Practical Algebraic Attacks on the HITAG2™ Stream Cipher in RFID Transponders

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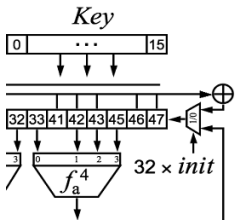
Disclaimer

First of all, this pure crypto research:

Spec of the cipher => Algebraic Attack.



Not all attacks work on actual industrial systems due to the protocol subtleties.

Moreover: one should not expect that every information found on the Internet is correct. One can expect some small glitches…

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Outline

1. Hitag2 cipher and products.
2. Discussion: open source vs. closed source crypto.
3. Algebraic attacks with SAT solvers.
4. Our results.
   [Full paper published in ISC 2009, Pisa Italy, 7-9 September 2009, Springer LNCS]
5. Industry impact, discussion.

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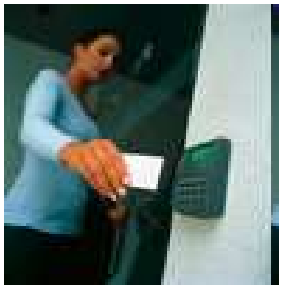
Hitag2

- A stream cipher used in car locks [e.g. BMW]: Philips Hitag2 family.

- Also used in building access.
  - According to [Nohl, Plotz HAR'09] used in German government and army buildings…
  - But Hitag2 proximity cards are not available anymore in shops. They have been discontinued.



Here we concentrate just on car locks.

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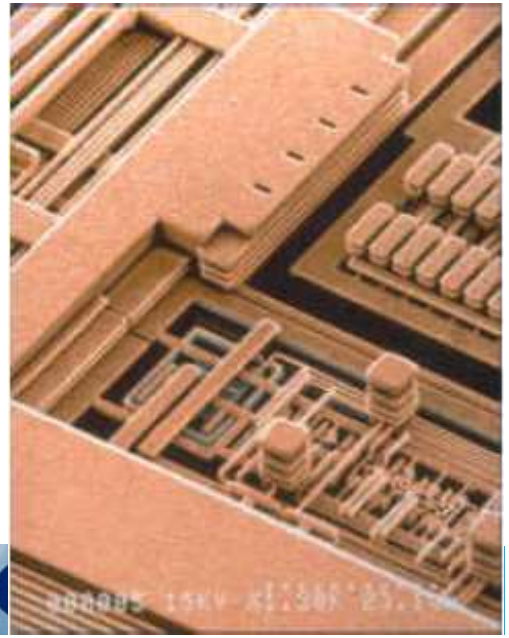
What's Inside?



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Open Source vs. Closed Source Crypto

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Secrecy:

Very frequently
an obvious
business decision.

- Creates entry barriers for competitors.
- But also defends against hackers.

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Kerckhoffs' principle: [1883]

"The system must remain secure should it fall in enemy hands …"

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*Remark:

Smart Cards:

They are already in ‘enemy’ hands

- even more for RFID…

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Kerckhoffs' principle: [1883]

Most of the time: incorrectly understood.

No obligation to disclose.

- Security when disclosed.
- Better security when not disclosed???

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Yes (1,2,3):

1. Military:
   layer the defences.

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Yes (2):

2)

Basic economics:

these 3 extra months

(and not more ☹)

are simply worth a

a lot of money.

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Yes (3):

3)

Prevent the erosion of profitability / barriers for entry for competitors / “inimitability”

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Kerckhoffs principle is kind of WRONG in the world of smart cards

Reasons:

- side channel attacks are HARD and COSTLY to prevent when the algo is known
- in some applications, for example Pay TV the system is broken immediately when the cryptographic algorithms are public.

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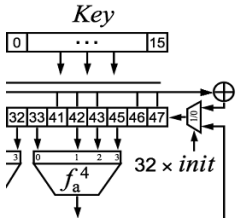
Kerckhoffs principle is kind of WRONG?

Well OK, but then we need other means to evaluate crypto algorithms used by the industry.

- [OLD] private consulting…
- [NEW] TODAY: Automated Cryptanalysis

Spec of the cipher => Try our software



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Silicon Hacking

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Tarnovsky Lab [Freelance Silicon Hacker]

Only a few thousands of dollars worth of equipment

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Clear and Present Danger

Reverse engineering is NOT that hard.

No need for a FIB device
(Focused Ion Beam, 0.5 M€).

A few thousand dollars microscope +software.

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Silicon Hacking => Wikipedia™

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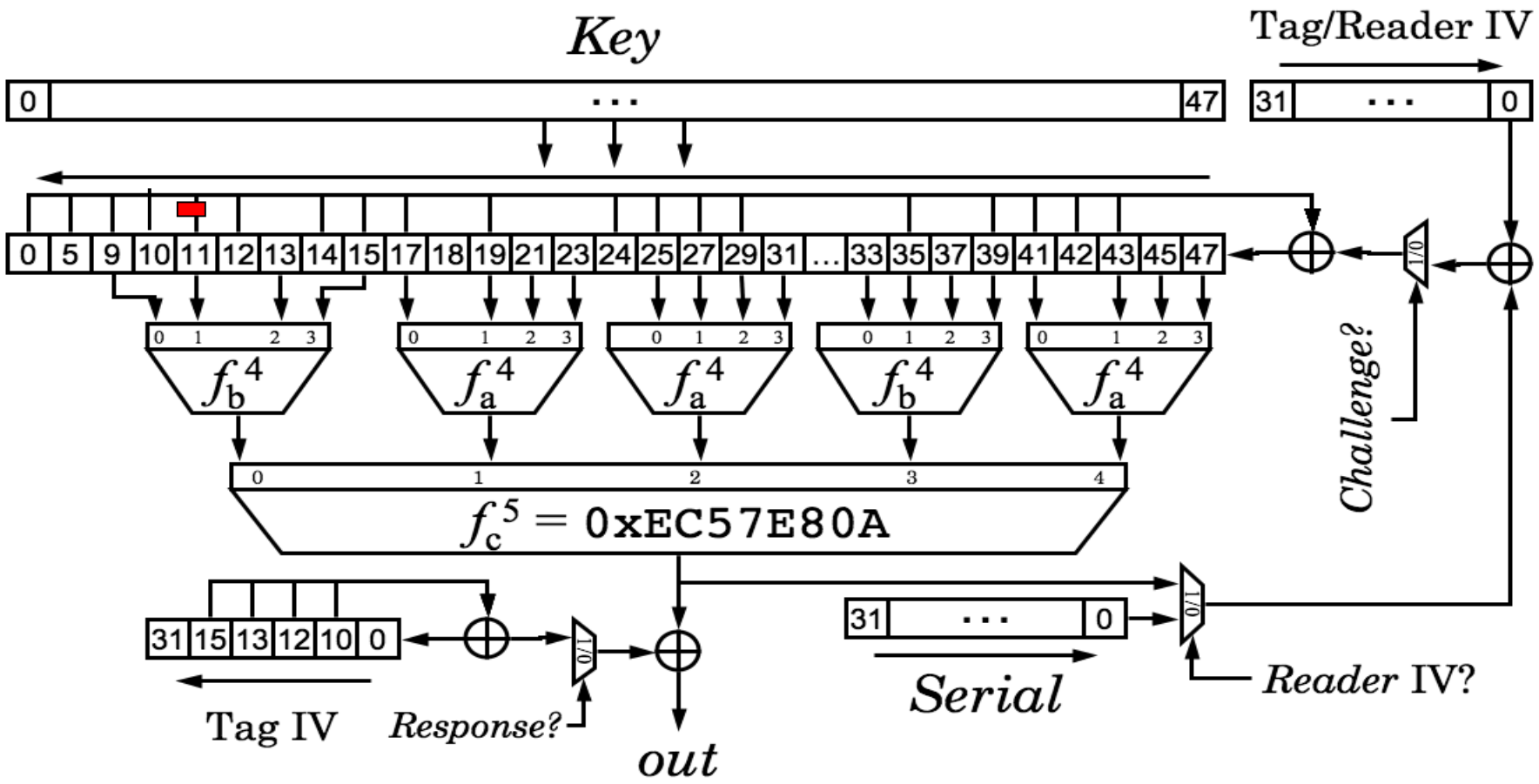
Crypto1 Cipher



$f_a^4 = 0x9E98 = (a+b)(c+1)(a+d)+(b+1)c+a$

$f_b^4 = 0xB48E = (a+c)(a+b+d)+(a+b)cd+b$

Tag IV ⊕ Serial is loaded first, then Reader IV ⊕ NFSR

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Crypto-1 is VERY WEAK

- Crypto 1 Has regular LFSR taps

  =>Broken in 0.05 seconds.

  [de Koning Gans et al, Esorics 2008]

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much better:

- Crypto 1 Has regular LFSR taps
  =>Broken in 0.05 seconds.
  [de Koning Gans et al, Esorics 2008]

- Hitag 2 has IRREGULAR taps. Not so easy.
- State of the art: Inversion attacks:
  - [Ross Anderson: Searching for the Optimum Correlation Attack, In FSE'94]
  - Our present work is a sort of automated inversion attack where human insights into how to invert the augmented filter function are replaced by the [clever] SAT solver software…

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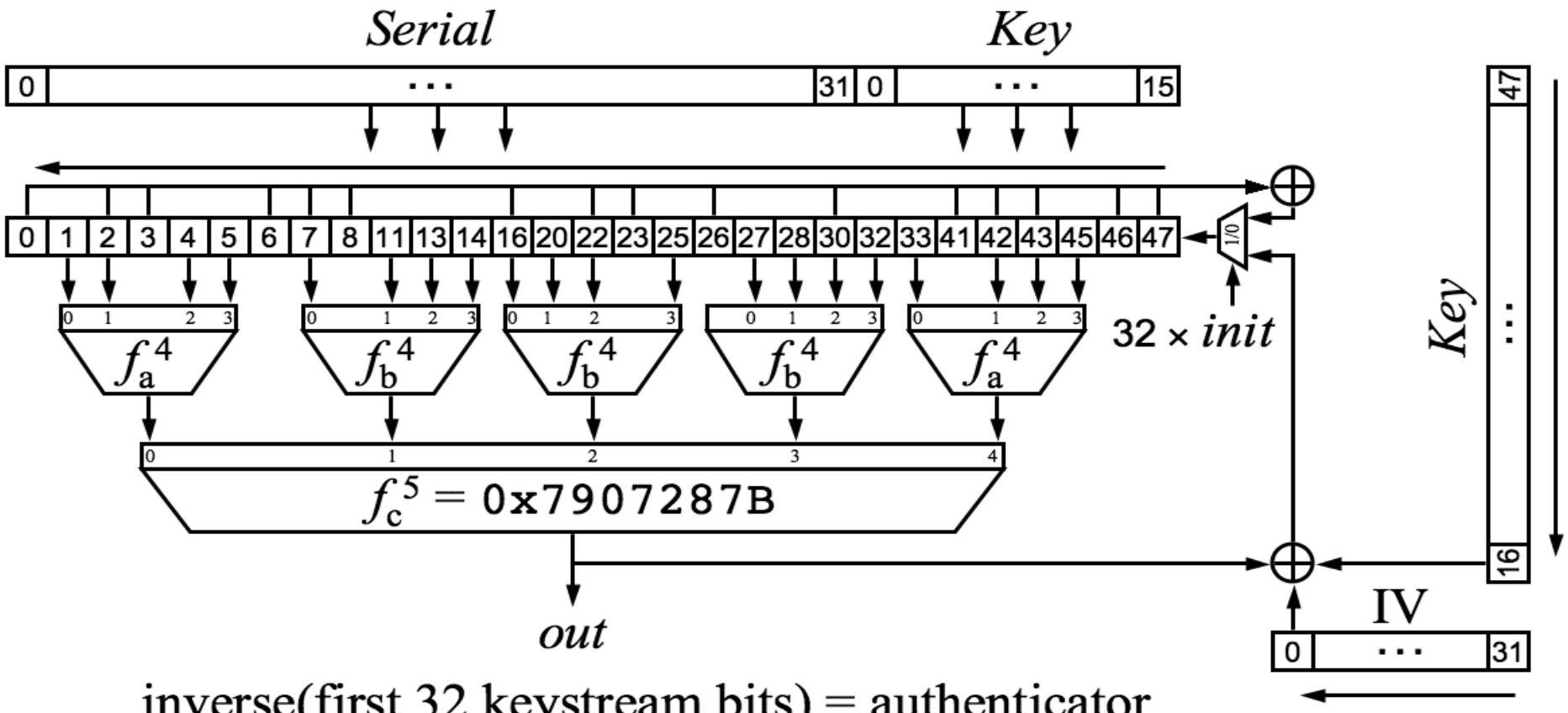
Hitag2 Cipher



inverse(first 32 keystream bits) = authenticator

$f_a^4 = 0x2C79 = abc+ac+ad+bc+a+b+d+1$

$f_b^4 = 0x6671 = abd+acd+bcd+ab+ac+bc+a+b+d+1$

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Silicon Hacking => Wikipedia

A Cryptanalyst can start working…

Exhaustive Key Search

- 48 bits, about 4 years on 1 CPU.
  - But only hours/days with more expensive devices such as FPGA/Copacobana etc…

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Algebraic Cryptanalysis

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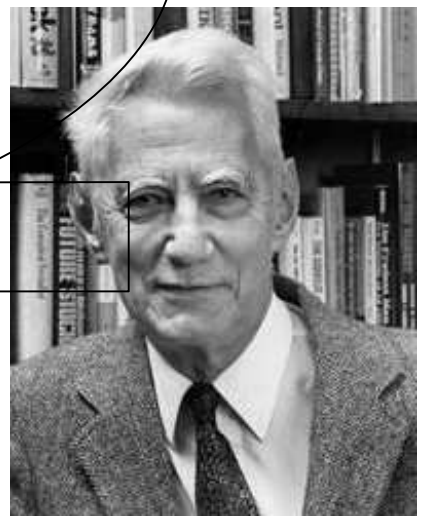
Algebraic Cryptanalysis [Shannon]

Breaking a « good » cipher should require:

"as much work as solving a system of simultaneous equations in a large number of unknowns of a complex type"

[Shannon, 1949]



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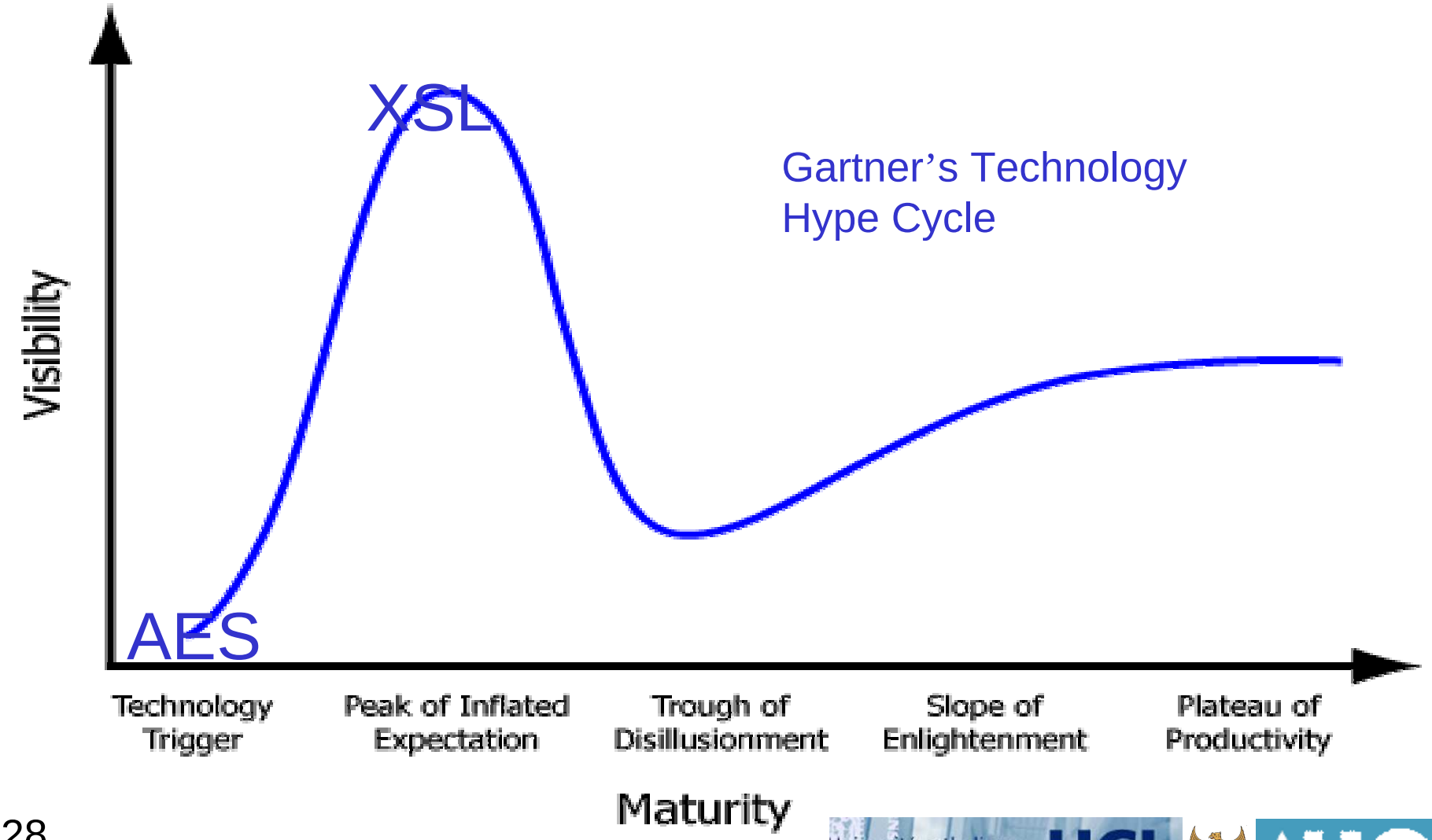
Algebraic Cryptanalysis: An Emerging Technology



Courtois, O'Neil, Quisquater

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Strong or Weak?

High Algebraic Immunity.

- Does NOT help.
- Many “direct” algebraic attacks exist. We can break “any cipher”, if not too complex…

Our fastest attacks use algebraic equations + conversion + SAT solvers

- [cf. recent attacks on DES and KeeLoq by Courtois and Bard 2007-08]

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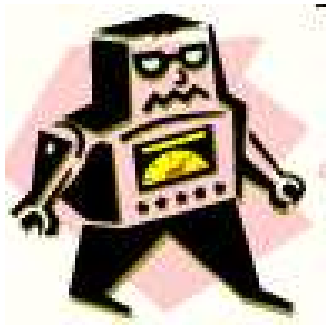
Our Attacks

…AC can break “any cipher”,

if not too complex…



Remark:

- Other attacks can be faster.
- However, this method is more generally applicable:
  - we can also break many modified versions of Hitag2
  - and this without any human intervention !

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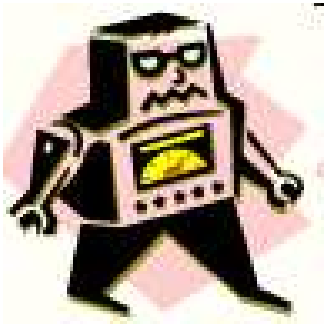
Algebraic Cryptanalysis

Step 1.

Write a system of Multivariate Quadratic equations [MQ]

Step 2.

Solve it.



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ANF-to-CNF method - The Outsider

[Courtois, Bard, Jefferson]

Before we did try,

we actually never believed it could work…

☺ ☺ ☺

Convert MQ to a SAT problem.

(both are NP-hard problems)

*ANF-to-CNF – Main Idea

Principle 1:

each monomial = one dummy variable.

$$a = wxyz$$

$$\Updownarrow$$

$$a \iff (w \wedge x \wedge y \wedge z)$$

$$\Updownarrow$$

$$(w \vee \bar{a})(x \vee \bar{a})(y \vee \bar{a})(z \vee \bar{a})(a \vee \bar{w} \vee \bar{x} \vee \bar{y} \vee \bar{z})$$

d+1 clauses for each degree d monomial

*Also

Principle 2:

Handling XORs – Not obvious. Long XORs known to be hard problems for SAT solvers.

$$a \oplus b \oplus c \oplus d = 0$$

$$\Updownarrow$$

$$(\bar{a} \vee b \vee c \vee d)(a \vee \bar{b} \vee c \vee \bar{d})(a \vee b \vee \bar{c} \vee d)(a \vee b \vee c \vee \bar{d})$$
$$(\bar{a} \vee \bar{b} \vee \bar{c} \vee d)(\bar{a} \vee \bar{b} \vee c \vee \bar{d})(\bar{a} \vee b \vee \bar{c} \vee \bar{d})(a \vee \bar{b} \vee \bar{c} \vee \bar{d})$$

- Split longer XORs in several shorter with more dummy variables.
- About 4 h clauses for a XOR of size h.

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*ANF-to-CNF

This description is enough to produce a working version.

Space for non-trivial optimisations. See:

Gregory V. Bard, Nicolas T. Courtois and Chris Jefferson:

“Efficient Methods for Conversion and Solution of Sparse Systems of Low-Degree Multivariate Polynomials over GF(2) via SAT-Solvers”. eprint.iacr.org/2007/024

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Solving SAT

What are SAT solvers?

Heuristic algorithms for solving SAT problems.

- Guess some variables.
- Examine consequences.
- If a contradiction found, I can add a new clause saying “In this set of constraints one is false”.

Very advanced area of research.

Introduction for “dummies”:

Gregory Bard PhD thesis.

MiniSat 2.0.

Winner of SAT-Race 2006 competition.

An open-source SAT solver package,
by Niklas Eén, Niklas Sörensson,

http://www.cs.chalmers.se/Cs/Research/FormalMethods/MiniSat/

Compiles with gcc under both Unix and Windows.

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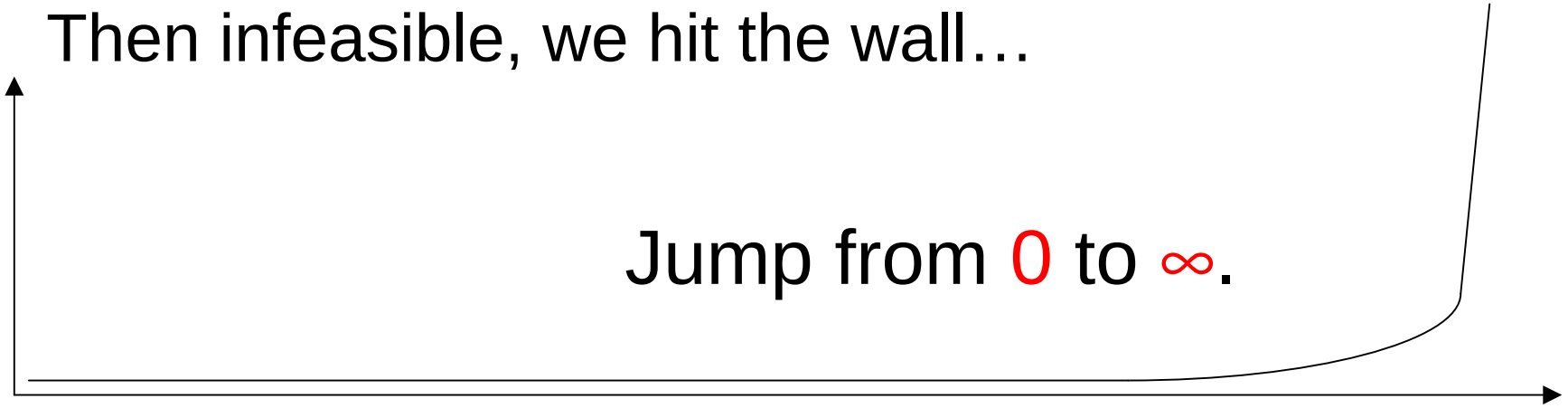
**ANF-to-CNF + MiniSat 2.0.

Gives amazing results in algebraic cryptanalysis of just any (not too complex/not too many rounds) cipher. Also for random sparse MQ.

- Certain VERY large systems solved in seconds on PC (thousands of variables !).
- Few take a couple hours/days…
- Then infeasible, we hit the wall…



**What Can Be Done with SAT Solvers ?

- Clearly it is not the size of the system but the nature of it.
- Sometimes more powerful than Grobner Bases, sometimes less.

Paradoxes:

- If you guess some variables, can become much slower ☺.
- Great variability in results (hard to compute an average running time, better to look at 20 % faster timings).
- Memory:
  - For many cases tiny: 9 Mbytes while Magma hangs at > 2Gbytes for the same system.
  - For some working cases: 1.5 Gbytes and substantial time. Then terminates with the solution as well.

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Hitag2 Protocols

From Original Philips Specs

- Found on a Russian web side(!)
- Hitag 2 have two modes.
  - Password mode [less secure]
  - Crypto mode.

- We focus on the crypto mode.

Sort of challenge-response protocol.

  - Mutual authentication.
  - But the reader is authenticated first.
    - Prevents tag-only attacks, or attacks at home:
      - sniffed data is needed.

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Mutual Authentication in the Crypto mode

- The tag sends:

$$11111 + SN \longrightarrow$$

5 +32 bits

- The car picks a random IV (32 bits) and sends:

$$IV + ks1 \longleftarrow$$

32 + 32 bits

- If the stream authenticator ks1 is correct, tag sends

$$11111 + (Config||PWST) \oplus ks2 \longrightarrow$$

5 + 32 bits

where PWST is a password, ks1,ks2 are the first 32+32 bits of Hitag 2 keystream initialised with (K,IV)

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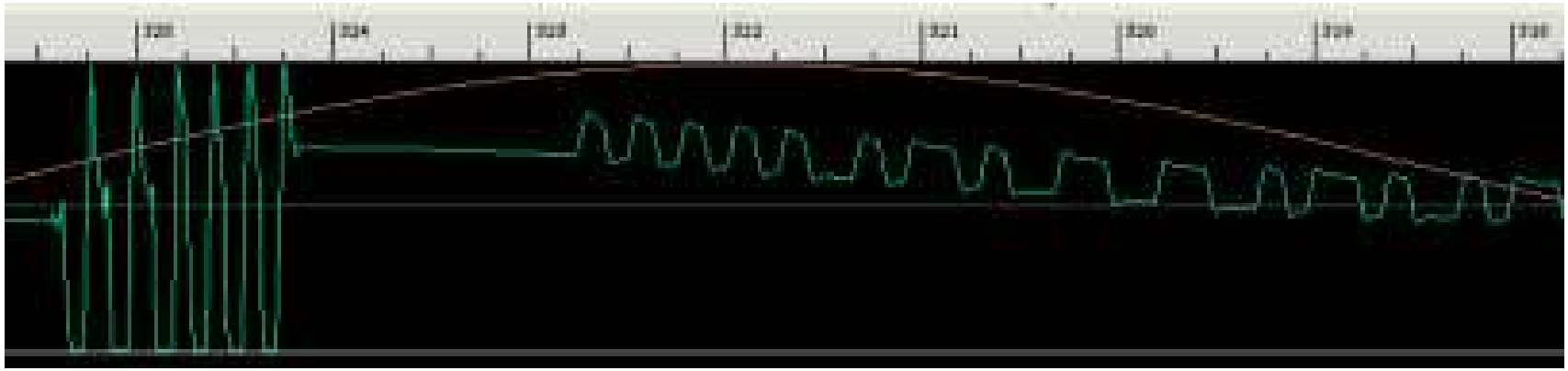
Sniffed Traces?

We did not do the actual hacking of car keys.

Some recorded Hitag2 traces
can be found in [Nohl, Plotz HAR'09]

https://har2009.org/program/attachments/113_breaking_hitag2_part1_hardware.pdf



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Our Results

Our Chosen IV Attack [not practical]

NOT practical.

- An active attacker can send the data to the tag, but the tag will NOT respond if the authenticator is incorrect…
- Purely theoretical attack:
  - We need to know the ks1 for 16 authentication attempts with 16 chosen IVs in the counter mode (consecutive integers on 32 bits).
  - We combine 16 systems of equations. We don't guess any bits.
  - The complete 48-bit key is then found in 6 hours on a PC with MiniSat 2.0.
- The full attack is 6 hours total.

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Our Known IV Attack [practical !]

This attack slower BUT it is practical given the protocol:

- Sniffed data from 4 transactions needed.
- 32 bits of the keystream per known IV are available (assuming PWST is already known).
- We fix/guess 14 bits of the key and combine 4 systems of equations for 4 known IVs.
  - The solution is then found in 10 seconds on a PC with MiniSat 2.0.
- The full attack on a full 48-bit key takes about

$2^{14}*10$ s which is less than 2 days.

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Cryptanalysis and the Industry

Industry Impact?

"old" industry:

- Good excuse to replace these old systems.
  - Nobody thought they would be very secure by today's standards…

"new" industry:

- Silicon hacking labs: we need to realize that:

  $\Rightarrow$ what people in Europe/US do so that they can evaluate the security of the product (and publish a nice paper)…,

  $\Rightarrow$ it will be done routinely in China and by several firms
  BUT not for research, but for the manufacturing industry
  (and it will be legal: in Chinese law),

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*Example, cf. made-in-china.com:

Supports:

Mercedes,

BMW

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*Programmer 2: [All come from China]

Supports: BMW
(2002 -2009)

CAS/CAS2/CAS3
DG512 / CAS3 +
DP512 key and
remote control

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*Programmer 3: [China]

Audi A8, VW Touareg, VW Phaeton, Bentley Continental, Porsche Cayenne, BMW

E38, E39, E46, E53, E60, E61, E63, E64, E65, E66, E87, E90, E91, E92

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*Programmer 4: [China]

Audi A8, VW Touareg,
VW Phaeton,
Bentley Continental,
Porsche Cayenne,
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*Programmer 5: [China]

Audi A8, VW Touareg,
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Conclusion

Old industrial ciphers can now be routinely broken by automated tools such as SAT solvers.

The industry needs to recognise that:

- Reverse engineering is cheaper and easier than ever. A microscope + software…
- "Kindegarten crypto" fails.

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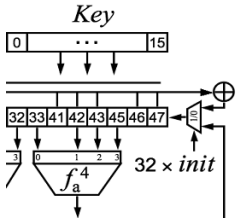
New Perspective for the Industry

- Old / Kindegarten crypto fails.
- Custom/secret crypto is OK.
  - But it needs to be evaluated and tested.

We propose a new method to evaluate crypto algorithms used by the industry.

- [OLD] private consulting…with selective disclosure.
- [NEW] TODAY: Automated Cryptanalysis

Spec of the cipher => Try our software



no need to DISCLOSE the SPEC!

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