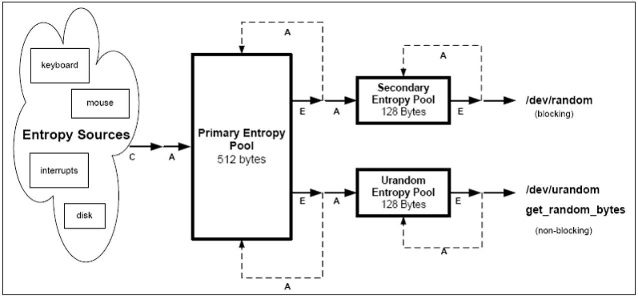
Pools and counters

- Internal state kept in three entropy pools:
  - Primary (512 B), secondary (128 B), and urandom (128 B)
  - Entropy sources add data to the primary (or secondary) pool
  - Output generated from secondary/urandom pool



  - Entropy extraction/transfer => feedback (hash of extracted bits)
  - Each pool has its own entropy estimation counter
    - ★ Important especially for secondary pool

Estimating the entropy amount

- Entropy of event is a function of its timing only
  - Type of event is not important
  - Let timing of event number n is t_n. Define $\delta_n = t_n - t_{n-1}$; $\delta_n^2 = \delta_n - \delta_{n-1}$; $\delta_n^3 = \delta_n^2 - \delta_{n-1}^2$ $t_n, \delta_n, \delta_n^2, \delta_n^3$ are each 32bit long
  - Amount of entropy added is defined as $log_2(min(|\delta_n|, |\delta_n^2|, |\delta_n^3|)_{[19-30]})$, where $S_{[19-30]}$ denotes bits a to b of S
- Entropy counter updated only if estimation is positive
  - Pool is updated even if estimation is equal to 0
- Estimation is relevant only for OS sources
  - When user writes data to device – counter not incremented
- Extraction/transfer of n bits => estimation is decremented by n
  - After transfer is counter in target pool incremented by n

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Updating the pools

- Based on twisted generalized feedback shift register (TGFSR)
  - The main advantage is extended cycle/period length
    - The period of a TGFSR with a state of 128 words (on a 32-bit PC) can be $2^{128\times 32} - 1$ steps
  - The implementation allows adding entropy in each iteration
    - Pools implemented as (indexed) arrays of 128 or 32 words
    - Adding entropy => array index also updated
- Each pool is updated based on a primitive polynomial
  - Polynomial chosen according to the size of the pool
    - For primary pool: $x^{128} + x^{103} + x^{76} + x^{51} + x^{25} + x + 1$
    - For secondary/urandom pool: $x^{32} + x^{26} + x^{20} + x^{14} + x^{7} + x + 1$
  - Entropy addition can be viewed as reseeding in each iteration
    - Reseeding process changes the elementary properties of the TGFSR
    - The process in no longer linear function of initial state/seed
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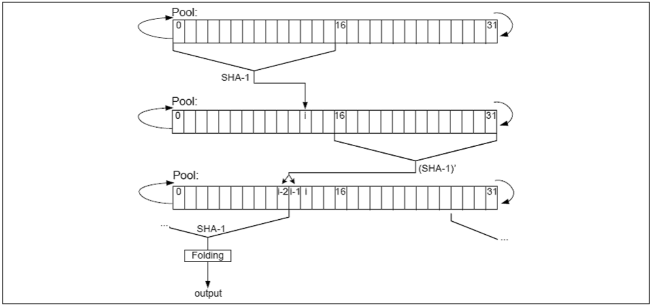
Extracting random bits

- Hashing the extracted bits, modifying the pools state, and decrementing the entropy estimate by the number of extracted bits
  - Process described for urandom or secondary pools (32 words long)
    - ★ Decrementing entropy estimation & entropy refilling process omitted



  - (SHA-1)' uses as IVs 5 words of previous hash result
  - Folding makes from 5 words (160 bits) 2.5 words (80 bits)
    - ★ W_0, W_1, W_2, W_3, W_4 yields $W_0 \oplus W_3, W_1 \oplus W_4, W_{2_{[0-15]}} \oplus W_{2_{[16-31]}}$

Forward security

- **Definition:** An adversary which learns the internal state of the generator at a specific time cannot learn anything about previous outputs of the generator.
- Output computed after the state of pool is updated
    - Observation: with knowledge of state in time t can be computed output in time $t-1$
- Attack allows compute state in time $t-1$, then in time $t-2$, ...
    - Applicable when the pool entropy is not often updated
    - WLOG imagine XOR mod $2^{32}-1$ instead addition over TGFSR
    - Generic attack with overhead 2^{96} (still impractical)
        - Only three 32bit values changed during extraction process
        - Much better then exhaustive search (overhead 2^{1024} for 32 word pool)
    - A more efficient attack with overhead 2^{64}
        - Pool can be reversed for 18 of 32 index values (1,2,16,...,31)
        - For index $18, \ldots, 31$ affected only words in upper half of pool

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Security engineering

- No limits for reading from devices => denial of service attacks
  - Local attacker: simply reads from `/dev/random` device
  - Remote attacker: can establish many TCP connections (TCP/SYN requires 128 bits of random data from urandom pool)
  - Solution: definition of quotas per user/group
- Guessable passwords (applicable on disk-less systems)
  - First user-operation in a computer system is user login
  - LRNG state might be a deterministic function of initial user password
  - Solution: keyboard entropy based on timing (not on typed values)
- An adversary can create noise that directly affects the LRNG output
  - Full primary pool => entropy is added directly to secondary pool
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Real-world implications

- Almost all Linux distributions use the same kernel source
  - LRNG structure is thus very often the same
  - Small changes occur only within the system up and down times
- Initialization of LRNG
  - Constant parameters, time-of-day, disk operations and system events
  - Might be easily predicted (especially in systems without HDD)
  - Solution: LRNG simulates continuity along shutdowns and startups
    - Saving random seed by special script (no part of kernel)
    - Not applicable to all distribtions (e.g., Knoppix, OpenWRT)
- OpenWRT – a Linux distribution for wireless routers
  - Very limited entropy sources (no keyboard, mouse, HDD)
  - Flash memory does not provide any entropy
  - The only entropy source are network interrupts
    - Easily observable (especially in wireless environment)

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