CHES2015 Writeup

From YobiWiki

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Intro

On https://ches15challenge.com/ four challenges were made available on 24/06/2015 21:00 CET and the CTF was open for 80 days till 13/09/2015 8:00 CET, first day of the CHES2015 conference.
A backup is available here (https://mega.co.nz/#!SAk1ACqS!dSK5gF_gHfwT38-5w6O4z_ExB5GW0RIKjBKNCU1CJBw) but the third challenge is online and needs the corresponding server to be up and running.
The Challenge is composed of 4 sub-challenges, which can be solved in any order. Each comes with at least one ciphertext, which contains a secret flag. Except if stated otherwise by the challenge itself, the ciphertext has been obtained thanks to an AES128 encryption in CBC mode with a null initialization vector. An intermediate flag can also appear during the resolution.

```
Archive:  /tmp/t/CHES15Challenge.zip
  Length   Method     Size  Cmpr    Date    Time   CRC-32   Name
--------  ------   ------- ---- ---------- ----- --------  ----
       0  Stored          0   0% 2015-06-19 17:06 00000000  CHES15Challenge/
       0  Stored          0   0% 2015-05-11 13:28 00000000  CHES15Challenge/Challenge1/
     128  Defl:N         87  32% 2015-05-05 16:49 dd1dd15e  CHES15Challenge/Challenge1/ctxt1.txt
17222400  Defl:N   14839121  14% 2015-05-09 02:45 ab195da9  CHES15Challenge/Challenge1/slowed.wav
       0  Stored          0   0% 2015-05-11 13:45 00000000  CHES15Challenge/Challenge2/
  326554  Defl:N     221223  32% 2015-05-05 16:14 e875231b  CHES15Challenge/Challenge2/Cseh.jpg
     128  Defl:N         85  34% 2015-05-05 16:59 adaa02b8  CHES15Challenge/Challenge2/ctxt2.txt
       0  Stored          0   0% 2015-06-20 11:22 00000000  CHES15Challenge/Challenge3/
    1634  Defl:N        719  56% 2015-06-11 16:27 b94132f8  CHES15Challenge/Challenge3/client.c
     128  Defl:N         86  33% 2015-05-05 17:14 a0a61997  CHES15Challenge/Challenge3/ctxt3a.txt
138720144  Stored  138720144   0% 2015-06-23 18:15 2fb47af4  CHES15Challenge/Challenge3/ctxt3b
       0  Stored          0   0% 2015-06-23 13:51 00000000  CHES15Challenge/Challenge4/
     128  Defl:N         86  33% 2015-05-14 19:35 b85ff4eb  CHES15Challenge/Challenge4/ctxt4.txt
 16975387  Defl:N   12560569  26% 2015-06-23 13:49 374b4ba4  CHES15Challenge/Challenge4/rom.png
--------          --------  ---                            -------
173246631         166342120   4%                            14 files
```

Challenge 1

```
    128 May  5 16:49 ctxt1.txt
17222400 May  9 02:45 slowed.wav
```

First step

Playing slowed.wav gives some unpleasant repetitive noise and a slowed-down voice.
Let's accelerate it:

```
sox slowed.wav fast.wav speed 3.2
```

We now hear a text-to-speech voice spelling some letters. It's quite painful to understand them all. Using Audacity to replay easily some parts was helpful.
This gives something like:

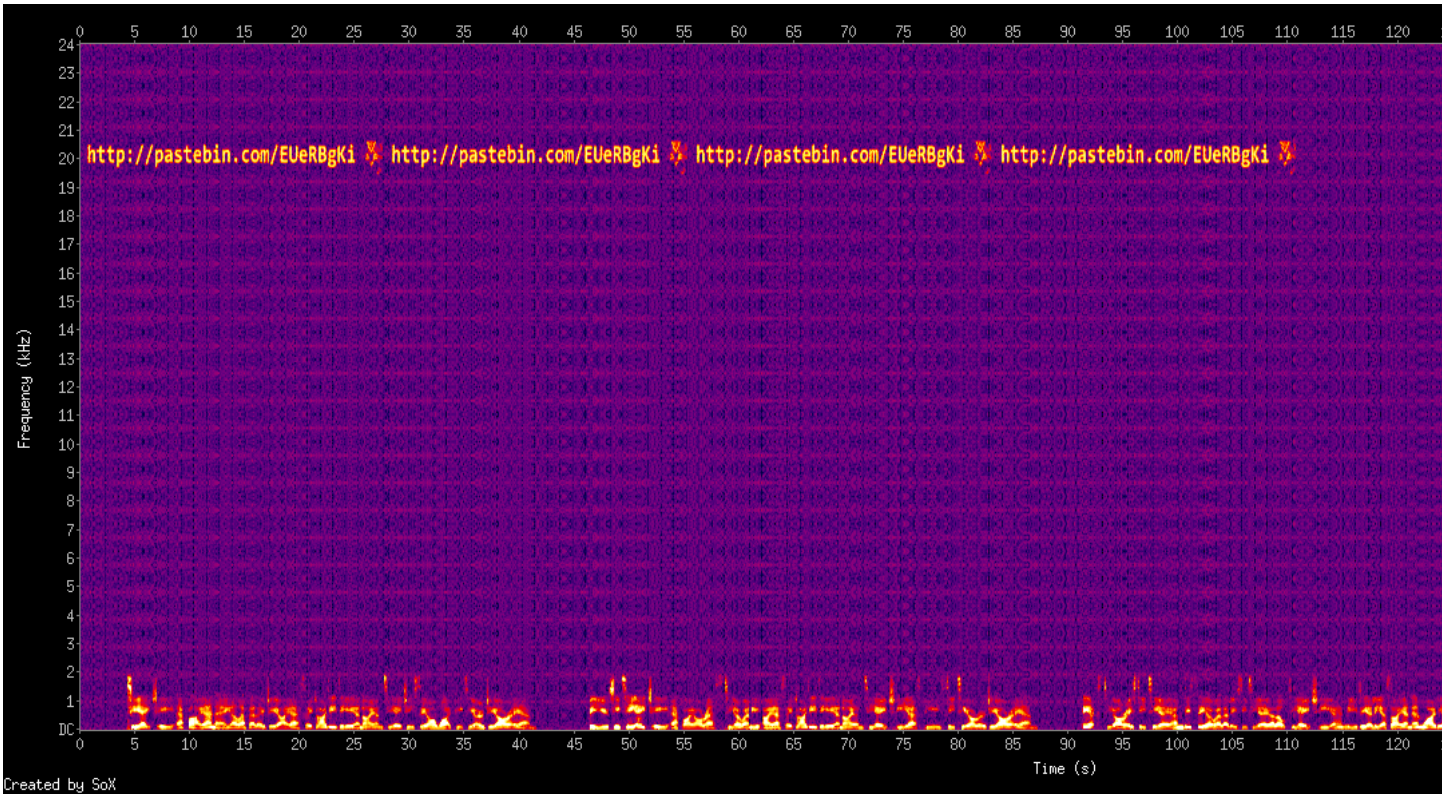
```
the final flag is hidden in the cryptogram
but the first one is hidden in the spectrogram
extract and collect all the needles(?) in my voice
analyze the curve weight is the model of choice
```

Spectrogram? Ok, let's display it:

```
sox slowed.wav -n spectrogram
```

Playing around with the parameters for a better rendering:

```
sox slowed.wav -n spectrogram -z 30 -Z -20 -x 1600
```



We get the URL http://pastebin.com/EUeRBgKi with the following content:

```
Congratulations ! Here is the flag: PaxH7".aoD10+a

The audio file also hides 156 successive consumption curves, that you might already have found.
The plaintexts used for the generation of these curves are from http://www.maryjones.us/ctexts/a01w.html,
without any caps or new lines, encoded in ASCII.
156 blocs of this poem were used (from I to X). As an example, here are the first 25 blocs:

gredyf gwr oed g
was gwrhyt am di
as meirch mwth m
(etc)
```

So the intermediate flag is PaxH7".aoD10+a

Second step

The different hints tell us that there are 156 power traces in the wav and that we should be able to break them with a differential power analysis (https://en.wikipedia.org/wiki/Power_analysis#Differential_power_analysis) attack, using the Hamming weight leakage model.
To mount such an attack, one must know which plaintexts were processed, which are here extracted from http://www.maryjones.us/ctexts/a01w.html

Firstly, there are visibly some errors in the 25 blocks described in the pastebin:

- #23 is too short (15 chars)
- #24 is too long (17 chars)
- #25 doesn't match my own processing
- it's not clear if one should use space between chapters or not

I told the organizers who signaled it in their FAQ but, still, attempts to attack the traces (we'll come to that soon) failed.
Actually one has to discard completely the examples and follow the rules: *without any caps or new lines* so new lines are removed entirely, not replaced by spaces as in the examples.

```
lynx -dump http://www.maryjones.us/ctexts/a01w.html |\
   sed '1,/ *I/d;
        / *[IVX]\+ *$/d;
        s/^ *//'|\
   tr A-Z a-z|\
   tr -d '\n'|\
   sed 's/\(.................\)/\1\n/g'|\
   head -n 156
```

As you can see the actual plaintexts differ from the example already at the second line:

```
gredyf gwr oed g
wasgwrhyt am dia
smeirch mwth myn
gvrasa dan vordw
(etc)
```

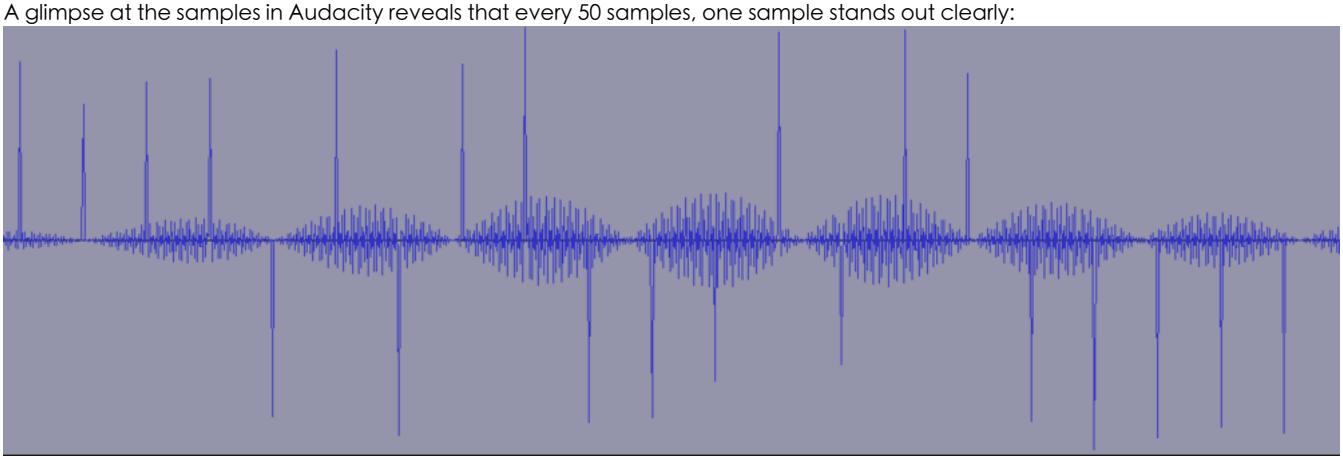
Later, the FAQ was changed to be more explicit:
The plaintext examples given in Challenge1 are wrong. End of lines are not to be replaced by spaces. For illustration, the second plaintext should not start by "was g" but by "wasg".

How to extract the traces from the wav file?

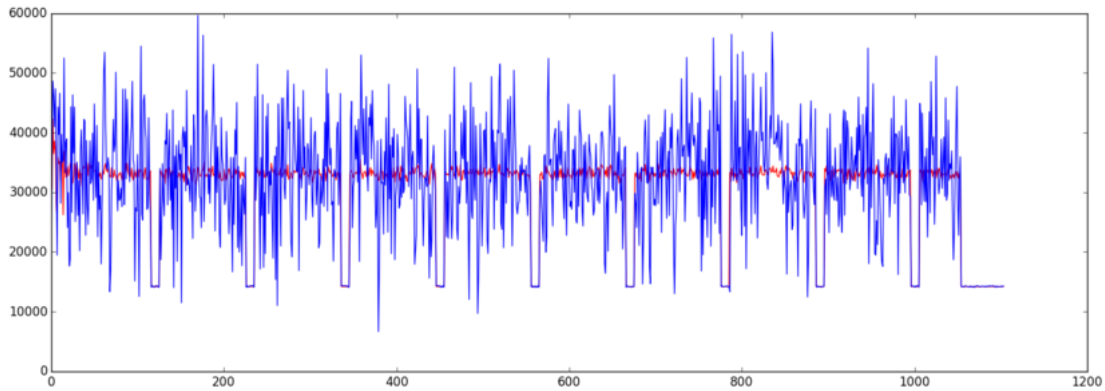
Let's check if it divides nicely:

```
17222400/156=110400
```

A glimpse at the samples in Audacity reveals that every 50 samples, one sample stands out clearly:



So we decimate the samples by 50 and divide the file in 156 equal chunks.
Some wrapping of the obtained signal suggests that I have to interpret samples as unsigned rather than signed (which makes sense for a power consumption...).
And here is the result, in blue the first trace and in red the average of all traces, showing that they're nicely aligned with a gap between rounds:



Here is a Python script to extract the traces and perform a CPA based on Hamming weight of the S-box outputs in Round 1 of an AES encryption.

```
#!/usr/bin/env python

# Philippe Teuwen

from numpy import *
import struct
import matplotlib.pyplot as plt

with open("a01w.txt", "rb") as ptf:
    plaintexts=array(ptf.read().split('\n'))

bps=2 # 2 bytes per sample
decim=50
# Nr of traces
ntraces=156
# Nr of samples
nsamples=110400/bps/decim
traces=zeros([ntraces, nsamples])
with open('../slowed.wav', 'rb') as wav:
    for i in range(ntraces):
        for j in range(nsamples):
            traces[i,j],=struct.unpack("<H",wav.read(bps*decim)[-2:])
```

```
# If one wants to observe the traces, here the first one and the average of all traces:
#plt.plot([average(t) for t in transpose(traces)], 'r')
#plt.plot(traces[0],'b')
#plt.show()

# Usually we truncate traces to target first round which ends around sample 124
# but those traces are so small we don't care


SBOX =  [0x63, 0x7c, 0x77, 0x7b, 0xf2, 0x6b, 0x6f, 0xc5, 0x30, 0x01, 0x67,
         0x2b, 0xfe, 0xd7, 0xab, 0x76, 0xca, 0x82, 0xc9, 0x7d, 0xfa, 0x59,
         0x47, 0xf0, 0xad, 0xd4, 0xa2, 0xaf, 0x9c, 0xa4, 0x72, 0xc0, 0xb7,
         0xfd, 0x93, 0x26, 0x36, 0x3f, 0xf7, 0xcc, 0x34, 0xa5, 0xe5, 0xf1,
         0x71, 0xd8, 0x31, 0x15, 0x04, 0xc7, 0x23, 0xc3, 0x18, 0x96, 0x05,
         0x9a, 0x07, 0x12, 0x80, 0xe2, 0xeb, 0x27, 0xb2, 0x75, 0x09, 0x83,
         0x2c, 0x1a, 0x1b, 0x6e, 0x5a, 0xa0, 0x52, 0x3b, 0xd6, 0xb3, 0x29,
         0xe3, 0x2f, 0x84, 0x53, 0xd1, 0x00, 0xed, 0x20, 0xfc, 0xb1, 0x5b,
         0x6a, 0xcb, 0xbe, 0x39, 0x4a, 0x4c, 0x58, 0xcf, 0xd0, 0xef, 0xaa,
         0xfb, 0x43, 0x4d, 0x33, 0x85, 0x45, 0xf9, 0x02, 0x7f, 0x50, 0x3c,
         0x9f, 0xa8, 0x51, 0xa3, 0x40, 0x8f, 0x92, 0x9d, 0x38, 0xf5, 0xbc,
         0xb6, 0xda, 0x21, 0x10, 0xff, 0xf3, 0xd2, 0xcd, 0x0c, 0x13, 0xec,
         0x5f, 0x97, 0x44, 0x17, 0xc4, 0xa7, 0x7e, 0x3d, 0x64, 0x5d, 0x19,
         0x73, 0x60, 0x81, 0x4f, 0xdc, 0x22, 0x2a, 0x90, 0x88, 0x46, 0xee,
         0xb8, 0x14, 0xde, 0x5e, 0x0b, 0xdb, 0xe0, 0x32, 0x3a, 0x0a, 0x49,
         0x06, 0x24, 0x5c, 0xc2, 0xd3, 0xac, 0x62, 0x91, 0x95, 0xe4, 0x79,
         0xe7, 0xc8, 0x37, 0x6d, 0x8d, 0xd5, 0x4e, 0xa9, 0x6c, 0x56, 0xf4,
         0xea, 0x65, 0x7a, 0xae, 0x08, 0xba, 0x78, 0x25, 0x2e, 0x1c, 0xa6,
         0xb4, 0xc6, 0xe8, 0xdd, 0x74, 0x1f, 0x4b, 0xbd, 0x8b, 0x8a, 0x70,
         0x3e, 0xb5, 0x66, 0x48, 0x03, 0xf6, 0x0e, 0x61, 0x35, 0x57, 0xb9,
         0x86, 0xc1, 0x1d, 0x9e, 0xe1, 0xf8, 0x98, 0x11, 0x69, 0xd9, 0x8e,
         0x94, 0x9b, 0x1e, 0x87, 0xe9, 0xce, 0x55, 0x28, 0xdf, 0x8c, 0xa1,
         0x89, 0x0d, 0xbf, 0xe6, 0x42, 0x68, 0x41, 0x99, 0x2d, 0x0f, 0xb0,
         0x54, 0xbb, 0x16]

HW = [bin(n).count("1") for n in range(0,256)]

varray = zeros((ntraces,256,16),uint8)
keys = arange(0,16)

############# Section computing hypotheses #############
# based on https://media.blackhat.com/eu-13/briefings/OFlynn/bh-eu-13-for-cheapstakes-oflynn-slides.pdf
# by Colin O'Flynn, slide #16

#For all 16 bytes of key
for bnum in range(0, 16):
    diffs = [0]*256
    #For each 0x00..0xFF possible value of the key byte
    for key in range(0, 256):
        #For each trace, do the following
        for tnum in range(len(traces)):
            #Generate the output of the SBOX
            varray[tnum,key,bnum]=HW[SBOX[ord(plaintexts[tnum][bnum]) ^ key]]

############# Section implementing the CPA attack #############
# based on https://github.com/ermin-sakic/first-order-dpa/blob/master/attack.py
# by Ermin Sakic, under http://www.apache.org/licenses/LICENSE-2.0

#Computing the mean values for the hypothetical plaintext values v (byte-wise)
hammingmeanvalue = zeros((varray[1,:,1].size,16),float32)
for i in range(0,varray[1,:,1].size):
        for n in range(0,16):
                hammingmeanvalue[i,n] = average(varray[:,i,n])

#Computing the difference to the actual values v
for i in range(0,16):
        for n in range(0,256):
                varray = varray.astype(float32)
                varray[:,n,i] = varray[:,n,i]-hammingmeanvalue[n,i]

#Computing the mean values of the power traces - sample-wise
powermeanvalue = zeros((traces[1,:].size),float32)
for i in range(0,traces[1,:].size):
        powermeanvalue[i] = average(traces[:,i])

#Computing the difference to the actual values
meanTraces = traces-powermeanvalue

#Creating the 3-dimensional correlation for all 16 Bytes
rarray = zeros((256,traces[1,:].size,16),float32)


for i in range(0,16):
        for j in range(0,256):
                rarray[j,:,i] = (dot(varray[:,j,i],meanTraces)) / sqrt(sum(varray[:,j,i]**2, axis=0) * sum(meanTraces**2, axis=0))

        #(^2) to get all the positive values
        s=rarray[:,:,i]**2
        #Find the highest correlation value
        keys[i] = nonzero(amax(s) == s)[0]
#################### End of Sections ####################
print ''.join(["%02x" % x for x in keys])

# Testing the recovered key:
from Crypto.Cipher import AES
with open("../ctxt1.txt", "rb") as f:
    c = f.read().decode('hex')

aes = AES.new(''.join([chr(x) % x for x in keys]), AES.MODE_CBC, '\x00'*16)
print aes.decrypt(c)
```

Running it:

```
./attack.py
074d9bb982d97d63b8c8fbea11bd7180
Congratulations! Here's the final flag for Step1: a1309*!POs/f8s
```

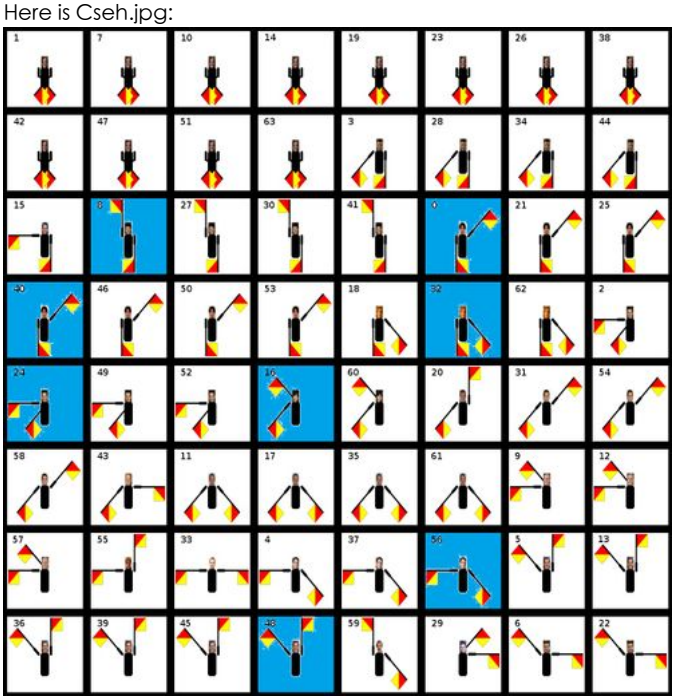
It appears that using the first 128 traces is enough to recover the key immediately.

Challenge 2

First step

```
326554 May  5 16:14 Cseh.jpg
   128 May  5 16:59 ctxt2.txt
```

The filename is a bit weird at first sight, Cseh<>Ches ?
Here is Cseh.jpg:



It shows flag semaphore characters (https://en.wikipedia.org/wiki/Flag_semaphore#Characters) , each with a photo of people famous in the crypto community. Hopefully we don't have to recognize them all to complete the challenge ;)

So each character represents a letter from the alphabet and they are sorted alphabetically.

Each square features a number from 0 to 63 and 8 of them are blue.

At this point the grid and the 8 blue squares (8 queens problem??) vaguely makes me thinking of chess game but not much.

Reordering the squares gives:

```
*E _ H A S T Y _
*D O _ N O T _ B
*I N G _ K E Y _
*H E _ D A W D L
*G R A N T S _ T
*E D _ M A T E _
*T H E _ H E L P
*S O L V I N G _
```

The blue squares line up nicely but the text doesn't make completely sense. It has to be read bottom-up so let's reorder again the grid:

```
*S O L V I N G _
*T H E _ H E L P
*E D _ M A T E _
*G R A N T S _ T
*H E _ D A W D L
*I N G _ K E Y _
*D O _ N O T _ B
*E _ H A S T Y _
```

Solving the helped mate grants the dawdling key Do not be hasty
Mate? So it has to do with chess in the end? At least counting rows bottom-up is typical of chess notation.

The blue squares now aligned in the first column reveal another word: "steghide", a well known steganography tool developed by Stefan Hetzl (http://www.logic.at/staff/hetzl/) .
steghide always takes a passphrase, so let's give it the clue we have:

```
steghide extract --stegofile Cseh.jpg --passphrase "SOLVING THE HELPED MATE GRANTS THE DAWDLING KEY DO NOT BE HASTY "
```

We get a file "Gabor.txt" and the intermediate flag:

```
Intermediate flag: pqq1\du52c:|fA


N7/3PP3/4p2p/1P2P3/3p2pP/3p2pb/3P1pnk/5K1n w - -

Solution= 51||59||47||39||59||35||AES256-Key
AES256-key= ??||??||??||??||??||??||??||??||??||??||??||??||??||??||??||??||??||??||??||??||??||??||??||??||??||??||??||??||??||??||??||??
```

The remaining is more cryptic, as well as the filename, again: Gabor.

Second step

Googling about Gabor, Cseh and chess reveals that Gabor Cseh (http://chesscomposers.blogspot.be/2012/11/november-21st.html) is a chess composer, specialist of helpmates, who tragically passed away 15 years ago.
We're on the right track.

A helpmate (https://en.wikipedia.org/wiki/Helpmate) is a type of chess problem in which both sides cooperate in order to achieve the goal of checkmating Black. In a helpmate in n moves, Black moves first, then White, each side moving n times, to culminate in White's nth move checkmating Black.

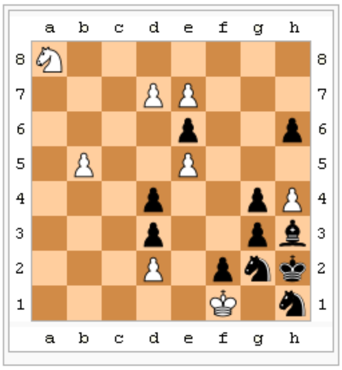
Ok that's not really chess but making a puzzle on a chess board with strange rules ;)

```
N7/3PP3/4p2p/1P2P3/3p2pP/3p2pb/3P1pnk/5K1n w - -
```

is a starting position encoded in FSN (https://en.wikipedia.org/wiki/Forsyth%E2%80%93Edwards_Notation) standard notation.
There is an online converter (http://www.dwheeler.com/misc/fen2wikipedia.html) to Wikipedia notation which gives:

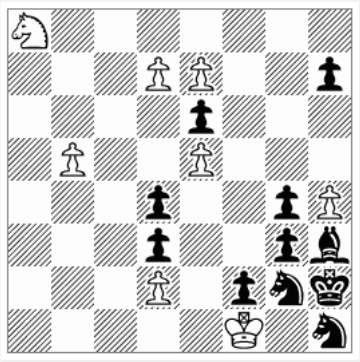
```
{{Chess diagram|=
| tright
|
|=
 8 |nl|  |  |  |  |  |  |  |=
 7 |  |  |  |pl|pl|  |  |  |=
 6 |  |  |  |  |pd|  |  |pd|=
 5 |  |pl|  |  |pl|  |  |  |=
 4 |  |  |  |pd|  |  |pd|pl|=
 3 |  |  |  |pd|  |  |pd|bd|=
 2 |  |  |  |pl|  |pd|nd|kd|=
 1 |  |  |  |  |  |kl|  |nd|=
    a  b  c  d  e  f  g  h
|
}}
```

As I don't have this renderer on my wiki, I simply edited the standard chess diagram (https://commons.wikimedia.org/wiki/Standard_chess_diagram) Wikipedia page and used the preview to render it.
Here is the result:



It's very close to one of the famous helpmates from Gabor Cseh (http://chesscomposers.blogspot.be/2012/11/november-21st.html) :

Cseh, Gábor
The Problemist, 1997
1st Prize



h#10 8+11

Hide solution

1.h6 d8=Q 2.h5 Qd5 3.Sxh4+ Qg2+ 4.Sxg2 e8=B 5.h4 Bc6 6.Sf4+ Bg2 7.Sd5 b6 8.Sc7 b7 9.Sxa8 bxa8=Q
10.Bxg2+ ~ 11.Qxg2#
A fantastic solution with 2 Queen promotions and far-fetched play by the bS.

The curious readers should also check this h#5 with an incredible Zilahi or this h#4.5 with two pairs of Queen promotions.

The difference is that the Black did already one move.
Other refs for the record here (http://www.geocities.ws/solvingchess/problems/CsehGabor.html) , here (http://christian.poisson.free.fr/problemesis99/hntheproblemist97.html) and here (http://www.theproblemist.org/sample-problems/35-favourite-problems/50-chosen-by-christopher-jones)

We got the solution, but it's not spelling an AES key yet:

```
1.h6 d8=Q 2.h5 Qd5 3.Sxh4+ Qg2+ 4.Sxg2 e8=B 5.h4 Bc6 6.Sf4+ Bg2 7.Sd5 b6 8.Sc7 b7 9.Sxa8 bxa8=Q 10.Bxg2+ ~ 11.Qxg2#
```

It's using the algebraic notation (https://en.wikipedia.org/wiki/Algebraic_notation_(chess))
There exists also a numeric notation (https://en.wikipedia.org/wiki/ICCF_numeric_notation) but it can't deal with values such as "59".

We know first moves are h6 (already done), d8=Q h5 Qd5 and they should match 51->59 47->39 59->35.
The solution is simply to reuse the notation of our initial reordered square, counting from 0 to 63.
Translating all next moves gives the AES-256 key:

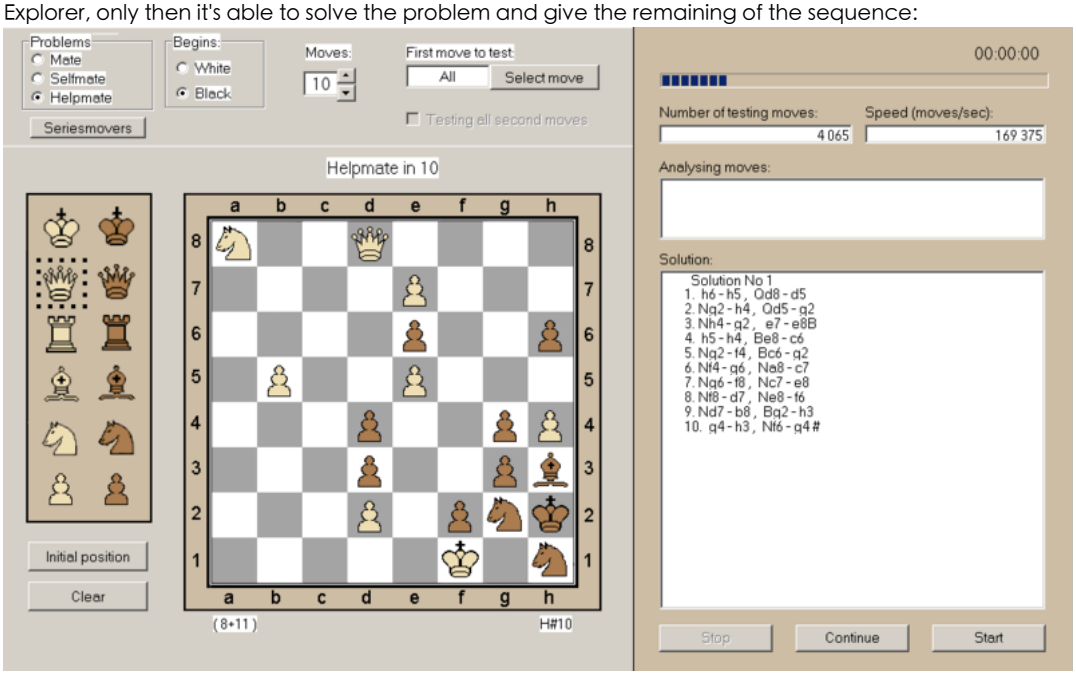
```
1.h6          already played
  d8=Q        51 59
2.h5          47 39
  Qd5         59 35
3.Sxh4+       14 31
  Qg2+        35 14
4.Sxg2        31 14
  e8=B        52 60
5.h4          39 31
  Bc6         60 42
6.Sf4+        14 29
  Bg2         42 14
7.Sd5         29 35
  b6          33 41
8.Sc7         35 50
  b7          41 49
9.Sxa8        50 56
  bxa8=Q      49 56
10.Bxg2+      23 14
11.Qxg2#      56 14
```

```
cat ctxt2.txt |xxd -r -p|openssl enc -d -aes-256-cbc -iv 00000000000000000000000000000000 -K 1431351431145260393160421429421429353341
```

```
Congratulations! Here's the final flag for Step2: 9qp0..-dhs19sA
```

Later @foxTN (https://twitter.com/foxtn) told me about Chess Explorer (http://chessexplorer.republika.pl/) v6.3, a Windows program that runs smoothly under Wine too. The trick with Chess Explorer and regular helpmate is that if White is supposed to win, Black should do the first move, which is not the case here. So assuming you didn't find about Gabor Cseh's problem, you have first to understand the initial moves

sequence 51->59 47->39 59->35 then e.g. play the first White move to promote Pawn to Queen then encode the board position in Chess Explorer, only then it's able to solve the problem and give the remaining of the sequence:



Challenge 3

```
    1634 Jun 11 16:27 client.c
     128 May  5 17:14 ctxt3a.txt
138720144 Jun 23 18:15 ctxt3b
```

First step

client.c is a little program that contacts IP 5.196.94.96 PORT 1337, no more intelligence on the client side.

```
gcc -o client client.c
./client
```

```
Usage: ./client AES128_ciphertext
AES128_ciphertext must be one bloc of 16 bytes.
Example: ./client 00112233445566778899aabbccddeeff
```

```
./client 00112233445566778899aabbccddeeff
```

```
Deciphering request recorded: 00112233445566778899aabbccddeeff

Authentication required.
Generating p...
/-//------//--------//-//---//------ (lengthy stream, cut for readability)
OK!

Generating q...
/---//--//-//------------------//--- (lengthy stream, cut for readability)
OK!

Generating exponents...
OK!

Public RSA Modulus N=28196896764884218723188704711043475233941557841021806381922851623915612177002285110448907284975469577470042981032214712077436006374273453665129408493100492119974988320621152260616765608608144761359259326611516496546936972337372556873489064259158654330233308423550767112058471028456229806713738566284216842620 3

Public RSA Exponent e=16791931623516163759232948791888052306720925887697219471185452084413072528496181482955857814936477791630898151127677357783836901437936391906579743197325527

Please prove your authorization by signing the following number:
25861333245200581549029752981437975835397787582361251752380039408533197378873324036472608043696936870393136937923280064885316920458913898712173041186513571902234826172382108074766731928787399492166675014884084576816341133729914418777824626068685024056244064716811045027053907267294253875846341416399343070344 2

Signature?
```

Then you can type in a number and it'll go on:

```
Deciphering AES ciphertext...
10
9
8
7
```

```
6
5
4
3
WARNING!!!!!!!!!! WRONG AUTHENTICATION!!UNAUTHORIZED ACCESS!
2
1
Plaintext=57d32bc8be00ac2e291a0a5ba657ce98
```

Every new attempt leads to new data.
So based on the info we get, we've to break the freshly generated 1024-bit RSA key and sign the challenge.

All the data shown while generating p and q seem to indicate that it could be used as side-channel info to recover p and q.
But after some poor attempts I wanted to try another simpler attack: the Common Factor attack, which is very well explained here (http://www.loyalty.org/~schoen/rsa/) .

So firstly I collected a few N.

Sending non-interactively the signature in bash wasn't that trivial:

```
python -c "print '0' * 123"|nc 5.196.94.96 1337
```

Sending less than 1024 bytes wasn't enough, the server was still asking for signature.
Sending between 1024 and 2046 did the job
Above 2046 -> crash before requesting the signature, ooops :-) Going further on that part is forbidden by the rules so...

```
#!/bin/bash

for ((i=0;i<1000;i++)); do
    python -c "print '0' * 1024"|nc 5.196.94.96 1337|grep -a N=|sed 's/.*N=//'|tee -a N.log
done
cat N.log |sort|uniq > Nuniq.log
```

Then try to find common factors between them:

```
#!/usr/bin/env python

from fractions import gcd
with open('Nuniq.log', 'rb') as f:
    table=f.read().split('\n')
table=[int(x.rstrip('\x00')) for x in table[:-1]]
for i in range(len(table)-1):
    for j in range(i+1, len(table)):
        if gcd(table[i], table[j]) != 1:
            print i, j, gcd(table[i], table[j]), '\n'
```

```
./gcd.py|tee factors
```

```
0 1 13467571150670687066957875085721965877832239113551705444143019591603700515153235000428172641836606112908781752701461471841368993247989009896064991

0 15 13522691794376224089868859278287899501033018902746299241330282162167180595895681147672319399654497784997302521749226127494937660644522050195279O

0 16 13467571150670687066957875085721965877832239113551705444143019591603700515153235000428172641836606112908781752701461471841368993247989009896064991

0 48 13467571150670687066957875085721965877832239113551705444143019591603700515153235000428172641836606112908781752701461471841368993247989009896064991

0 59 13467571150670687066957875085721965877832239113551705444143019591603700515153235000428172641836606112908781752701461471841368993247989009896064991
```

Indeed, bingo, some common factors are found which means the corresponding keys can be factorized!

Let's verify one of the broken keys:

```
#!/usr/bin/env python

import gmpy2
def inv_mod(a,n):
    return long(gmpy2.invert(a,n))

N=48968312974330694132280509588241922473637081471839254821112178733989808761702643138616354669915984656940923963663924636195529165822E
e=22128785094155235645734655029153146544996333536428633068744601079808079739933367737532667883249081632568925074568802041762302172470E
m=44198742570274777485568124746581875311367908659158525582082514106974282541139738371627160320554011659074421812910419512684898389079S
p=21563957808398119329545349513312897291720371794644161565433575994922624494866014735925135594671402533520230648695949559828278766299C
q=22708406967509416561081471369947020796745437757938294005271339336356008357234294069698063747451399564794968797317330497407167861251S
assert p*q==N
phi=(p-1)*(q-1)
d=inv_mod(e,phi)
assert (e*d)%phi==1
sign=pow(m,d,N)
assert pow(sign,e,N)==m
```

Everything runs smoothly.
Now time to write a full attack:

```
#!/usr/bin/env python

import sys
```

```
import socket
import random
from fractions import gcd

def log(m):
    with open('log.txt', 'ab') as log:
        log.write(m)

def verbose(m):
    pass
#    print m

import gmpy2
def inv_mod(a,n):
    return long(gmpy2.invert(a,n))

Ntable=[]
def fact(N):
    for n in Ntable:
        if N==n:
            return False
        if gcd(n, N) != 1:
            p=gcd(n, N)
            q=N/p
            Ntable.append(N)
            return (p,q)
    Ntable.append(N)
    return False

TCP_IP = "5.196.94.96"
TCP_PORT = 1337
BUFFER_SIZE = 1024

with open('ctxt3a.txt', 'rb') as f:
    ciphertext=f.read()
ivs='00'*16+ciphertext

for ci in range(0,len(ciphertext),32):
    c=ciphertext[ci:ci+32]
    iv=ivs[ci:ci+32]

    decoded=False
    print iv, '+', c
    while not decoded:
        print '.',
        sys.stdout.flush()
        try:
            s = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
            s.settimeout(5.0)
            s.connect((TCP_IP, TCP_PORT))
            s.send(c)
            log("\nSEND "+c)
            data = ""
            watch1="Modulus N="
            watch2="\n\nPublic RSA Exponent e="
            watch3="\n\nPlease prove your authorization by signing the following number:\n"
            watch4="\n\nSignature?"
            data=""
            while watch4 not in data:
                dd = s.recv(BUFFER_SIZE)
                log(dd)
                data += dd
            N=int(data[data.index(watch1)+len(watch1):data.index(watch2)].rstrip('\x00'))

            f=fact(N)
            if f:
                print '!'
                sys.stdout.flush()
                verbose("N=%i" % N)
                p,q=f
                e=int(data[data.index(watch2)+len(watch2):data.index(watch3)].rstrip('\x00'))
                verbose("e=%i" % e)
                m=int(data[data.index(watch3)+len(watch3):data.index(watch4)].rstrip('\x00'))
                verbose("m=%i" % m)
                phi=(p-1)*(q-1)
                # d, the modular multiplicative inverse of e (mod phi(n))
                d=inv_mod(e,phi)
                sign=pow(m,d,N)
                verbose("p=%i" % p)
                verbose("q=%i" % q)
                verbose("phi=%i" % phi)
                verbose("d=%i" % d)
                verbose("sign=%i" % sign)
                s.send("%i" % sign)
                log("\nSEND ")
                log("%i" % sign)
                watch="Plaintext="
                data=""
                while watch not in data:
                    dd = s.recv(BUFFER_SIZE)
                    log(dd)
                    data += dd
                if "Authentication complete" not in data:
                    print "FAILED??"
                    verbose(data)
                    continue
                plain=data[data.index(watch)+len(watch):].rstrip('\x00').rstrip('\x00\n')
                plain="".join([chr((ord(x)) ^ (ord(y))) for (x,y) in zip(plain.decode('hex'), iv.decode('hex'))])
                print plain
                decoded=True
            s.close()
        except ZeroDivisionError:
            print "Error captured"
```

```
./client.py
```

```
00000000000000000000000000000000 + bddb6ba6569c7e079c76c48a67c9fc68
. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . !
Congratulations!
bddb6ba6569c7e079c76c48a67c9fc68 + 55bd14dd8ac2a717075a598bed0a986d
. !
 Here's the firs
55bd14dd8ac2a717075a598bed0a986d + c8b9f818cffc47e214c81e0f3d01d948
. . . . . . . . . . . . . . . . . . . . . !
t flag for Step3
c8b9f818cffc47e214c81e0f3d01d948 + fd2de97665d496ba405a304945623ee7
. . !
: 7Pqmd85(8dd)x(
```

The attack takes 35s on my laptop.

First step, "fox" version

@foxTN (https://twitter.com/foxtn) found how to take advantage of the stream when p and q are generated.

The attack is described in this paper: A New Side-Channel Attack on RSA Prime Generation (https://www.iacr.org/archive/ches2009/57470141/57470141.pdf) (pdf) by Thomas Finke et al. and presented at CHES 2009.

It works if the primes are generated by following this algorithm:

- Prepare a table of the first N odd primes, starting from 3,5,7,11,... (we can drop 2 as we've just to take odd numbers to avoid it)
- Pick a random odd number about the size of the desired prime length
- Perform a quick check if it's divisible by one of the primes from the table
- If yes, add 2 and start over
- If not, then go for a more thorough test of its primality, e.g. the Miller-Rabin primality test (https://en.wikipedia.org/wiki/Miller%E2%80%93Rabin_primality_test)
- Again, if it's not prime, add 2 and start over

At the end you get your prime

What we can observe here looks like this:

```
Generating p...
/-//------//--------//-//---//------ (lengthy stream, cut for readability)
```

Where the streams are each made of about 25000 to 65000 symbols.
Length of "---" segments varies between 1 and 256 so we can guess it's following the algorithm described above:

- Prepare a table of the first 256 odd primes
- Pick a random number about the size of the desired prime length
- Perform a quick check if it's divisible by 2 or one of the primes of the table, starting from 3,5,7,11,... and output "-" for each successful test
- If one of the test fails, add 1, output "/" and start over
- If all division tests pass, then test more thoroughly its primality
- Again, if it's not prime, add 1, output "/" and start over
- If all tests pass, output "/" and we're done, we found a prime

Looking at the end of a stream, e.g. if it's

```
...//---//--------------------------------//-//-(*256)/
```

this means, reading from right to left, that if p is prime, p-2 is divisible by the first element of the prime table: 3, p-4 is divisible by the 33rd: 139, p-6 is divisible by 7, etc

```
...//---//--------------------------------//-//-(*256)/
   divisible, take next: i+=2
     try /3: pass
      try /5: pass
       try /7:
        divisible, take next: i+=2
          try /3: pass
           ...
                                          try /139:
                                           divisible, take next: i+=2
                                             try /3:
                                              divisible, take next: i+=2
                                                try /3: pass
                                                 ...
                                                  do a Miller-Rabin test: pass => outputs p
```

So

- (p-2) mod 3 = 0
  - p mod 3 = 2
- (p-4) mod 139 = 0
  - p mod 139 = 4
- (p-6) mod 7 = 0
  - p mod 7 = 6
- etc.

And of course

- (p-1) mod 2 = 0
  - p mod 2 = 1

Then combining all those equations via the Chinese remainder theorem (https://en.wikipedia.org/wiki/Chinese_remainder_theorem) tells us there is a unique solution for p mod (2*3*139*7*...)
If the stream is long enough and we collected enough equations such that the product (2*3*139*7*...) is large enough (paper says about 300 bits for a 1024-bit RSA, so 512-bit p), the solution is p.
Do the same for q then check if p*q==N
The paper goes on to find p and q in case there is less information, but the challenge was apparently made such that the streams were long enough (we get about 500 to 1100 equations per prime and the product is always above 512 bits).
Here is the code of fox' attack:

```
#!/usr/bin/env python

import sys
import gmpy
from operator import mul
from sympy.ntheory.modular import crt
from socket import socket

def recv_until(s, string):
    buf = ""
    while not buf.endswith(string):
        r = s.recv(1)
        buf += r
        if len(r) == 0:
            print "remote server terminated connection: '%s'" % buf
            raise socket.error
            exit()
    return buf[:-len(string)]

def xor(s1, s2):
    return "".join([chr(ord(s1[i]) ^ ord(s2[i])) for i in range(len(s1))])

def chunks(l, n):
    """Yield successive n-sized chunks from l."""
    for i in xrange(0, len(l), n):
        yield l[i:i+n]

primes = [  3,    5,    7,   11,   13,   17,   19,   23,   29,
     31,   37,   41,   43,   47,   53,   59,   61,   67,   71,
     73,   79,   83,   89,   97,  101,  103,  107,  109,  113,
    127,  131,  137,  139,  149,  151,  157,  163,  167,  173,
    179,  181,  191,  193,  197,  199,  211,  223,  227,  229,
    233,  239,  241,  251,  257,  263,  269,  271,  277,  281,
    283,  293,  307,  311,  313,  317,  331,  337,  347,  349,
    353,  359,  367,  373,  379,  383,  389,  397,  401,  409,
    419,  421,  431,  433,  439,  443,  449,  457,  461,  463,
    467,  479,  487,  491,  499,  503,  509,  521,  523,  541,
    547,  557,  563,  569,  571,  577,  587,  593,  599,  601,
    607,  613,  617,  619,  631,  641,  643,  647,  653,  659,
    661,  673,  677,  683,  691,  701,  709,  719,  727,  733,
    739,  743,  751,  757,  761,  769,  773,  787,  797,  809,
    811,  821,  823,  827,  829,  839,  853,  857,  859,  863,
    877,  881,  883,  887,  907,  911,  919,  929,  937,  941,
    947,  953,  967,  971,  977,  983,  991,  997, 1009, 1013,
   1019, 1021, 1031, 1033, 1039, 1049, 1051, 1061, 1063, 1069,
   1087, 1091, 1093, 1097, 1103, 1109, 1117, 1123, 1129, 1151,
   1153, 1163, 1171, 1181, 1187, 1193, 1201, 1213, 1217, 1223,
   1229, 1231, 1237, 1249, 1259, 1277, 1279, 1283, 1289, 1291,
   1297, 1301, 1303, 1307, 1319, 1321, 1327, 1361, 1367, 1373,
   1381, 1399, 1409, 1423, 1427, 1429, 1433, 1439, 1447, 1451,
   1453, 1459, 1471, 1481, 1483, 1487, 1489, 1493, 1499, 1511,
   1523, 1531, 1543, 1549, 1553, 1559, 1567, 1571, 1579, 1583,
   1597, 1601, 1607, 1609, 1613, 1619, 1621]

cipher = open("./ctxt3a.txt").read().decode('hex')
iv = '\x00'*16

counter = 0
for chunk in chunks(cipher, 16):
    while True:
        s = socket()
        s.connect(("5.196.94.96", 1337))
        s.send(chunk.encode('hex') + "\n")
        content = recv_until(s, "?")

        p = content.split("\n")[4]
        q = content.split("\n")[8]
        n = int(content.split("\n")[14].split("=")[1].replace("\x00", ""))
        e = int(content.split("\n")[16].split("=")[1].replace("\x00", ""))
        to_sign = int(content.split("\n")[19].replace("\x00", ""))

        primes_p = [len(x.replace("/", "")) for x in p.split("//")]
        primes_q = [len(x.replace("/", "")) for x in q.split("//")]

        Sp = [2]
        Sp_v = [1]
        for i, p_idx in enumerate(primes_p):
            p_idx = int(p_idx)
            if p_idx == 256:
                continue
            Sp.append(primes[p_idx-1])
            Sp_v.append(2*(len(primes_p) - i - 1))

        Sq = [2]
        Sq_v = [1]
        for i, p_idx in enumerate(primes_q):
            p_idx = int(p_idx)
```

```
            if p_idx == 256:
                continue
            Sq.append(primes[p_idx-1])
            Sq_v.append(2*(len(primes_q) - i - 1))

        ap = crt(Sp, Sp_v)[0]
        bq = crt(Sq, Sq_v)[0]

        p, q = ap, bq
        if p * q != n:  # FAIL! Retry...
            continue

        phi = (p-1) * (q-1)
        d = gmpy.invert(e, phi)
        assert pow(pow(42, e, n), d, n) == 42
        resp = pow(to_sign, d, n)

        s.send(str(resp))
        recv_until(s, "Authentication complete!")
        plain = s.recv(1024).split("=")[1].split()[0]
        plain = xor(plain.decode('hex'), iv)
        iv = chunk
        sys.stdout.write(plain)
        sys.stdout.flush()
        break
print
```

```
Congratulations! Here's the first flag for Step3: 7Pqmd85(8dd)x(
```

The attack takes 3.1s on my laptop.

Retrospectively I think the authors of this challenge intended us to solve it this way because the gaps before finding p and q are abnormally long, which helps a lot this attack.
But to do so, they constrained their set of primes so much that the common factor attack became feasible.
Well, that's just an hypothesis...

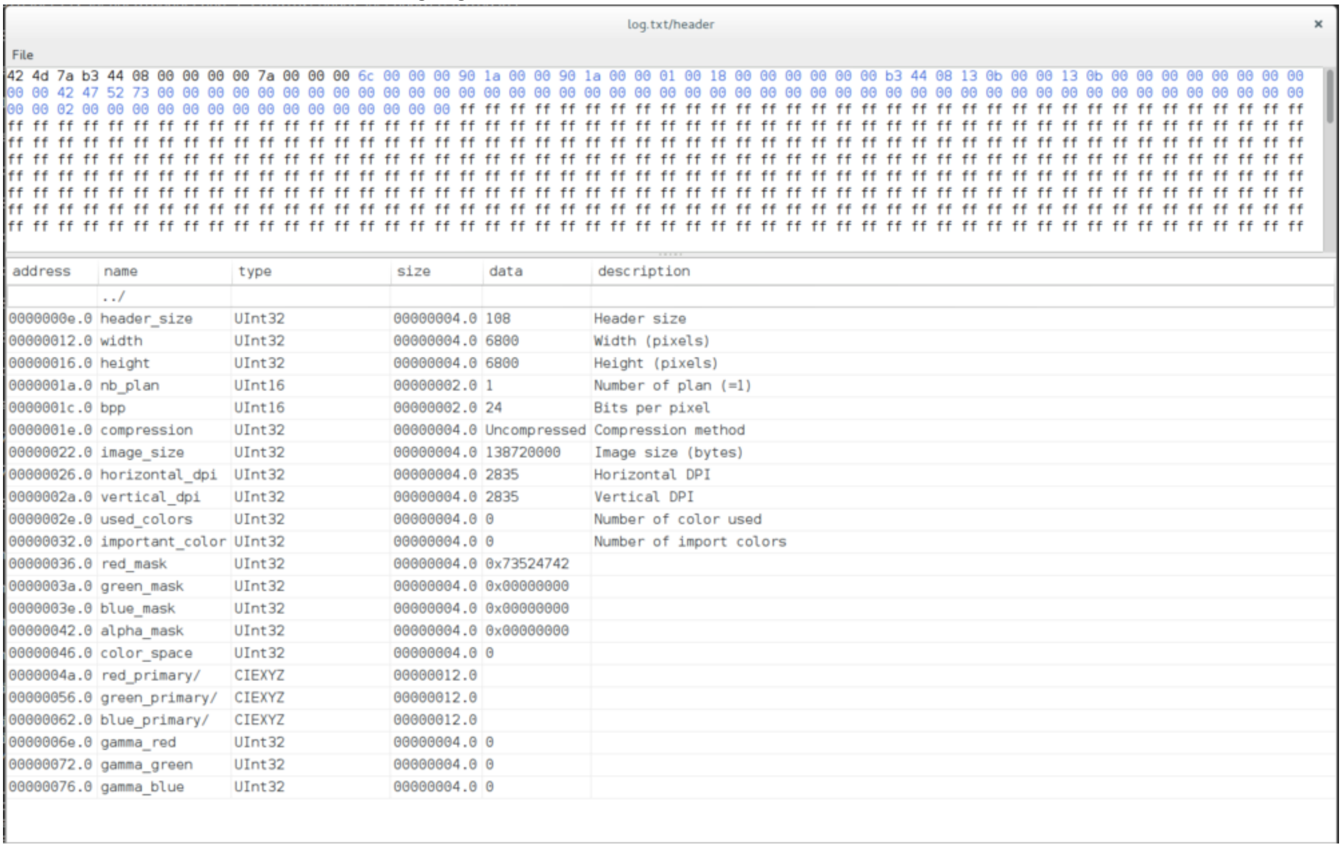
I've also the feeling the code on the server changed somewhere like one week after the beginning because there were differences in the network packets and in the streams: at the beginning the last stream segment was always //-(*257)/ while after it was always //-(*256)/

Second step

Second ciphertext: ctxt3b
No extension but the file is large, 135Mb!
If we want to use the same attack to decode the entire file it will take ages.
ctxt3b seems to be also aes-128-cbc encoded (no repetition of blocks) and starts with 16*'\x00', the IV?
Let's decode the first 1500 bytes and analyze the result:

```
file result
result: PC bitmap, Windows 95/NT4 and newer format, 6800 x 6800 x 24
```

It's a BMP, more details can be seen using e.g. hachoir-wx:




```
42 4d 7a b3 44 08 00 00 00 00 7a 00 00 00 6c 00 00 00 90 1a 00 00 90 1a 00 00 01 00 18 00 00 00 00 00 00 b3 44 08 13 0b 00 00 13 0b 00 00 00 00 00 00 00 00
00 00 42 47 52 73 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00 00 02 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff
ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff
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ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff ff
```

address	name	type	size	data	description
	../				
0000000e.0	header_size	UInt32	00000004.0	108	Header size
00000012.0	width	UInt32	00000004.0	6800	Width (pixels)
00000016.0	height	UInt32	00000004.0	6800	Height (pixels)
0000001a.0	nb_plan	UInt16	00000002.0	1	Number of plan (=1)
0000001c.0	bpp	UInt16	00000002.0	24	Bits per pixel
0000001e.0	compression	UInt32	00000004.0	Uncompressed	Compression method
00000022.0	image_size	UInt32	00000004.0	138720000	Image size (bytes)
00000026.0	horizontal_dpi	UInt32	00000004.0	2835	Horizontal DPI
0000002a.0	vertical_dpi	UInt32	00000004.0	2835	Vertical DPI
0000002e.0	used_colors	UInt32	00000004.0	0	Number of color used
00000032.0	important_color	UInt32	00000004.0	0	Number of import colors
00000036.0	red_mask	UInt32	00000004.0	0x73524742	
0000003a.0	green_mask	UInt32	00000004.0	0x00000000	
0000003e.0	blue_mask	UInt32	00000004.0	0x00000000	
00000042.0	alpha_mask	UInt32	00000004.0	0x00000000	
00000046.0	color_space	UInt32	00000004.0	0	
0000004a.0	red_primary/	CIEXYZ	00000012.0		
00000056.0	green_primary/	CIEXYZ	00000012.0		
00000062.0	blue_primary/	CIEXYZ	00000012.0		
0000006e.0	gamma_red	UInt32	00000004.0	0	
00000072.0	gamma_green	UInt32	00000004.0	0	
00000076.0	gamma_blue	UInt32	00000004.0	0	

A quick check on the sizes:

```
0x7a+(6800*6800*3)=138720122
+iv=138720138
+pad=138720144
```

Ok so there is nothing after the BMP.
BMP is not compressed so we can sample it and we don't have to decrypt it entirely.
Oh wait but it's CBC encrypted, so all blocks are chained, right?
Well it's not much a problem when *decrypting*, cf PoC||GTFO 0x06 Section 7 and Wikipedia (https://en.wikipedia.org/wiki/Block_cipher_mode_of_operation#Cipher_Block_Chaining_.28CBC.29) : you just need to XOR with the previous ciphertext block, no chaining.

The tactic will be the following one: complete the decoded header to create an empty BMP, sample randomly the encrypted bmp and paint on our empty BMP.

Here we keep the header and the first 400px (=1200 bytes), then we paint with some pastel green color so we'll be able to see where we're painting on, being in white or in other colors:

```
#!/usr/bin/env python

with open('decoded_first1500','rb') as h, open('decoded.bmp', 'wb') as b:
    b.write(h.read()[:0x7A+3*400])
    b.write('\x99\xff\xee'*(6800*6800-400))
```

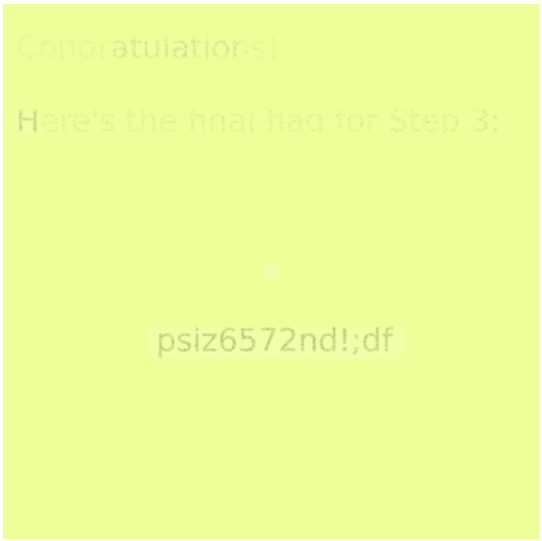
The attack code is almost identical to the first step, just the way to select ciphertexts and complete the BMP are different.
We saw "fox" version was faster, but only at the beginning as finding common factors require first to collect some public keys. On the long run both attacks are equivalent for this second step.

```
#!/usr/bin/env python

import sys
import socket
import random
from fractions import gcd

def log(m):
    pass
#    with open('log.txt', 'wb') as log:
#        log.write(m)

def verbose(m):
    pass
#    print m

import gmpy2
def inv_mod(a,n):
    return long(gmpy2.invert(a,n))

Ntable=[]
def fact(N):
    for n in Ntable:
        if N==n:
            return False
        if gcd(n, N) != 1:
            p=gcd(n, N)
            q=N/p
            Ntable.append(N)
            return (p,q)
    Ntable.append(N)
    return False

TCP_IP = "5.196.94.96"
TCP_PORT = 1337
BUFFER_SIZE = 1024

with open('ctxt3b', 'rb') as f:
    ciphertext=f.read()

xpos=0
ypos=0
width=6800
height=6800

# flag coordinates:
#xpos=1850
#ypos=4100
#width=5100-xpos
#height=4500-ypos

with open('decoded.bmp', 'rb+',0) as bmp:
    for i in range(1000000):
        ci=(((0x7A+(random.randint(xpos,xpos+width)*3)+(6800-(random.randint(ypos,ypos+height)))*6800*3)/16)+1)*16
        c=ciphertext[ci:ci+16].encode('hex')
        iv=ciphertext[ci-16:ci].encode('hex')
        decoded=False
        print iv, '+', c
        while not decoded:
            print '.',
            sys.stdout.flush()
            try:
                s = socket.socket(socket.AF_INET, socket.SOCK_STREAM)
                s.settimeout(5.0)
                s.connect((TCP_IP, TCP_PORT))
```

```
            s.send(c)
            log("\nSEND "+c)
            data = ""
            watch1="Modulus N="
            watch2="\n\nPublic RSA Exponent e="
            watch3="\n\nPlease prove your authorization by signing the following number:\n"
            watch4="\n\nSignature?"
            data=""
            while watch4 not in data:
                dd = s.recv(BUFFER_SIZE)
                log(dd)
                data += dd
            N=int(data[data.index(watch1)+len(watch1):data.index(watch2)].rstrip('\x00'))

            f=fact(N)
            if f:
                print '!'
                sys.stdout.flush()
                verbose("N=%i" % N)
                p,q=f
                e=int(data[data.index(watch2)+len(watch2):data.index(watch3)].rstrip('\x00'))
                verbose("e=%i" % e)
                m=int(data[data.index(watch3)+len(watch3):data.index(watch4)].rstrip('\x00'))
                verbose("m=%i" % m)
                phi=(p-1)*(q-1)
                # d, the modular multiplicative inverse of e (mod phi(n))
                d=inv_mod(e,phi)
                sign=pow(m,d,N)
                verbose("p=%i" % p)
                verbose("q=%i" % q)
                verbose("phi=%i" % phi)
                verbose("d=%i" % d)
                verbose("sign=%i" % sign)
                s.send("%i" % sign)
                log("\nSEND ")
                log("%i" % sign)
                watch="Plaintext="
                data=""
                while watch not in data:
                    dd = s.recv(BUFFER_SIZE)
                    log(dd)
                    data += dd
                if "Authentication complete" not in data:
                    print "FAILED??"
                    verbose(data)
                    continue
                plain=data[data.index(watch)+len(watch):].rstrip('\x00').rstrip('\x00\n')
                plain="".join([chr((ord(x)) ^ (ord(y))) for (x,y) in zip(plain.decode('hex'), iv.decode('hex'))])
                bmp.seek(ci-16,0)
                bmp.write(plain)
                decoded=True
            s.close()
        except ZeroDivisionError:
            print "Error captured"
```

We let it run for a while and we can inspect the BMP from time to time to see how it progresses.
Then when interesting spots are identify we can restrict the random sampling to that region.
And soon:

Apparently I got lucky because the first area I revealed was the flag, while actually there were two other (useless) lines in the picture:



Challenge 4

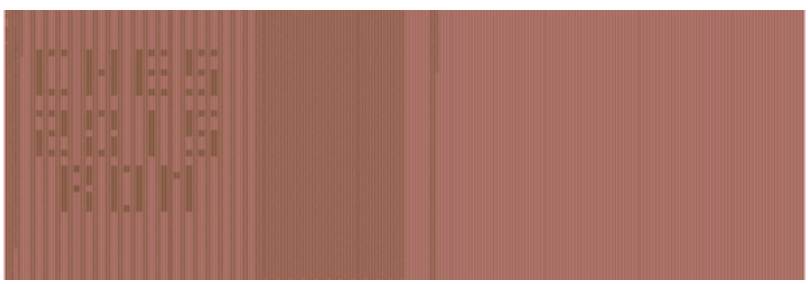
```
    128 May 14 19:35 ctxt4.txt
16975387 Jun 23 13:49 rom.png
```

First step

```
file rom.png
rom.png: PNG image data, 30598 x 10240, 8-bit/color RGB, non-interlaced
```

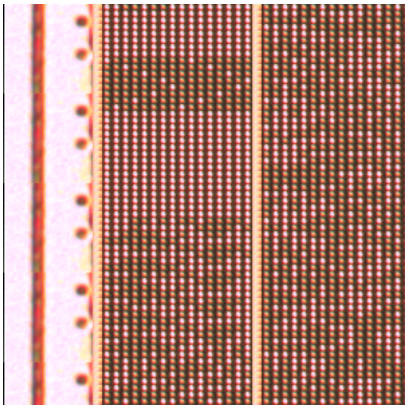
That's a huge image!
To give an idea, here is a scaled-down version:

```
convert rom.png -resize 5% rom_scaled.png
```



And a zoom at scale 1:1 on the top left corner:

```
convert rom.png -crop 300x300-0-0 +repage rom_corner.png
```

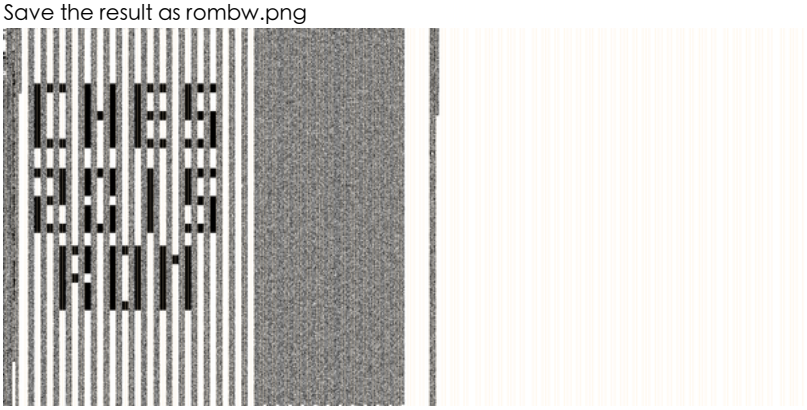


It's apparently the photo of a chip die, a ROM by the filename and aspect and we can distinguish clear and dark spots, zeros and ones, or vice versa.

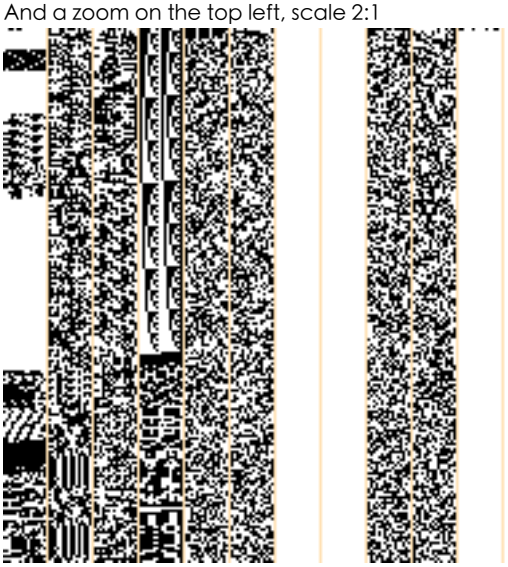
ROM dots are rectangles of 7x5 pixels, separators are 7px wide
Let's open the file in Gimp and crop borders on both sides, now we get a 30457x10240 grid, which lead to exact multiples:

```
30457/7 = 4351
10240/5 = 2048
```

Still in Gimp, let's resize it to 4351x2048 so one pixel per ROM dot and disable any interpolation!
We're left with two tones for the dots and a third for the separators.
Select the two tones of ROM dots and color them in black and white.
Save the result as rombw.png



And a zoom on the top left, scale 2:1



This simple technique worked because the ROM image was artificially created and was very regular.
For real ROM die pictures, see rompar (https://github.com/ApertureLabsLtd/rompar) by Adam Laurie.
In the last image we see the column structure:

```
8:8:1 8:8:1 ...
```

Fourth column shows something like a font table and the top half shows probably incremental values so given their pattern we guess we've to interpret those dots as 2-byte words, MSB, the left byte then the right byte, from top of the column to bottom of the column.

Adding one separator to the count to have as many separators as columns, we get (4351+1)/17 = 256 pairs of columns
Let's isolate the data by converting the image in PNM format, very convenient to manipulate.
So convenient that the only thing we've to do to convert to raw data is to convert to PBM (the black and white format) and cut the PBM header:

```
#!/bin/bash

pngtopnm rombw.png > rombw.pnm
for ((i=0;i<256;i++)); do
# Should we interpret black / white as 0/1 or 1/0 ?
    pnmcut -left $(($i*17)) -width 16 rombw.pnm |ppmtopgm|pgmtopbm|pnminvert|dd bs=1 skip=11 >> rom.bin
#   pnmcut -left $(($i*17)) -width 16 rombw.pnm |ppmtopgm|pgmtopbm|dd bs=1 skip=11 >> rom2.bin
done
rm rombw.pnm
```

```
file rom.bin
rom.bin: Gameboy ROM: "4", [ROM+MBC1], ROM: 8Mbit, RAM: 64Kbit
```

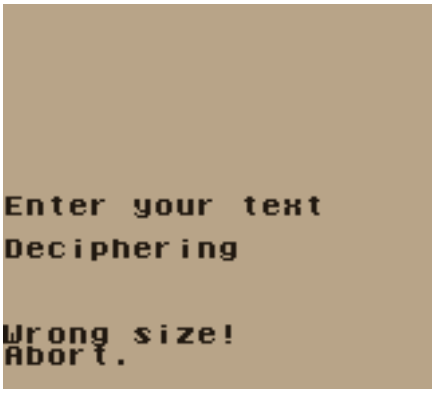
Sounds like we got something!
I made rom.bin available here (https://mega.co.nz/#!ycFzkB4J!cxkfGhAs9urIXxuFGBW7xccSb35CnSQRzx4eahZJ_pc) .
Running it in an emulator such as gngb (http://m.peponas.free.fr/gngb/) shows a first message with the intermediate flag (here zoomed at 2:1):

So the intermediate flag is UGA-+pcnsgxp93

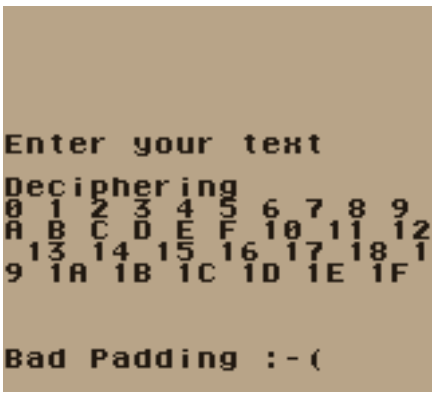
Second step

The it says "Enter your text" with a cursor that can move on an invisible 4x4 grid.

Pressing Enter (Gameboy Start):



Moving around and pressing X (Gameboy A) 64 times makes the "game" moving to the deciphering stage, where we see the text we entered, so the 4x4 grid is the 16 hexadecimal symbols.
Then:



It smells like padding oracle attack (https://en.wikipedia.org/wiki/Padding_oracle_attack) ;-)
All the difficulty will be to automate the attack.
It's also possible to enter only 32 symbols (16 bytes) and press Start but I didn't figure out if it can be useful for something or not.
Trying to launch the ROM in a more advanced tool such as no$gmb (http://problemkaputt.de/gmb.htm) debugger fails and suggests VisualBoyAdvance (https://en.wikipedia.org/wiki/VisualBoyAdvance) :

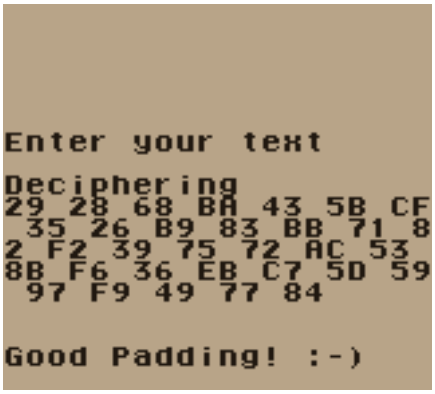
I finally chose to drive directly gngb with xdotool (http://www.semicomplete.com/projects/xdotool/) and take screen snapshots with xwd, from x11-apps.

```
#!/bin/bash

DELAY=300
SLEEP1=2
SLEEP2=5

cc="${1}"
if [ ${#cc} != 64 ]; then
    echo "Error ciphertext too short: $cc" >&2
    exit 1
fi

gngb -a rom.bin &

dd() {
    case $1 in
```

```
        0)  x2=0;y2=0;;
        1)  x2=1;y2=0;;
        2)  x2=2;y2=0;;
        3)  x2=3;y2=0;;
        4)  x2=0;y2=1;;
        5)  x2=1;y2=1;;
        6)  x2=2;y2=1;;
        7)  x2=3;y2=1;;
        8)  x2=0;y2=2;;
        9)  x2=1;y2=2;;
        a)  x2=2;y2=2;;
        b)  x2=3;y2=2;;
        c)  x2=0;y2=3;;
        d)  x2=1;y2=3;;
        e)  x2=2;y2=3;;
        f)  x2=3;y2=3;;
    esac
    while [ $x2 -gt $x ]; do s="${s} Right"; x=$(($x+1)); done
    while [ $x2 -lt $x ]; do s="${s} Left"; x=$(($x-1)); done
    while [ $y2 -gt $y ]; do s="${s} Down"; y=$(($y+1)); done
    while [ $y2 -lt $y ]; do s="${s} Up"; y=$(($y-1)); done
    s="${s} x"
}

x=0
y=0
sleep $SLEEP1
s="xdotool search Gngb key --delay $DELAY "
for i in $(echo $cc|sed 's/\(.\)/ \1/g'); do dd $i ;done
$s 2>/dev/null
sleep $SLEEP2
xwd -name Gngb|convert - png: > shot_${cc}.png
pkill gngb
```

Let's try the last block of ctxt4.txt where padding should be correct and the one before as IV:

```
./run-once.sh 292868ba435bcf3526b983bb7182f2397572ac538bf636ebc75d5997f9497784
```



But it's still awfully slow to type in the ciphertexts and it's just not doable without the --autoframeskip option of gngb.
In total it takes about 76s for one single run and we can't reduce the delay of keypresses below 300ms without missing key strokes.

So I patched gngb to run it faster (with --autoframeskip):

```
--- gngb-20060309/src/frame_skip.c      2015-06-26 09:01:51.867400703 +0200
+++ gngb-20060309/src/frame_skip.c      2015-06-26 09:01:51.867400703 +0200
@@ -100,7 +100,7 @@

   if (conf.autoframeskip) {
     if (rfd<target && f2skip==0 ) {
-      while(get_ticks()<target) {
+      while(get_ticks()<target/25) { // faster!
        if (conf.sleep_idle)
 #ifdef HAVE_USLEEP
          usleep(10);
```

So now I could take down the delay when pressing keys with xdotool to 20ms and the full run takes now 6.6s:

```
DELAY=20
SLEEP1=1
SLEEP2=1
```

Now the padding attack:
To check if the run went smoothly and led to a good or bad padding, we take a snapshot of the Gameboy screen at the end, crop it to keep the bottom, hash it and compare it with the known hashes of a good or a bad padding result.
The script is a bit ugly because I started in bash then moved to python for the tricky parts... CTF quality ;-)

```
#!/bin/bash

DELAY=20
SLEEP1=1
SLEEP2=1
KNOWN=""
```

```
pkill gngb
fast_patch/gngb-20060309/src/gngb -a rom.bin &

dd() {
    case $1 in
        0)  x2=0;y2=0;;
        1)  x2=1;y2=0;;
        2)  x2=2;y2=0;;
        3)  x2=3;y2=0;;
        4)  x2=0;y2=1;;
        5)  x2=1;y2=1;;
        6)  x2=2;y2=1;;
        7)  x2=3;y2=1;;
        8)  x2=0;y2=2;;
        9)  x2=1;y2=2;;
        a)  x2=2;y2=2;;
        b)  x2=3;y2=2;;
        c)  x2=0;y2=3;;
        d)  x2=1;y2=3;;
        e)  x2=2;y2=3;;
        f)  x2=3;y2=3;;
    esac
    while [ $x2 -gt $x ]; do s="${s} Right"; x=$(($x+1)); done
    while [ $x2 -lt $x ]; do s="${s} Left"; x=$(($x-1)); done
    while [ $y2 -gt $y ]; do s="${s} Down"; y=$(($y+1)); done
    while [ $y2 -lt $y ]; do s="${s} Up"; y=$(($y-1)); done
    s="${s} x"
}

for ((n=$((${#KNOWN}/2)+1));n<17;n++)); do
    ccorig="292868ba435bcf3526b983bb7182f2397572ac538bf636ebc75d5997f9497784"
    #ccorig="4ac2c9e5ac61834bda70725000435fa6292868ba435bcf3526b983bb7182f239"
    #ccorig="023aed0485f26b3b066349bc7856adad4ac2c9e5ac61834bda70725000435fa6"
    #ccorig="00000000000000000000000000000023aed0485f26b3b066349bc7856adad"

    # Trying all padding characters:
    for ((bn=16;bn>0;bn--)); do
    # Trying all printable characters:
    #for ((bn=$((0x7E));bn>$((0x1F));bn--)); do
    # or trying specific chars first
    #for bc in " " ":" e t a i r o n s l h c d u p m g y f w b v k x j q z  E T A I R O N S L H C D U P M G Y F W B V K X J Q Z 0 1 2

        xdotool search Gngb key F11 2>/dev/null
        x=0
        y=0
        sleep $SLEEP1
        [ "$bn" != "" ] && bb=$(python -c "print '%02x' % (0x${ccorig:$(((16-$n)*2)):2}^$n^$bn)")
        [ "$bc" != "" ] && bb=$(python -c "print '%02x' % (0x${ccorig:$(((16-$n)*2)):2}^$n^ord(\"$bc\"))")
        cc=${ccorig:0:$(((16-n)*2))}
        cc+=$bb
        pad=$(python -c "print ('%02x' % $n)*$(($n-1))")
        [ $n -gt 1 ] && cc+=$(python -c "print \"%0$(($n-1)*2))x\" % (0x${ccorig:$(((16-$n+1)*2)):$(($n-1)*2))}^0x${pad}^0x$KNOWN)")
        cc+=${ccorig:32:32}
        echo -n "$bn $bc $bb $cc"
        s="xdotool search Gngb key --delay $DELAY "
        for i in $(echo $cc|sed 's/\(.\)/ \1/g'); do dd $i ;done
        $s 2>/dev/null
        sleep $SLEEP2
        # capture screen:
        xwd -name Gngb|convert - pnm: > shot$cc.pnm
        echo " done"
        h="$(cat shot$cc.pnm|pnmcut -top 120 |md5sum|cut -d ' ' -f 1)"
        if [ "$h" == 3b803e5a3e03d39288848a99f41a27b8 ]; then
            # Didn't get the full input
            echo Missed
            [ "$bn" != "" ] && bn=$(($bn+1))
            continue
        fi
        if [ "$h" == 4cad20f4a813ca01ee6709b7654dd8c0 ]; then
            # Good padding
            echo Good
            echo $cc >> padding.log
            touch shot$cc.flag
            c=$(python -c "print chr(0x${ccorig:$(((16-$n)*2)):2}^$n^0x$bb)")
            KNOWN=$(echo -n "$c"|xxd -p)$KNOWN
            echo $KNOWN
            echo $KNOWN|xxd -r -p|strings -n 1
            break
        fi
        if [ "$h" == 505b8e70d3b80346a361132fb82161cf ]; then
            # Bad padding
            # At this point it may happen that we've enough input but
            # some symbol was mistyped.
            # We can check that last part of input was properly typed but
            # we've up to 4 variants depending on the IV for each block
            ##h2="$(cat shot$cc.pnm|pnmcut -top 103 |md5sum|cut -d ' ' -f 1)"
            ##if [ "$h2" != 5a1dd1cb0823d108ac482890d129ba08 ] && \
            ##   [ "$h2" != 0c6991bb943791f24774dd28974e1656 ] && \
            ##   [ "$h2" != 5c82befbbfceb246c21ecad92e9a07fa ] && \
            ##   [ "$h2" != 91dbd4d85b8216e70b1e3979bd78aab8 ]; then
            ##    echo Missed
            ##    [ "$bn" != "" ] && bn=$(($bn+1))
            ##fi
            rm shot$cc.pnm
            continue
        fi
        if [ "$h" != 505b8e70d3b80346a361132fb82161cf ]; then
            # So far but not a bad padding? sth went wrong
            echo Error
            echo $cc >> padding.log
            touch shot$cc.err
            exit
        fi
    done
```

```
done
```

For the first run, we use the last two ciphertext blocks

```
ccorig="292868ba435bcf3526b983bb7182f2397572ac538bf636ebc75d5997f9497784"
```

We could just try all possible 256 values for each byte and let it run for hours, or do smarter hypotheses on the ciphertext.
Let's try to find the last byte of padding, should be between 0x01 and 0x0a (actually if it's 0x01 there is no other modification of the IV that could lead to a good padding):

```
for ((bn=16;bn>0;bn--)); do
```

This finds 0x05, so we can guess the padding is 0505050505

```
KNOWN="0505050505"
```

And from now on, only printable characters:

```
for ((bn=$((0x7E));bn>$((0x1F));bn--)); do
```

Or even a more restricted ordered set for faster findings (but this requires much more baby-sitting to adapt guesses accordingly to the findings)

```
for bc in " " ":" e t a i r o n s l h c d u p m g y f w b v k x j q z  E T A I R O N S L H C D U P M G Y F W B V K X J Q Z 0 1 2 3 4
```

Next characters are "C", "o", "n", "g". We're supposed to discover the plaintext backwards but it seems it has been forged backwards to discover it in a more natural order. So we can guess the first word is "Congratulations".
Let's test this hypothesis and find the first char of that block:

```
KNOWN=$(echo -n "alutargnoC"|xxd -p)"0505050505"

for bc in t; do
```

Good padding! This means we successfully revealed the last block:

```
talutargnoC\x05\x05\x05\x05\x05
```

Next one:

```
KNOWN=$(echo -n "noi"|xxd -p)
ccorig="4ac2c9e5ac61834bda70725000435fa6292868ba435bcf3526b983bb7182f239"
for bc in " " ":" e t a i r o n s ...
```

And so forth. Each time trying to guess parts of the plaintext, narrowing or widening the charset to explore to accelerate the padding attack.
Omitting the padding and writing the plaintext backwards, it gives:

```
Congratulations! The final flag for Step4 is Ozn"9269dC&d75
```

Second step revisited

Due to the very large ROM size and the nature of the challenge, I suspect there is some white-box cryptography in there.

Let's analyze the ROM.
Two useful documents to understand a Gameboy CPU and ROM:

- unofficial Game Boy CPU Manual (http://marc.rawer.de/Gameboy/Docs/GBCPUman.pdf) (pdf)
- Game Boy opcodes (http://www.pastraiser.com/cpu/gameboy/gameboy_opcodes.html)

The ROM cartridge is not entirely directly accessible, only the first bank of 0x4000 bytes (16kB), then other banks are mapped between 0x4000 and 0x8000. How this mapping is done depends on the cartridge memory controller.
Some bytes at the beginning of the ROM give us some info:

- 0x134-0x142: title="4"
- 0x143=0x00: not col or gb(?)
- 0x146=0x00: gb functions
- 0x147=0x01: cartridge type: ROM+MBC1
- 0x148=0x05: ROM size = 8Mbits = 1 MB = 64 banks
- 0x149=0x02: RAM = 64kbits = 8kB = 1 bank

So it's using Memory Bank Controller 1:
The MBC1 defaults to 16Mbit ROM/8KByte RAM mode on power up.
Writing a value (XXXXXXXS - X = Don't care, S = Memory model select) into 6000-7FFF area will select the memory model to use. S = 0 selects

16/8 mode. S = 1 selects 4/32 mode.
I didn't observe any writing in that area.
Writing a value (XXXBBBBB - X = Don't cares, B = bank select bits) into 2000-3FFF area will select an appropriate ROM bank at 4000-7FFF.
Values of 0 and 1 do the same thing and point to ROM bank 1. Rom bank 0 is not accessible from 4000-7FFF and can only be read from 0000-3FFF.
Writing a value (XXXXXXBB - X = Don't care, B = bank select bits) into 4000-5FFF area will set the two most significant ROM address lines.
I didn't observe any writing in that area.

I'm anticipating a bit but I observed memory reads and writes during emulation and there were only writes "on ROM" in the area 0x2000-0x3FFF, even some with value 0x22 (bank 34) while MBC1 description suggests that bank 34 should be accessed by writing 0x02 in 0x2000-0x3FFF and 0x01 in 0x4000-0x5FFF and writing 0x22 would be the same as writing 0x02.

I like to reverse things visually so let's trace all memory accesses by patching again gngb.
Actually every single instruction is preceded by an explicit memory read as fetch in the emulator, so we want to filter those reads out by patching again gngb.

```
diff --git a/src/cpu.c b/src/cpu.c
index f03a811..1227fa4 100644
--- a/src/cpu.c
+++ b/src/cpu.c
@@ -30,6 +30,7 @@ GB_CPU *gbcpu=0;

 //extern Sint32 gdma_cycle;

+Uint8 myflag_fetch=0;
 static Uint8 t8;
 static Sint8 st8;
 static Uint16 t16;
@@ -183,7 +184,10 @@ __inline__ Uint8 gbcpu_exec_one(void)
                gbcpu->int_flag=1;
                gbcpu->ei_flag=0;
        }
+       myflag_fetch=1;
        mem_read_fast(PC,opcode);
+        myflag_fetch=0;
+       printf("I%c%c%c", gbcpu->pc.b.h, gbcpu->pc.b.l, opcode);
        PC++;
        switch(opcode) {

diff --git a/src/memory.h b/src/memory.h
index 995da0a..3f8a75f 100644
--- a/src/memory.h
+++ b/src/memory.h
@@ -23,6 +23,7 @@
 #include "global.h"
 #include <SDL.h>

+extern Uint8 myflag_fetch;
 /* mbc1 mem mode type */

 #define MBC1_16_8_MEM_MODE 0
@@ -156,14 +157,17 @@ void mem_write_ff(Uint16 adr,Uint8 v);

 /* To use this macro you don't have to use autoincrementation in argument */
 #define mem_read_fast(a,v) {\
+    if (!myflag_fetch) printf("R%c%c", a >> 8, a & 0xff);\
     if (mem_read_tab[((a)>>12)&0xff].type!=MEM_DIRECT_ACCESS) {\
        (v)=mem_read_tab[((a)>>12)&0xff].f((a));\
     } else {\
        (v)=mem_read_tab[((a)>>12)&0xff].b[(a)&0xfff];\
     }\
+    if (!myflag_fetch) printf("%c", v);\
   }

 #define mem_write_fast(a,v) {\
+    printf("W%c%c%c", a >> 8, a & 0xff, v);\
     if (mem_write_tab[((a)>>12)&0xff].type!=MEM_DIRECT_ACCESS) {\
        mem_write_tab[((a)>>12)&0xff].f((a),(v));\
     } else {\
```

Because tracing is slightly slowing down gngb, it's good to make the xdotool delay slightly longer:

```
DELAY=30
```

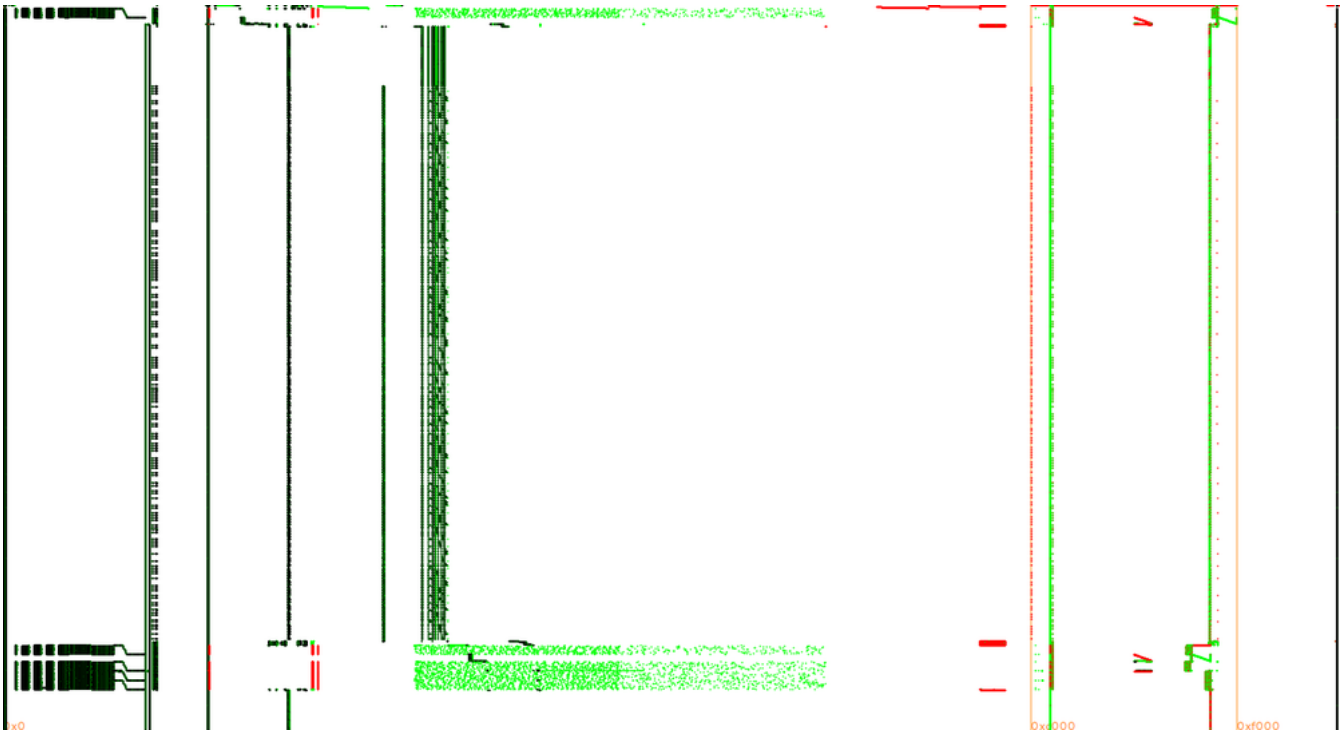
General memory map:

```
Interrupt Enable Register
--------------------------- FFFF
Internal RAM
--------------------------- FF80
Empty but unusable for I/O
--------------------------- FF4C
I/O ports
--------------------------- FF00
Empty but unusable for I/O
--------------------------- FEA0
Sprite Attrib Memory (OAM)
--------------------------- FE00
Echo of 8kB Internal RAM
--------------------------- E000
8kB Internal RAM
--------------------------- C000
8kB switchable RAM bank
--------------------------- A000
8kB Video RAM
--------------------------- 8000
```

```
16kB switchable ROM bank
--------------------------- 4000
16kB ROM bank #0
--------------------------- 0000
```

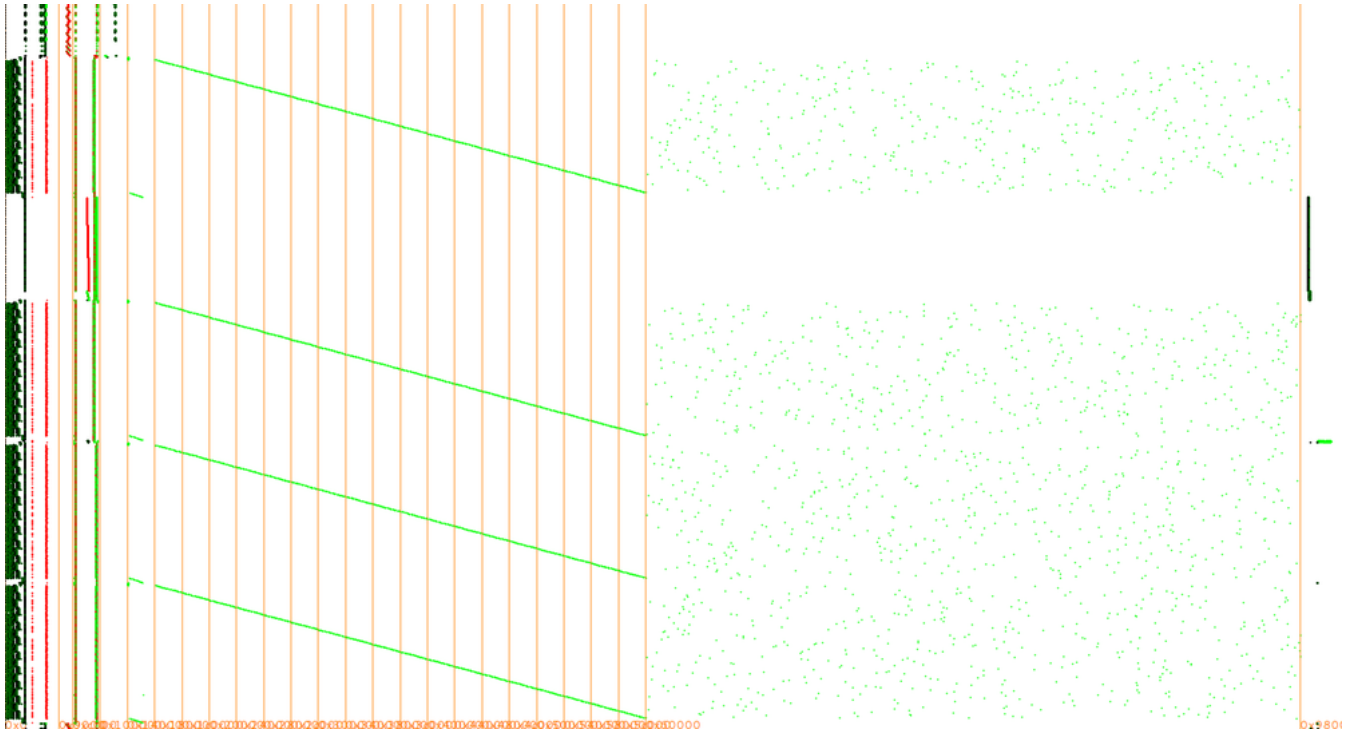
By default gngb outputs some info on the console, you can clean them from the log or comment the corresponding printf() in src/rom.c

Then I traced one single execution with the last two ciphertext blocks.
The trace has 68M instructions, 31M reads and 1.6M writes.



The lengthy part is when the ciphertext is typed in.
We observe five similar patterns that look like a white-box execution with all those "random" reads from a large memory area.
Instructions in black, reads in green and writes in red, X axis is memory addresses and Y axis is time axis, starting on top and going down:

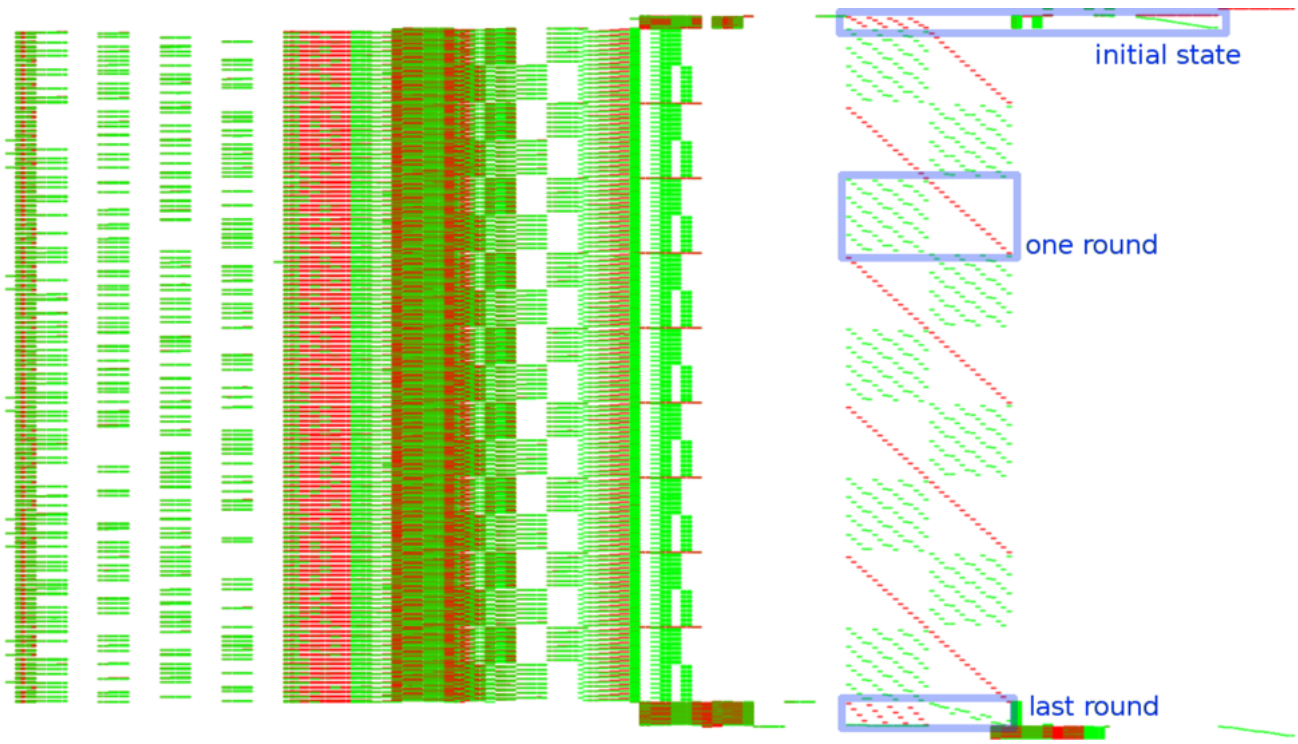
Let's filter the trace to the bottom part (from when instruction address == 0x5041 to when addr == 0x5395).
It's not visible at this scale but there are also annoying regular interrupt handlers that we can filter out too: from when addr == 0x0040 to when addr == 0x007d.
Remember that it's not the ROM but the memory as seen by the CPU, where all ROM banks (except the first one) are mapped successively in 0x4000-0x7fff.
So let's interpret all writes to 0x2000-0x3fff and remap 0x4000-0x7fff at 0x100000 (so e.g. something visible at 0x23456 is actually from ROM address 0x13456).



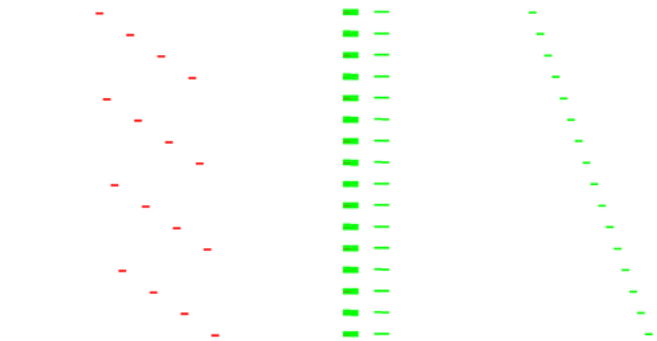
In each of the four white-box executions we see nine bumps, corresponding to the nine *MixColumns* of a 10-round AES-128.
Further analysis and zooms on the graph show functionality of that part of the trace:

- white-box #2: processes one fixed block (5FEEB70AE1C37984A46EFBC9F523EA32) and outputs E8CBF8217D54F8042272F8395E235621
- This sequence is used to XOR a range of ROM 0x57c-0x82b (minus some bytes) and decode it in RAM at 0xd000-0xd2b9. This will become some executable code after some more manipulation of some of its bytes... That code will be used after the third white-box to check the padding.
- white-box #3: the one processing the input ciphertext (the second block, as the first one is the IV, so here: 7572ac538bf636ebc75d5997f9497784). The plaintext, still, is not directly observable, even p^iv is not.
- then comes some processing from the decoded instructions to check the padding. We'll come back on that one later.
- white-box #4: depending on the padding check, it'll decipher f24e78e4b9c0e075fba1b518e065b146 into "Good Padding! :-" or another block if bad padding.
- white-box #5: idem, the second part of the result message, here 3bcc1cc8f9a44d9c09ae48064fb73e2f producing ")\n\x00..."

Now we've to figure out the structure and location of the white-box tables.
Let's zoom on the stack of one white-box.



It starts with

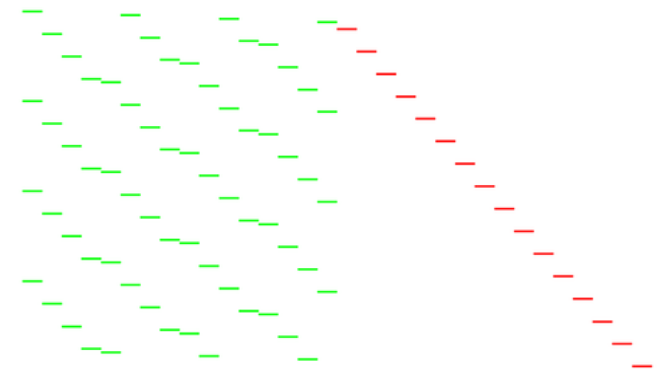


with some "random" accesses to a small table of 256 bytes around 0x04000.
Actually for each input byte x it reads at 0x04008+x so 0x04008:0x04107 is our first white-box table T1 and the accesses we observe are to transpose the AES input (green) into its internal state (red) and apply T1() on each byte, typically to apply the input encoding.
So if input bytes are stored as 0,1,2,3,4,5,6,7,8,9,a,b,c,d,e,f the AES state is represented as a grid:

```
0  4  8  c
1  5  9  d
2  6  a  e
3  7  b  f
```

and stored in memory row by row as 0,4,8,c,1,5,9,d,2,6,a,e,3,7,b,f.

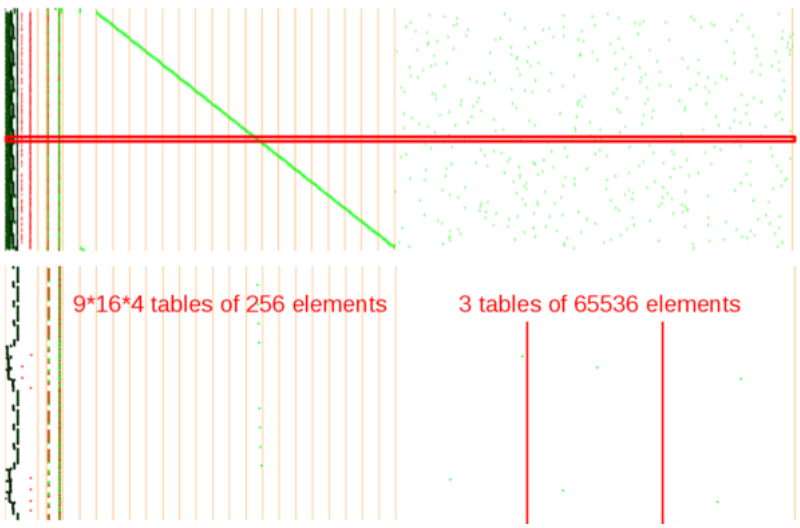
Then nine rounds with for each this type of pattern:



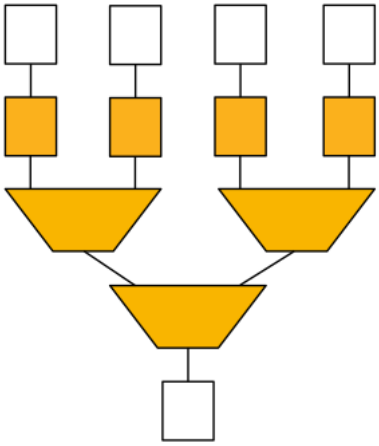
Again the read (green) and write (red) patterns show the structure:

- cells 0,1,2,3 are written from 0,5,a,f
- cells 4,5,6,7 are written from 4,9,e,3
- cells 8,9,a,b are written from 8,d,2,7
- cells c,d,e,f are written from c,1,6,b

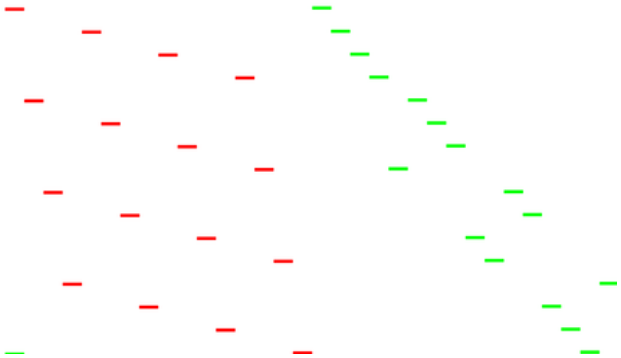
They come together with 64 "random" reads from 64*9 successive 256-byte tables and 48 reads from 3 very large 65536-byte tables that can be observed when zooming out on the whole memory:



Observing the actual values show that to compute cell 0, assume w,x,y,z are read from cells 0,5,a,f, then they are replaced at round N by w'=T_roundN_byte0_0(w), x'=T_roundN_byte0_1(x), y'=T_roundN_byte0_2(y), z'=T_roundN_byte0_3(z), then wx=Tlarge1(w', x') and yz=Tlarge2(y', z') and finally cell0=Tlarge3(wx, yx):



Then the final round:



Besides the table substitution, the reordering of the state is interesting:

```
0  4  8  c    048c 159d 26ae 37bf
1  5  9  d
2  6  a  e
3  7  b  f
```

becomes

```
0  5  a  f    05af 49e3 8d27 c16b
4  9  e  3
8  d  2  7
c  1  6  b
```

This reordering can only be explained by a *ShiftRows* and a transposition to restore the natural order of the output.
Note that I didn't say the inversed ShiftRow, so actually just by looking at those dots we can affirm that it's very probably an AES-128 encryption!!, and not a decryption as we could have expected.

Similarly the intermediate rounds are reordering the internal state

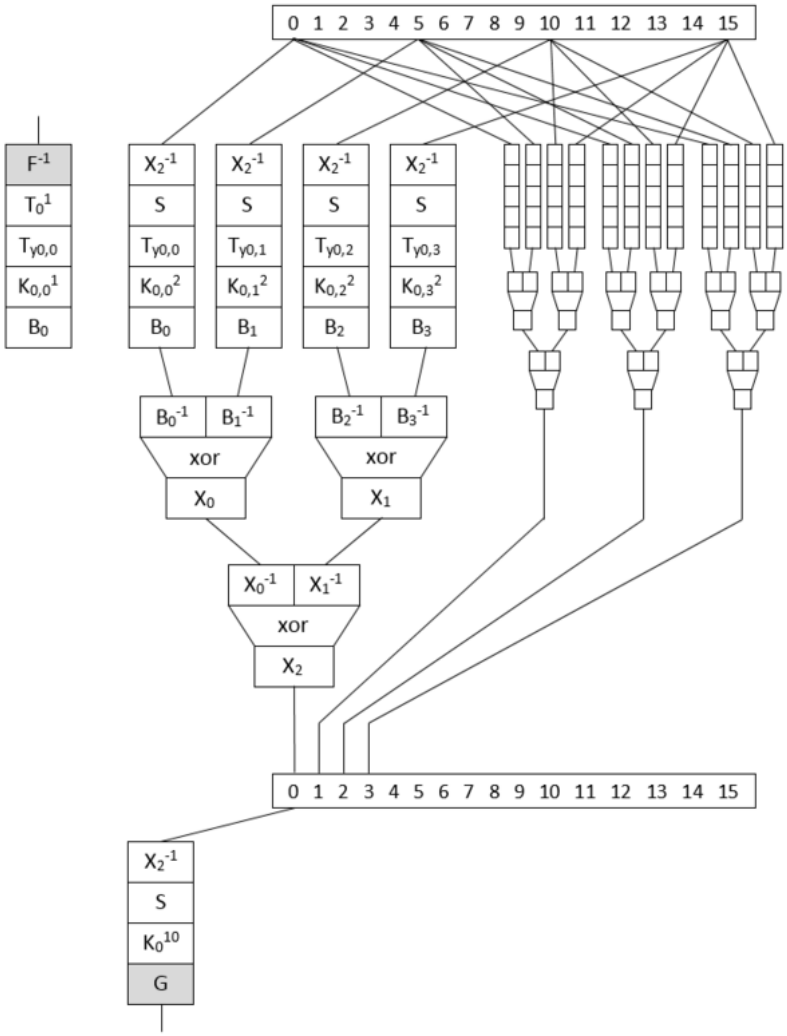
```
0  4  8  c
1  5  9  d
2  6  a  e
3  7  b  f
```

as

```
f(0,5,a,f) f(4,9,e,3) f(8,d,2,7) f(c,1,6,b)
f(0,5,a,f) f(4,9,e,3) f(8,d,2,7) f(c,1,6,b)
f(0,5,a,f) f(4,9,e,3) f(8,d,2,7) f(c,1,6,b)
f(0,5,a,f) f(4,9,e,3) f(8,d,2,7) f(c,1,6,b)
```

which is explained by the application of a *ShiftRows* and a *MixColumns*

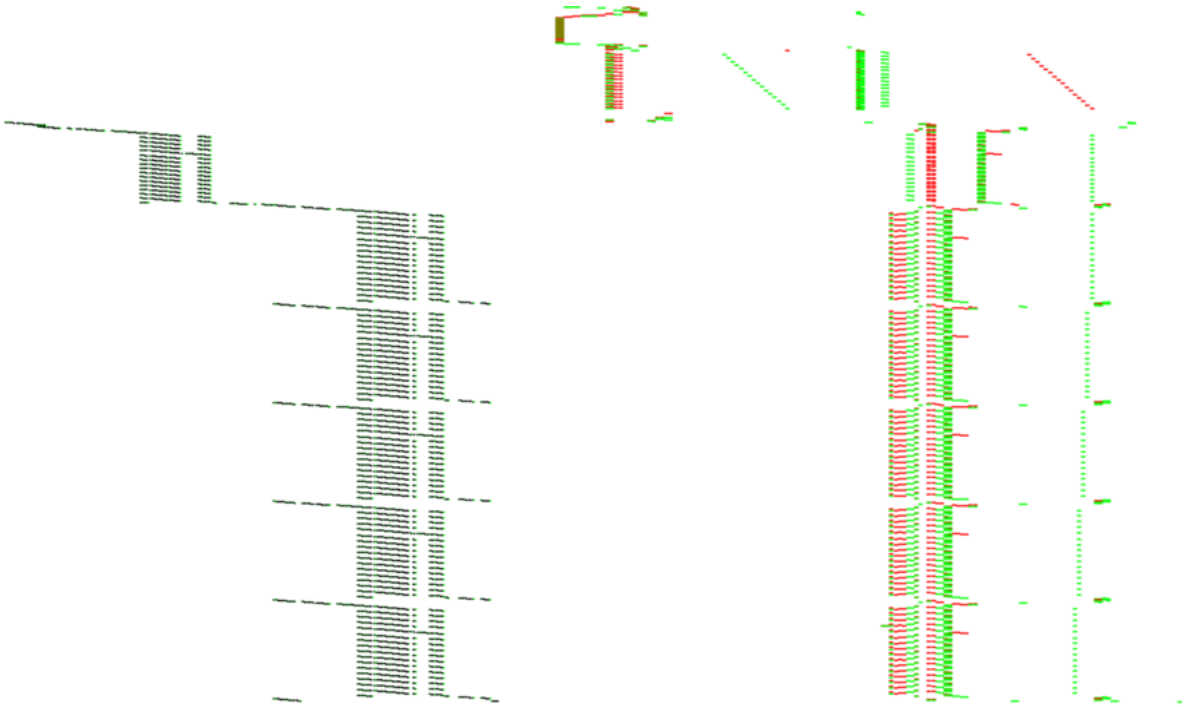
This structure is not the one of Chow or derivatives but we've seen it before, in the NoSuchCon 2013 challenge:



Eloi Vanderbéken, author of the NSC challenge, published his generator (http://pastebin.com/MvXpGZts) so let's try to extract our tables and reuse some of the NSC code.
When extracting tables, it's always good to verify them by checking their statistical distribution and this was useful to see there was a little quirk in the large XOR tables: tables are split in ROM banks where first two bytes were always 0x02 0x40 so the table started with an offset of 2 bytes, but last 14 bytes were some 0xff so for every bank, there is 16 bytes missing. One read access in the last white-box shows that when it needs to access one of those 16 bytes, it reads it from another table of 192 bytes (for 12 banks) from 0x5208 to 0x52c7. To find the exact positions, I made the stats on the tables of each bank, short by 16 bytes, and looked for those 16 missing values in a consecutive chunk of memory around 0x5200.

While knowing the external encodings is not required to break the white-box, as we'll see in a moment, it would be nice to recover the output external encoding table as well to get a functional white-box. For that one, it's important to come back on the code checking the plaintext padding because the other white-boxes don't use any external encoding table to recover the output! What you see in plain such as the "Good Padding! :-" seen earlier is still technically encoded with external encodings, it was just constructed as such so those white-boxes are not a strict equivalent of a plain AES.

This padding checking code was decoded earlier, remember? and it's quite convoluted. The reason is that if the AES plaintext was made more accessible, it would have been easy to spot it in the trace (e.g. by data correlation over a few traces) and to observe directly the flag present in the first block (to be xored with a null IV, so in plain).
Here is a zoom on the instructions and stack:



The processed block is the last one of the challenge ciphertext, with a padding 0505050505.
We see some effort was made to run in constant time: it always run 16 times, with one a bit different (the fifth).
A first loop identifies the value of the last padding byte, here 0x05.
Then five loops test successively the last five bytes (including the one read just before!)
So to get the value of the padding bytes, the external encoding table was used, right?
Actually not.
To "decode" one padding byte, it takes the corresponding IV byte, it makes a guess on the padding value (between 1 and 16) and read the corresponding externally encoded value in one of 16 tables then compares it with the white-box output.
So e.g. for the last byte, IV=0x39 and the 16 tests in the loop are:

```
G(0x39^0x01)=0x30 != white-box output=0x2c
...
G(0x39^0x05)=0x2c == white-box output=0x2c
...
```

We don't have directly the table to revert the external encoding but we've 16 related tables. So by taking e.g. the first one, taking care of the xor 0x01 and inverting it we can forge the missing table.

Here is my current understanding of the ROM map:

```
0x00000:0x000ff vector table
0x00100-0x00103 entry point: NOP, JP 0x150
0x00104-0x0014f internal ROM information
0x00150:0x03bd2 second entry point, some code
0x0215a:0x023f1 some code for padding checking that is decoded (xor) after second white-box

0x04000         08 40 08 41 08 42 08 52
0x04008:0x04107 init_invsub
0x04108:0x05207 finalTable
0x05208:0x052c7 xorTables 12*16 missing parts

0x08000         02 40
0x08002:0x0a001 roundTable1.0

0x0c000         02 40
0x0c002:0x0e001 roundTable1.1
...
0x48000         02 40
0x48002:0x4a001 roundTable9.0

0x4c000         02 40
0x4c002:0x4e001 roundTable9.1

0x50000         02 40
0x50002:0x53FF1 \
...               xorTables (last 16 bytes missing: chunks of 0x3ff8 instead of 0x4000)
0x7c002:0x7FFF1 /

0x88000:...     some code
0x893a6:0x8a3a5 16 G(iv^pad) tables
0x8a3a6         A8 63  00 11 22 33  44 55 66 77  88 99 AA BB  CC DD EE FF
```

We've now everything to extract all tables and write them in a file compatible with the NSC2013 white-box code:

```
#!/usr/bin/env python

# pad=1..16 whatever
pad=1
```

```
def validate(t):
    stats=[0]*256
    for x in t:
        stats[ord(x)]+=1
    # all elements must appear the same nr of times
    assert stats.count(stats[0]) == len(stats)

def inv(t):
    tinv=[0]*256
    for i in range(len(t)):
        tinv[ord(t[i])]=chr(i)
    return ''.join(tinv)

rom = open('rom.bin', 'rb').read()

with open('wbt_rom', 'wb') as wbt:
    init_invsub = rom[0x4008:0x4008+0x100]
    validate(init_invsub)
    init_sub = inv(init_invsub)
    validate(init_sub)
    wbt.write(init_sub)
    wbt.write(init_invsub)
    final_IV1 = rom[0x892a6+(0x100*pad):0x892a6+(0x100*pad)+0x100]
    final_sub = ''. join([final_IV1[i^pad] for i in range(256)])
    validate(final_sub)
    wbt.write(final_sub)
    final_invsub = inv(final_sub)
    validate(final_invsub)
    wbt.write(final_invsub)
    xorTable1=""
    for i in range(0x10000/0x4000):
        xorTable1+=rom[0x50002+(i*0x4000):0x50002+(i*0x4000)+0x3ff0]
        xorTable1+=rom[0x5208+(i*16):0x5208+(i*16)+16]
    validate(xorTable1)
    xorTable2=""
    for i in range(0x10000/0x4000):
        xorTable2+=rom[0x60002+(i*0x4000):0x60002+(i*0x4000)+0x3ff0]
        xorTable2+=rom[0x5248+(i*16):0x5248+(i*16)+16]
    validate(xorTable2)
    xorTable3=""
    for i in range(0x10000/0x4000):
        xorTable3+=rom[0x70002+(i*0x4000):0x70002+(i*0x4000)+0x3ff0]
        xorTable3+=rom[0x5288+(i*16):0x5288+(i*16)+16]
    validate(xorTable3)
    wbt.write(xorTable1)
    wbt.write(xorTable2)
    wbt.write(xorTable3)
    for i in range(9):
        roundTable=rom[0x8002+0x8000*i:0x8002+0x8000*i+0x2000]+rom[0x8002+0x8000*i+0x4000:0x8002+0x8000*i+0x4000+0x2000]
        validate(roundTable)
        wbt.write(roundTable)
    finalTable = rom[0x4208:0x4208+(0x100*16)]
    validate(finalTable)
    wbt.write(finalTable)
```

The resulting file is to be used with some white-box code derived directly from Eloi's generator.

```
#include <stdio.h>
#include <stdlib.h>
#include <stdint.h>

typedef struct sub_s {
    uint8_t sub[0x100];
    uint8_t inv_sub[0x100];
} *sub_t;

typedef struct aes_wb_s {
    struct sub_s initSub;
    struct sub_s finalSub;
    uint8_t xorTables[3][0x10000];
    uint8_t roundTables[9][16][4][0x100];
    uint8_t finalTable[16][0x100];
} *aes_wb_t;

unsigned char is_hex_char(char c)
{
    return (
        (c >= '0' && c <= '9') ||
        (c >= 'a' && c <= 'f') ||
        (c >= 'A' && c <= 'F')
    );
}
int main(int argc, char *argv[])
{
    struct aes_wb_s aes;
    uint8_t i, round;
    uint8_t t[12][16];
    uint8_t m[16];

    for(i = 0; i < 32; i += 2)
    {
        if(is_hex_char(argv[1][i]) == 0 || is_hex_char(argv[1][i + 1]) == 0)
            return EXIT_FAILURE;
        unsigned char str_bytes[3] = {
            argv[1][i],
            argv[1][i + 1],
            0
        };
        m[ i / 2] = strtoul((const char*)str_bytes, NULL, 16);
    }
```

```
    FILE* f;
    f = fopen("wbt_rom", "rb");
    fread(&aes, 1, sizeof(aes), f);
    fclose(f);

    printf("Input:    ");
    for (i = 0; i < 16; i++)
        printf("%02X ", m[i]);
    printf("\n");
    for (i = 0; i < 16; i++)
        t[0][(i%4u)*4 + (i/4u)] = aes.initSub.inv_sub[m[i]];

    printf("Enc in:   ");
    for (i = 0; i < 16; i++)
        printf("%02X ", t[0][i]);
    printf("\n");
    for (round = 1; round < 10; round ++)
    {
        for (i = 0; i < 16; i++)
        {
            uint8_t b[4];
            uint8_t j;
            for (j = 0; j < 4; j++) {
                b[j] = aes.roundTables[round-1][i][j][t[round-1][j*4+((i+j)%4u)]];
            }
            t[round][i] = aes.xorTables[2][(aes.xorTables[0][(b[0]<<8)|b[1]] << 8) | aes.xorTables[1][(b[2]<<8)|b[3]]];
        }
    }
    for (i = 0; i < 16; i++)
        t[10][i/4u + (i%4u)*4] = aes.finalTable[i][t[9][(i&(~3)) +((i+i/4)%4u)]];

    printf("Enc out:  ");
    for (i = 0; i < 16; i++)
        printf("%02X ", t[10][i]);
    printf("\n");
    printf("Output:   ");
    for (i = 0; i < 16; i++)
        printf("%02X ", aes.finalSub.inv_sub[t[10][i]]);
    printf("\n");
    return 0;
}
```

Let's try on our last ciphertext block:

```
./nosuchcon_2013_whitebox 7572ac538bf636ebc75d5997f9497784
Input:    75 72 AC 53 8B F6 36 EB C7 5D 59 97 F9 49 77 84
Enc in:   A3 5C 58 89 6A 90 D9 3F 6F 4F 2F 51 37 3A BC 16
Enc out:  A7 C7 58 98 72 74 59 F9 0D F7 89 E3 B0 7A D0 2C
Output:   5D 49 04 CF 37 3A BD 52 48 D6 C0 BE 74 87 F7 3C
```

XORing the output with the previous block as IV:

```
"%x" % (0x5D4904CF373ABD5248D6C0BE7487F73C ^0x292868ba435bcf3526b983bb7182f239)
=> '74616c75746172676e6f430505050505'
```

which is indeed the 'talutargnoC' followed by the padding.

Last white-box, the one outputting ")\n" :

```
./nosuchcon_2013_whitebox 3bcc1cc8f9a44d9c09ae48064fb73e2f
Input:    3B CC 1C C8 F9 A4 4D 9C 09 AE 48 06 4F B7 3E 2F
Enc in:   B4 89 83 1E 84 6D A0 DF 92 7E 98 C3 C1 5B 59 4C
Enc out:  29 0A 00 00 00 00 00 00 00 00 00 00 00 00 00 00
Output:   C4 90 72 72 72 72 72 72 72 72 72 72 72 72 72 72
```

Useful output is, as said earlier, the encoded output.

So we've a working code-lifting, err I mean table-lifting, of the white-box \o/

Second step revisited, again

But we didn't have to go that far and reverse the external encodings because only with the inner rounds and xor tables, we can break the key, as explained in our NoSuchCon 2013 challenge write-up because the internal encoding X2 is reused between rounds (normal, it's already very large).

Running the attack on the white-box file with the code from my NSC write-up reveals immediately the key (here attacking round 3, could be any between 2 and 9):

```
./nosuchcon_2013_whitebox_rom_break
R3K candidate: F886846C0E10C0A3867562504BC9BF60
K00: 4A7BB85DC1446AA1112222223B2A99FF
K01: AE95AEBF6FD1C41E7EF3E63C45D97FC3
K02: 994780D1F69644CF8865A2F3CDBCDD30
K03: F886846C0E10C0A3867562504BC9BF60
K04: 2D8E54DF239E947CA5EBF62CEE22494C
K05: AEB57DF78D2BE98B28C01FA7C6E256EB
K06: 160494439B2F7DC8B3EF626F750D3484
K07: 811CCBDE1A33B616A9DCD479DCD1E0FD
K08: 3FFD9F5825CE294E8C12FD3750C31DCA
K09: 0A59EB0B2F97C245A3853F72F34622B8
K10: 66CA8706495D4543EAD87A31199E5889
aes.xorTables[2] mapping:
00:7B 01:02 02:DA 03:5C 04:2C 05:70 06:F0 07:E9 08:D6 09:3D 0A:F3 0B:42 0C:F2 0D:ED 0E:A3 0F:79
```

```
10:A7 11:67 12:9D 13:07 14:EC 15:43 16:23 17:6D 18:11 19:4E 1A:10 1B:3B 1C:CA 1D:A4 1E:74 1F:F8
20:E3 21:EE 22:8F 23:9C 24:38 25:1B 26:AF 27:D1 28:6E 29:06 2A:1C 2B:A0 2C:4B 2D:AE 2E:68 2F:9F
30:6A 31:C8 32:E4 33:5E 34:E0 35:A8 36:05 37:F6 38:30 39:69 3A:57 3B:9E 3C:51 3D:B8 3E:D9 3F:62
40:5D 41:E1 42:56 43:36 44:FB 45:5B 46:C3 47:AC 48:BE 49:93 4A:7E 4B:27 4C:59 4D:A2 4E:BA 4F:91
50:AD 51:C1 52:EA 53:92 54:7C 55:76 56:29 57:4D 58:EB 59:71 5A:54 5B:D3 5C:13 5D:28 5E:35 5F:12
60:D2 61:20 62:F1 63:2F 64:3E 65:E7 66:CB 67:9A 68:DB 69:61 6A:C6 6B:3A 6C:DE 6D:FD 6E:1A 6F:B9
70:2B 71:F4 72:00 73:2A 74:8E 75:17 76:D8 77:96 78:80 79:99 7A:83 7B:15 7C:33 7D:84 7E:08 7F:52
80:CF 81:7F 82:BB 83:E2 84:1F 85:1E 86:89 87:01 88:0B 89:0C 8A:90 8B:0D 8C:98 8D:E5 8E:14 8F:94
90:53 91:25 92:DD 93:CE 94:3C 95:D5 96:87 97:16 98:0F 99:24 9A:95 9B:1D 9C:22 9D:E8 9E:77 9F:40
A0:DF A1:C0 A2:82 A3:19 A4:50 A5:8D A6:65 A7:49 A8:9B A9:D7 AA:B1 AB:63 AC:81 AD:34 AE:73 AF:78
B0:BF B1:37 B2:60 B3:3F B4:64 B5:32 B6:8C B7:44 B8:09 B9:86 BA:FF BB:75 BC:FE BD:D4 BE:A5 BF:45
C0:C4 C1:C9 C2:C5 C3:BC C4:CD C5:EF C6:66 C7:0A C8:4F C9:0E CA:5F CB:A9 CC:6C CD:2E CE:B3 CF:F5
D0:47 D1:48 D2:21 D3:FC D4:55 D5:D0 D6:46 D7:E6 D8:97 D9:04 DA:72 DB:5A DC:FA DD:C7 DE:DC DF:58
E0:AB E1:A6 E2:A1 E3:F7 E4:6B E5:B6 E6:26 E7:8A E8:CC E9:C2 EA:03 EB:85 EC:B5 ED:B2 EE:39 EF:41
F0:B4 F1:F9 F2:AA F3:18 F4:7D F5:88 F6:6F F7:31 F8:4C F9:B7 FA:7A FB:B0 FC:BD FD:4A FE:8B FF:2D
```

So the AES-128 key is 4A7BB85DC1446AA1112222223B2A99FF!
This attack took 1.8s on my laptop.

Let's try it on the last ciphertext block (taken as AES plaintext...):

```
echo "7572ac538bf636ebc75d5997f9497784"|xxd -r -p|openssl enc -aes-128-ecb -nopad -K 4A7BB85DC1446AA1112222223B2A99FF|xxd -p
5d4904cf373abd5248d6c0be7487f73c
```

```
"%x" % (0x5D4904CF373ABD5248D6C0BE7487F73C ^0x292868ba435bcf3526b983bb7182f239)
=> '74616c75746172676e6f430505050505'
```

Note that we can't decrypt the challenge file in one single call to openssl because what we have is a mix of a CBC *decryption* mode with an AES *encryption*...

Second step revisited, the sequel

Compared to NoSuchCon 2013, here we have recovered the external encodings (even if they made some effort to not include directly such a table to check the padding) therefore there is another attack possible on the finalTable with the knowledge of the output external encoding table:

- For the first finalTable, choose arbitrarily a (externally encoded) output byte value
- Make a guess for the corresponding round key byte
- Propagate output byte till getting the corresponding clear input byte (via reverse G, then xor with kR10[0], then reverse Sbox) and encoded input byte (via reverse finalTable), this gives us one correspondence of X2 table.
- We know substitution tables are the same for all bytes of the state so let's use the same input and so the same X2 entry for the next finalTable table. It determines uniquely the value before xor with the kR10[1] (via X2_inv, then Sbox) and the value after (via finalTable, then reverse G) therefore the value of that key byte
- Go on for all kR10 key bytes. So per kR10[0] key byte guess this gives one single full 16-byte kR10 key.
- Try other guesses for the initial kR10[0] key byte
- At the end we have 256 possible kR10 keys -> roll back the AES key scheduling to get the 256 corresponding AES keys and bruteforce them with one plaintext/ciphertext pair.

If one wants to reverse completely X2, he can run the attack with all different values for the externally encoded output byte. Here we computed only one entry of the X2 table.

```
#!/usr/bin/env python

from Crypto.Cipher import AES

rom=open('wbt_rom', 'rb').read()
Ginv=[ord(x) for x in rom[3*256:4*256]]
rom=rom[4*256 + 3*256*256 + 9*16*4*256:]
finalTable=[]
for i in range(0,16*256,256):
    finalTable.append([ord(x) for x in rom[i:i+256]])

pref="3BCC1CC8F9A44D9C09AE48064FB73E2F".decode('hex')
cpref="290A0000000000000000000000000000".decode('hex')
cref=''.join([chr(Ginv[ord(x)]) for x in cpref])

finalTable_inv=range(16)
for b in range(16):
    finalTable_inv[b]=range(256)
    for i in range(256):
        finalTable_inv[b][finalTable[b][i]]=i

Sbox=\
[0x63,0x7C,0x77,0x7B,0xF2,0x6B,0x6F,0xC5,0x30,0x01,0x67,0x2B,0xFE,0xD7,0xAB,0x76,
 0xCA,0x82,0xC9,0x7D,0xFA,0x59,0x47,0xF0,0xAD,0xD4,0xA2,0xAF,0x9C,0xA4,0x72,0xC0,
 0xB7,0xFD,0x93,0x26,0x36,0x3F,0xF7,0xCC,0x34,0xA5,0xE5,0xF1,0x71,0xD8,0x31,0x15,
 0x04,0xC7,0x23,0xC3,0x18,0x96,0x05,0x9A,0x07,0x12,0x80,0xE2,0xEB,0x27,0xB2,0x75,
 0x09,0x83,0x2C,0x1A,0x1B,0x6E,0x5A,0xA0,0x52,0x3B,0xD6,0xB3,0x29,0xE3,0x2F,0x84,
 0x53,0xD1,0x00,0xED,0x20,0xFC,0xB1,0x5B,0x6A,0xCB,0xBE,0x39,0x4A,0x4C,0x58,0xCF,
 0xD0,0xEF,0xAA,0xFB,0x43,0x4D,0x33,0x85,0x45,0xF9,0x02,0x7F,0x50,0x3C,0x9F,0xA8,
 0x51,0xA3,0x40,0x8F,0x92,0x9D,0x38,0xF5,0xBC,0xB6,0xDA,0x21,0x10,0xFF,0xF3,0xD2,
 0xCD,0x0C,0x13,0xEC,0x5F,0x97,0x44,0x17,0xC4,0xA7,0x7E,0x3D,0x64,0x5D,0x19,0x73,
 0x60,0x81,0x4F,0xDC,0x22,0x2A,0x90,0x88,0x46,0xEE,0xB8,0x14,0xDE,0x5E,0x0B,0xDB,
 0xE0,0x32,0x3A,0x0A,0x49,0x06,0x24,0x5C,0xC2,0xD3,0xAC,0x62,0x91,0x95,0xE4,0x79,
 0xE7,0xC8,0x37,0x6D,0x8D,0xD5,0x4E,0xA9,0x6C,0x56,0xF4,0xEA,0x65,0x7A,0xAE,0x08,
 0xBA,0x78,0x25,0x2E,0x1C,0xA6,0xB4,0xC6,0xE8,0xDD,0x74,0x1F,0x4B,0xBD,0x8B,0x8A,
 0x70,0x3E,0xB5,0x66,0x48,0x03,0xF6,0x0E,0x61,0x35,0x57,0xB9,0x86,0xC1,0x1D,0x9E,
 0xE1,0xF8,0x98,0x11,0x69,0xD9,0x8E,0x94,0x9B,0x1E,0x87,0xE9,0xCE,0x55,0x28,0xDF,
 0x8C,0xA1,0x89,0x0D,0xBF,0xE6,0x42,0x68,0x41,0x99,0x2D,0x0F,0xB0,0x54,0xBB,0x16]

Sbox_inv=[0x00] * 256
for i in range(256):
    Sbox_inv[Sbox[i]]=i
```

```
e_ctxt=[-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1]
ctxt  =[-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1]
k     =[-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1,-1]

rcon=[0x01,0x02,0x04,0x08,0x10,0x20,0x40,0x80,0x1b,0x36]

def key_schedule_inv(key):
        # encryption round keys
        Ke = [[0] * 4 for i in range(11)]
        # copy user material bytes into temporary ints
        tk = []
        for i in range(0, 4):
            tk.append((ord(key[i * 4]) << 24) | (ord(key[i * 4 + 1]) << 16) |
                (ord(key[i * 4 + 2]) << 8) | ord(key[i * 4 + 3]))
        # copy values into round key arrays
        for j in range(4):
            Ke[j / 4][j % 4] = tk[j]
        rconpointer = 10
        for n in range(1,11):
            # extrapolate using phi (the round key evolution function)
            for i in range(4-1,0, -1):
                tk[i] ^= tk[i-1]
            rconpointer -= 1
            tt = tk[3]
            tk[0] ^= (Sbox[(tt >> 16) & 0xFF] & 0xFF) << 24 ^  \
                     (Sbox[(tt >>  8) & 0xFF] & 0xFF) << 16 ^  \
                     (Sbox[ tt        & 0xFF] & 0xFF) <<  8 ^  \
                     (Sbox[(tt >> 24) & 0xFF] & 0xFF)      ^  \
                     (rcon[rconpointer]    & 0xFF) << 24
            # copy values into round key arrays
            for j in range(4):
                Ke[(j+(n*4)) / 4][(j+(n*4)) % 4] = tk[j]
        return ''.join(["%08X" % k for k in Ke[10]])

def find_kb(b=1):
        # We use same encoding st10:e_st10 for all bytes of the state
        e_ctxt[b] = finalTable[b][e_st10]
        # Guess k[b]
        for k[b] in range(256):
            ctxt[b] = Sbox[st10]^k[b]
            if Ginv[e_ctxt[b]]!=ctxt[b]:
                continue
            if b < 15:
                return (find_kb(b+1))
            else:
                return k

# finalTable implements for each ith byte x of the state G(kR10[i] ^ Sbox(X2_inv(x)))
# e_st10 = x                          = internally encoded state before round 10
#   st10 = X2_inv(x)                  = plain state before round 10
#   ctxt = kR10[i] ^ Sbox(X2_inv(x))  = plain ciphertext after round 10
# e_ctxt = G(kR10[i] ^ Sbox(X2_inv(x))) = externally encoded ciphertext after round 10

# Choose arbitrary first e_ctxt:
e_ctxt[0]=0
ctxt[0] = Ginv[e_ctxt[0]]
e_st10 = finalTable_inv[0][e_ctxt[0]]
# Guess first k[0] -> deduce the other bytes of the round-10 key
for k[0] in range(256):
    st10 = Sbox_inv[ctxt[0]^k[0]]
    kb=find_kb()
    kR10=[kb[j/4 + j%4*4] for j in range(16)]
    kAES=key_schedule_inv(''.join([chr(x) for x in kR10]))
#    print 'kR10=','.join(["%02X" % i for i in kR10]), '=> K=', kAES
    aes = AES.new(kAES.decode('hex'), AES.MODE_ECB)
    if aes.encrypt(pref)==cref:
        print "FOUND!"
        print 'kR10=','.join(["%02X" % i for i in kR10]), '=> K=', kAES
        print "Partial aes.xorTables[2] mapping: %02X:%02X " % (st10, e_st10)
```

```
FOUND!
kR10= 66CA8706495D4543EAD87A31199E5889 => K= 4A7BB85DC1446AA1112222223B2A99FF
Partial aes.xorTables[2] mapping: 9B:1D
```

This attack took 0.12s on my laptop.

Final word

The challenges were great, fun and educative!
The organizers did a great job to build them!

If I may suggest something to the organizers of the next edition: please change the rules.
First blood bonus work well for short CTFs (2-3 days) but for such long CTF (80.5 days!) it can become very frustrating: first blood bonuses were distributed quite fast, within 3 days I think, and then I sat in the uncomfortable situation where I was the first to finish all the challenges after 4.5 days and then had no choice but to watch the other participants playing for 76 days, till those who collected more first blood bonuses than I at the very beginning managed to complete all challenges and finally ended up above me. Hopefully only @hellmann1908 had enough bonuses to potentially threaten my position and indeed he eventually finished first (п о з д р а в л е н и я!!).
In the same spirit, till the very last moment the 2 participants who got one first blood bonus but didn't solve any other challenge could potentially jump ahead of the 5 participants who solved all challenges since a while but were not active in the very first hours of the challenge.

CTFs are fun, except when you can't play anymore but witness helplessly the others slowly overtaking you...

So I suggest to adapt the first blood rule for a next edition, e.g.:

- either by attributing also substantial first blood points to those who solve all challenges first
- or by dropping first blood mechanism and by weighting points with remaining days: a 10pts challenge solved the first day (80 days remaining) gives you 10*(80-1)=720pts; a 20pts challenge solved after 30 days gives you 20*(80-30)=1000pts, or similar mechanism to keep some incentive to solve the challenges as fast as possible during the entire competition.

For such long CTFs I like also the SSTIC (http://communaute.sstic.org/ChallengeSSTIC2015) rule: motivate people to submit a write-up and promote the best ones. So it will also be educational for those who didn't play the CTF but are eager to learn.

If you've comments, remarks, questions, suggestions, etc, you can contact me here or via Twitter @doegox