Turing: a fast software stream cipher

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DISCLAIMER!

- This version (1.8 of TuringRef.c) is what we expect to publish. Any changes from now on will be because someone broke it. (Note: we said that about 1.5 and 1.7 too.)
- This is an experimental cipher. Turing might not be secure. We've already found two attacks (and fixed them). We're starting to get confidence.
- Comments are welcome.
- Reference implementation source code agrees with these slides.

Introduction

- Stream ciphers
- Design goals
- Using LFSRs for cryptography
- Turing
- Keying
- Analysis and attacks
- Conclusion

Stream ciphers

- Very simple
  - generate a stream of pseudo-random bits
  - XOR them into the data to encrypt
  - XOR them again to decrypt
- Some gotchas:
  - can’t ever reuse the same stream of bits
    - so some sort of facility for Initialization Vectors is important
  - provides privacy but not integrity / authentication
  - good statistical properties are not enough for security… most PRNGs are no good.

Turing's Design goals

- Mobile phones
  - cheap, slow, small CPUs, little memory
- Encryption in software
  - cheaper
  - can be changed without retooling
- Stream cipher
  - two-level keying structure (re-key per data frame)
  - stream is "seekable" with low overhead
- Very fast and simple, aggressive design
- Secure (? – we think so, but it's experimental)

Using LFSRs for Cryptography

- Linear Feedback Shift Registers have been intensively studied
  - Good and proven distribution properties
  - Fast
- Empirical techniques thought to produce good characteristics
  - decimation, irregular clocking, *stuttering* (not used)
  - nonlinear function of state, or memory
  - combining multiple registers (not used in Turing)
- Theory all works for any field
  - but some things are more efficient in software

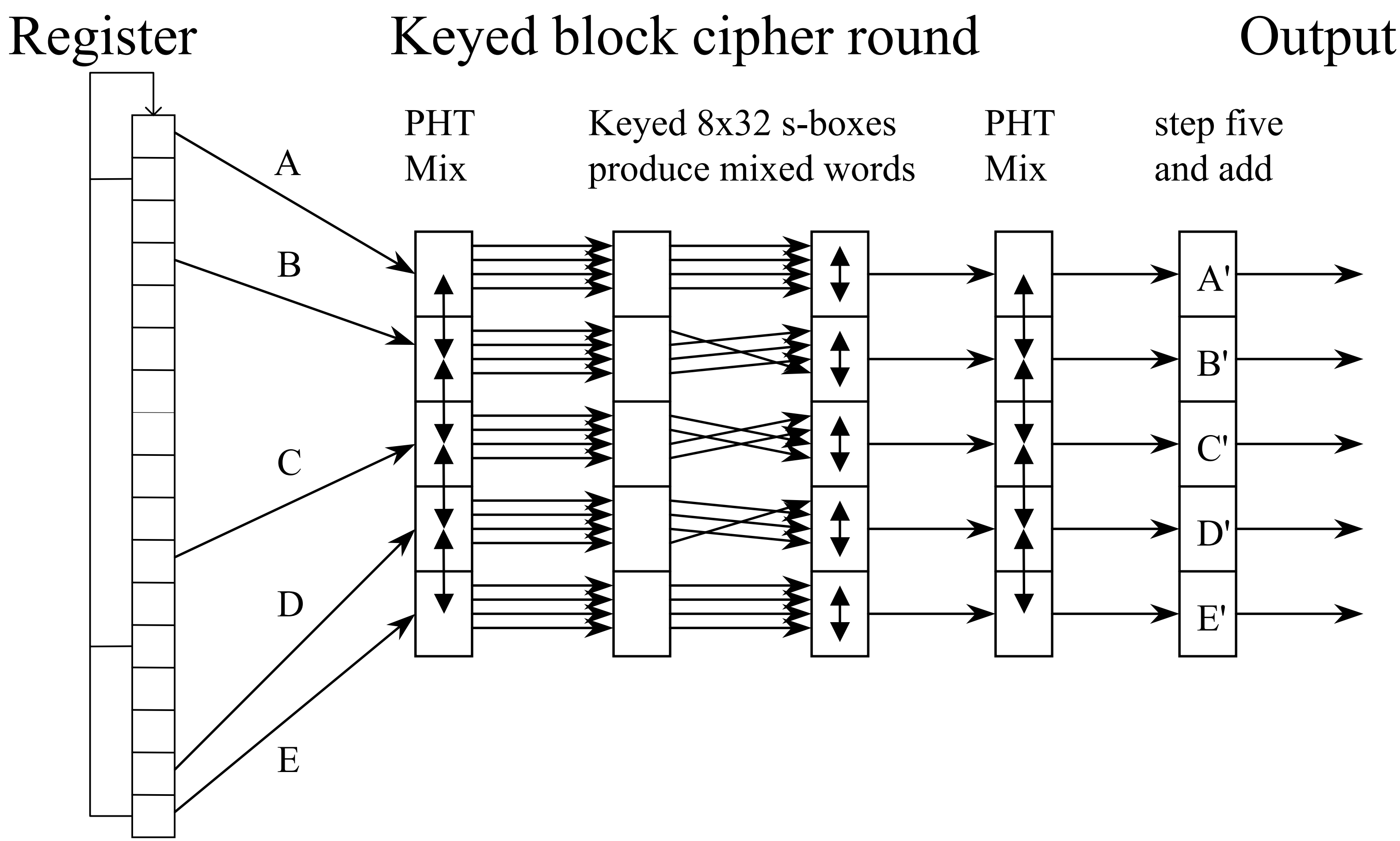
Elements in Turing

- LFSR structure based on SOBER-t32 and SNOW 2.0
- Nonlinear filter function is a keyed transformation
  - Based on a round of a block cipher
  - Blowfish/Twofish for the key-dependent s-box
  - SAFER for the pseudo-Hadamard diffusion function
  - concept spawned from Tom St Denis' *tc24*

LFSRs over $GF(2^8)^4$

- Elements of field are words-sized polynomials of byte-sized binary polynomials
- Addition operation is XOR, $\oplus$
- Multiplication is poly-mod multiplication, $\otimes$
  - only multiply by constant
  - use single 8->32 table lookup, shift word by 8 bits
- Instead of shifting the shift register, can use:
  - pointers to memory -- sliding window or circular buffer
  - or inline code for real speed

Turing block diagram



The Shift Register

- Generates nearly maximal length sequence
  - period $(2^{544} - 1)/5$, 5 possible cycles
- Recurrence:
  - $s_{n+17} = s_{n+15} \oplus s_{n+4} \oplus y \otimes s_n$
- Each bit position behaves as output from a 544-bit binary shift register
  - recurrence relation has exactly half non-zero coefficients.
- Shift register is "free running"
  - that is, its state is used directly instead of its output

The Nonlinear Function

- Offsets are carefully chosen
  - feedback taps plus function inputs form "full positive difference set"
- Combine 10 words of state in a key-dependent manner
  - mix 5 words with PHT
  - pass bytes through keyed 8->32 S-boxes
  - mix words with PHT again
  - step LFSR five times and add other words mod 2^{32}

Pseudo-Hadamard Transform

- **Matrix multiply mod 2^{32}:**

$$\begin{bmatrix} A \\ B \\ C \\ D \\ E \end{bmatrix} = \begin{bmatrix} 2 & 1 & 1 & 1 & 1 \\ 1 & 2 & 1 & 1 & 1 \\ 1 & 1 & 2 & 1 & 1 \\ 1 & 1 & 1 & 2 & 1 \\ 1 & 1 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} A \\ B \\ C \\ D \\ E \end{bmatrix}$$

- **Actually:**
  - `E += A + B + C + D;`
  - `A += E; B += E; C += E; D += E`
- **Extend to n-PHT for key loading**

Basic S-box

- Permutation
- Fairly nonlinear (min nonlinearity 104)
- made by:
  - keying RC4 with "Alan Turing"
  - throwing away 736 bytes
  - using its permutation
  - best observed nonlinearity in 10,000 cycles, used first one found.

QUT's "Q-box"

- Developed by Queensland University of Technology
- 8->32 bit S-box
- bit positions are:
  - Highly nonlinear (112)
  - Balanced
  - Pairwise uncorrelated

keyed S-boxes

- Push through fixed S-box multiple times:
  - next slide for details
- four logical S-boxes, one for each byte position, due to different key material
- words of key are mixed when loaded to help thwart related-key attacks.
- every byte of key affects each sbox
- S-boxes can be precalculated

More on keyed S-boxes

- $S_i(x) = \mathrm{Sbox}[K_{i,N-1} \oplus \mathrm{Sbox}[K_{i,N-2} \oplus \ldots \mathrm{Sbox}[K_{i,0} \oplus x]\ldots]]$
- at each stage, XOR (Qbox[…] rotated left (i*8+j)) to temporary word
  - Thanks to David McGrew and Scott Fluhrer for observing that this was better mixing than the MDS matrix
- Clobber the byte corresponding to the input byte with $S_i(x)$
  - This ensures that the corresponding output bits are balanced w.r.t. x.
  - If not, there's a possible bias introduced that might be exploitable.
- not invertible

Keying

- Two stage keying
  - secret key from 4 to 32 bytes (32 to 256 bits)
    - length is significant
    - must be multiple of 4
  - requires further keying operations (eg. frame IV)
- Keying process:
  - pass bytes through an invertible S-box construct, then words through PHT for mixing
  - use output in keyed S-boxes
  - can set up fast table lookups for the keyed S-boxes

Initialization Vector

- mixed key material and initialisation vector are used to fill the LFSR
  - IV
  - mixed key
  - word made from length of key and IV (0x010203*kv*, where *k* is keylength in words, *v* is IV length in words)
  - rest of words made by recurrence of some previous words
- each word is mixed through S-box
  - IV goes through an invertible key-independent S-box-based transformation to avoid equivalent IVs
  - key is already mixed
  - Others go through the keyed S-box
- Finally whole register is mixed with PHT

Polynomial details

- Byte polynomial is
  - $z^8 + z^6 + z^3 + z^2 + 1$
- Word polynomial is
  - $y^4 + \mathit{0xD0}.y^3 + \mathit{0x2B}.y^2 + \mathit{0x43}.y + \mathit{0x67}$
- LFSR polynomial is
  - $x^{17} + x^{15} + x^4 + \alpha$, **where α is the polynomial "y"**
- **"binary equivalent" polynomial has 272 out of 544 non-zero terms**

Performance

- Generates 160 bits at a time
- highly parallel operations
- 2304 bytes ROM tables, plus code
  - 8x8 S-box, 8x32 Q-box, 8x32 Multiplication table
- Fast implementation:
  - 4-5 cycles per byte on newer Pentium-style machines with multiple parallel instructions
  - requires 4K RAM tables computed at key setup
- Small implementation:
  - 68 bytes RAM, very little key setup

Security

- LFSR guarantees good statistical properties input to the nonlinear function
- Strength is derived from the combination of unknown input from the LFSR and keyed non-linear transformation
- Either by itself is potentially weak
- Each frustrates attacks on the other
- If the "block cipher part" is secure, CTR mode proof applies (but we don't claim this)

Numbers

Cipher	cycles/B	Key	IV setup	tables	RAM	MByte/s
TuringRef	149.01	477.00	4272.31	2304.00	68.00	6.04
TuringLazy	33.44	1802.70	991.80	2304.00	4164.00	26.91
TuringTab	30.06	72457.93	900.90	2304.00	4164.00	29.94
TuringFast	6.12	72417.12	882.90	2304.00	4164.00	146.95
arrsyfor	37.49	0.00	10347.42	0.00	258.00	24.00
AES enc.	26.85	239.00	0.00	20480.00	176.00	33.53
MHz	900.00	(Mobile Pentium III IBM laptop)				

Recent attack

- paper at http://www.qualcomm.com.au/Turing_attack.pdf
- Basically, LFSR wasn't being stepped enough
- Reuse of words in final "add" phase allowed algebraic attack on LSB's
- Attack very specific to Turing 1.6.
- Solution:
  - step LFSR total 5 times between blocks
  - use a different full positive difference set to extract the words for the final addition round
- Attack doesn't actually work, but scared us

Conclusion

- Turing is *not* conservatively designed
  - I (ggr) think it may be secure, but it's clearly "close to the edge". Maybe too close.
- OK for hardware implementation
- Suitable for medium embedded applications
- Extremely fast in software
  - 146MBytes/sec on 900MHz PIII laptop, 6 cycles/byte
- Source code available worldwide:
  - http://people.qualcomm.com/ggr/QC/Turing.tgz
- Being published, reviewed

Stop the presses

- Free licenses!
  - for Turing or SOBER (or future ciphers)
  - for any purpose
  - for hardware or software
  - for ever
  - our code or yours
- It only took me 5 years to get management agreement…