StuxNNet:

Practical Live Memory Attacks on Machine Learning Systems

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Background

- Prior work:
    - Mostly focused on generating/producing robustness to **adversarial inputs**
    - No one has attempted to modify the model itself
- DNN logic = Weights and Bias parameters in memory
    - Easy to change with traditional malware
- Software 1.0 attack on a Software 2.0 system
- Our approach:
    - Directly modifies model weights at runtime
    - A **naive attack** - scramble weights
    - A **trojan attack** - introduce a specific malicious response to particular inputs

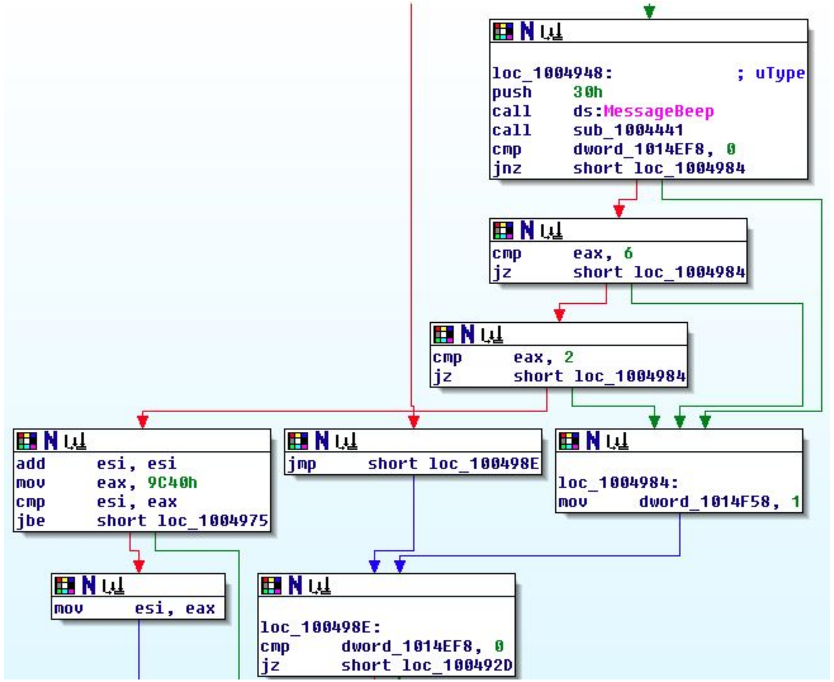
Overview

- L-2 white-box attack
- Assume access to an instance of a commodity system
  - Malware detection (Windows Defender) → Buy a Windows Machine
  - self-driving car software (Tesla steering software) → Buy a Tesla
- Use memory forensics to extract **network architecture**, **weights**, and **bias parameters** stored in these systems
- Apply change to weights at runtime
- Demonstrate attack on Windows 8
  - Naive C++ NN framework
  - Tensorflow Malicious PDF classifier
- Research: Limit Network communication

Extraction

Forensics and Reverse Engineering

VOLATILITY FOUNDATION



```
loc_1004948:                    ; uType
push    30h
call    ds:MessageBeep
call    sub_1004441
cmp     dword_1014EF8, 0
jnz     short loc_1004984
```

```
cmp     eax, 6
jz      short loc_1004984
```

```
cmp     eax, 2
jz      short loc_1004984
```

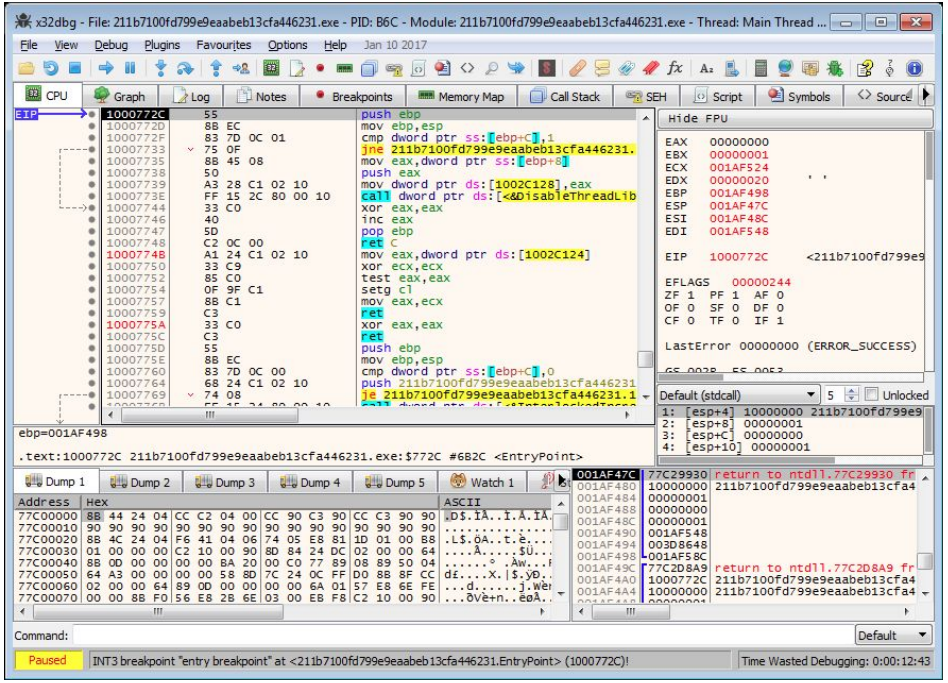
```
add     esi, esi
mov     eax, 9C40h
cmp     esi, eax
jbe     short loc_1004975
```

```
jmp     short loc_100498E
```

```
loc_1004984:
mov     dword_1014F58, 1
```

```
mov     esi, eax
```

```
loc_100498E:
cmp     dword_1014EF8, 0
jz      short loc_100492D
```



x32dbg - File: 211b7100fd799e9eaabeb13cfa446231.exe - PID: B6C - Module: 211b7100fd799e9eaabeb13cfa446231.exe - Thread: Main Thread ...

File View Debug Plugins Favourites Options Help Jan 10 2017
CPU Graph Log Notes Breakpoints Memory Map Call Stack SEH Script Symbols Source

```
EIP  1000772C  55                push ebp
     1000772D  8B EC             mov ebp,esp
     1000772F  83 7D 0C 01       cmp dword ptr ss:[ebp+C],1
     10007733  75 0F             jne 211b7100fd799e9eaabeb13cfa446231.
     10007735  8B 45 08          mov eax,dword ptr ss:[ebp+8]
     10007738  50                push eax
     10007739  A3 28 C1 02 10    mov dword ptr ds:[1002C128],eax
     1000773E  FF 15 2C 80 00 10 call dword ptr ds:[<&DisableThreadLib
     10007744  33 C0             xor eax,eax
     10007746  40                inc eax
     10007747  5D                pop ebp
     10007748  C2 0C 00          ret C
     1000774B  A1 24 C1 02 10    mov eax,dword ptr ds:[1002C124]
     10007750  33 C9             xor ecx,ecx
     10007752  85 C0             test eax,eax
     10007754  0F 9F C1          setg cl
     10007757  8B C1             mov eax,ecx
     10007759  C3                ret
     1000775A  33 C0             xor eax,eax
     1000775C  C3                ret
     1000775D  55                push ebp
     1000775E  8B EC             mov ebp,esp
     10007760  83 7D 0C 00       cmp dword ptr ss:[ebp+C],0
     10007764  68 24 C1 02 10    push 211b7100fd799e9eaabeb13cfa446231
     10007769  74 08             je 211b7100fd799e9eaabeb13cfa446231.1
```

```
Hide FPU

EAX   00000000
EBX   00000001
ECX   001AF524
EDX   00000020       ' '
EBP   001AF498
ESP   001AF47C
ESI   001AF48C
EDI   001AF548

EIP   1000772C      <211b7100fd799e9

EFLAGS   00000244
ZF 1  PF 1  AF 0
OF 0  SF 0  DF 0
CF 0  TF 0  IF 1

LastError 00000000 (ERROR_SUCCESS)
```

Default (stdcall) 5 Unlocked

```
1: [esp+4] 10000000 211b7100fd799e9
2: [esp+8] 00000001
3: [esp+C] 00000000
4: [esp+10] 00000001
```

```
ebp=001AF498

.text:1000772C 211b7100fd799e9eaabeb13cfa446231.exe:$772C #6B2C <EntryPoint>
```

```
Address   Hex                                              ASCII
77C00000  8B 44 24 04 CC C2 04 00 CC 90 C3 90 CC C3 90 90  .D$.ÌÂ..Ì.Ã.ÌÃ.
77C00010  90 90 90 90 90 90 90 90 90 90 90 90 90 90 90 90  ................
77C00020  8B 4C 24 04 F6 41 04 06 74 05 E8 81 1D 01 00 B8  .L$.öA..t.è....
77C00030  01 00 00 00 C2 10 00 90 8D 84 24 DC 02 00 00 64  ....Â.....$Ü...
77C00040  8B 0D 00 00 00 00 BA 20 00 C0 77 89 08 89 50 04  ......º .Àw....
77C00050  64 A3 00 00 00 00 58 8D 7C 24 0C FF D0 8B 8F CC  d£....X.|$.ÿÐ..
77C00060  02 00 00 64 89 0D 00 00 00 00 6A 01 57 E8 6E FE  ...d......j.Wèn
77C00070  00 00 8B F0 56 E8 2B 6E 03 00 EB F8 C2 10 00 90  ...ðVè+n..ëøÂ..
```

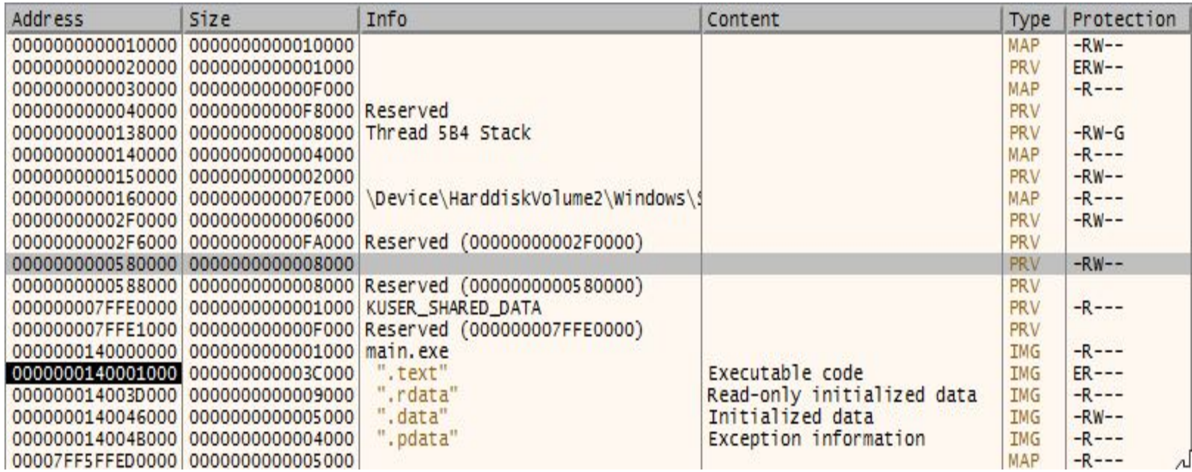
```
001AF47C  77C29930  return to ntdll.77C29930 fr
001AF480  10000000  211b7100fd799e9eaabeb13cfa4
001AF484  00000001
001AF488  00000000
001AF48C  00000001
001AF490  001AF548
001AF494  003D8648
001AF498  001AF58C
001AF49C  77C2D8A9  return to ntdll.77C2D8A9 fr
001AF4A0  1000772C  211b7100fd799e9eaabeb13cfa4
001AF4A4  10000000  211b7100fd799e9eaabeb13cfa4
```

Command: Default

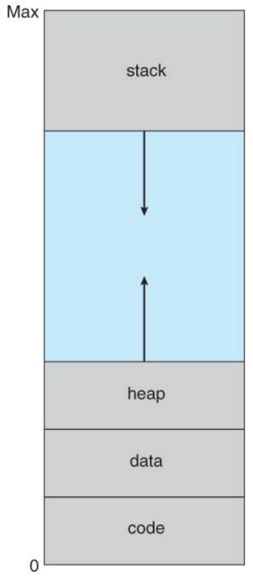
Paused INT3 breakpoint "entry breakpoint" at <211b7100fd799e9eaabeb13cfa446231.EntryPoint> (1000772C)! Time Wasted Debugging: 0:00:12:43

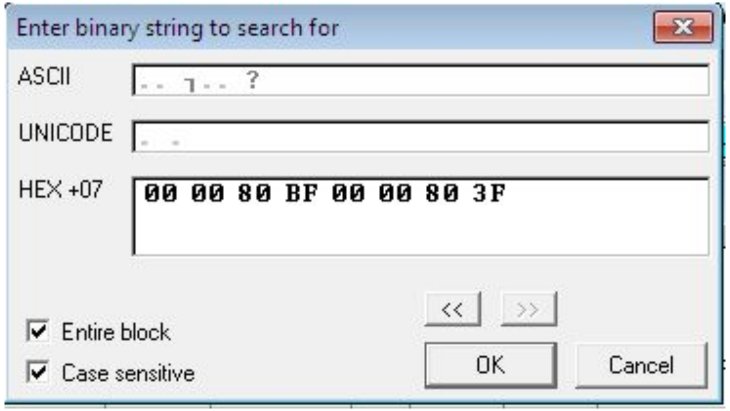
Malware functionality

- Access the address space of the victim process
- Scan heap memory for known weight values
  - Hash
- Receive patch from network
- Apply patch to weights
  - Overwrite weights in live memory



Address	Size	Info	Content	Type	Protection
0000000000010000	0000000000010000			MAP	-RW--
0000000000020000	0000000000001000			PRV	ERW--
0000000000030000	000000000000F000			MAP	-R---
0000000000040000	00000000000F8000	Reserved		PRV	
0000000000138000	0000000000008000	Thread 5B4 Stack		PRV	-RW-G
0000000000140000	0000000000004000			MAP	-R---
0000000000150000	0000000000002000			PRV	-RW--
0000000000160000	000000000007E000	\Device\HarddiskVolume2\Windows\		MAP	-R---
00000000002F0000	0000000000006000			PRV	-RW--
00000000002F6000	00000000000FA000	Reserved (00000000002F0000)		PRV	
0000000000580000	0000000000008000			PRV	-RW--
0000000000588000	0000000000008000	Reserved (0000000000580000)		PRV	
000000007FFE0000	0000000000001000	KUSER_SHARED_DATA		PRV	-R---
000000007FFE1000	000000000000F000	Reserved (000000007FFE0000)		PRV	
0000000140000000	0000000000001000	main.exe		IMG	-R---
0000000140001000	000000000003C000	".text"	Executable code	IMG	ER---
000000014003D000	0000000000009000	".rdata"	Read-only initialized data	IMG	-R---
0000000140046000	0000000000005000	".data"	Initialized data	IMG	-RW--
000000014004B000	0000000000004000	".pdata"	Exception information	IMG	-R---
00007FF5FFED0000	0000000000005000			MAP	-R---





Enter binary string to search for

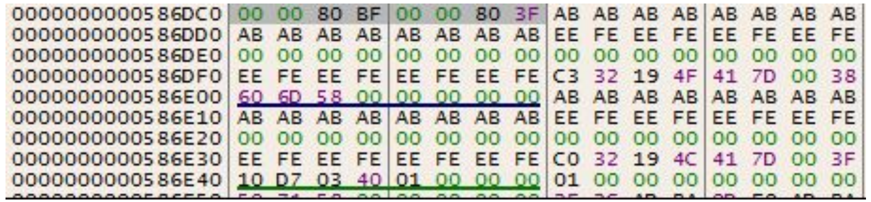
ASCII: `.. ..1.. ?`

UNICODE: `. .`

HEX +07: `00 00 80 BF 00 00 80 3F`

[✓] Entire block

[✓] Case sensitive



```
00000000000586DC0 00 00 80 BF 00 00 80 3F AB AB AB AB AB AB AB AB
00000000000586DD0 AB AB AB AB AB AB AB AB EE FE EE FE EE FE EE FE
00000000000586DE0 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00000000000586DF0 EE FE EE FE EE FE EE FE C3 32 19 4F 41 7D 00 38
00000000000586E00 60 6D 58 00 00 00 00 00 AB AB AB AB AB AB AB AB
00000000000586E10 AB AB AB AB AB AB AB AB EE FE EE FE EE FE EE FE
00000000000586E20 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00000000000586E30 EE FE EE FE EE FE EE FE C0 32 19 4C 41 7D 00 3F
00000000000586E40 10 D7 03 40 01 00 00 00 01 00 00 00 00 00 00 00
```

Key Challenge: Network Communication

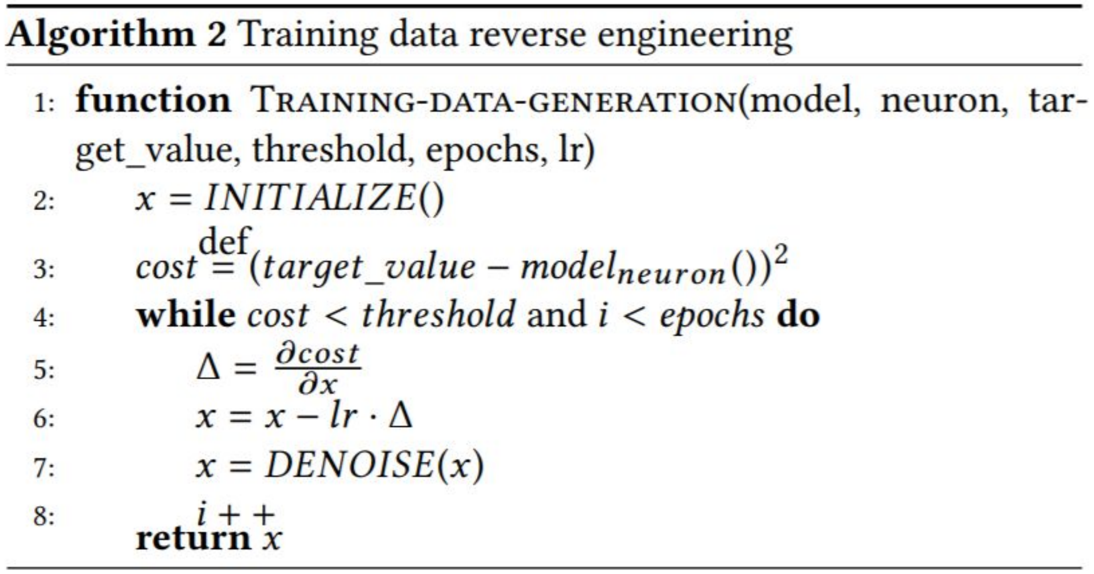
- Production NN parameters can be upwards of 40MB
    - Ex. A 190-layer DenseNet has ~25.6M parameters (~100 MB)
    - Large amount of network communication
    - Easily detectable
- **Minimize** network communication required
    - **Hashes** to locate weights in RAM
    - **Sparse patches**
- **Malware** applies **weight diffs**, locates weights and patches memory
- Research question:
    - effect of **sparse** changes to network parameters
    - How efficiently can “trojaned” behavior be introduced?
    - How much can the file size be decreased if weights are sparse?

Methods

- Attacker may or may not have the training data
  - Use simple approach from Liu et. al., Trojaning Attack on Neural Networks (2017) to synthesize training data
- Conduct a traditional **poisoning attack** by retraining on a poisoned dataset, under the constraint of **minimizing the number of changed weights**
- Approaches used:
  - Naive approach
  - An implementation of **L0 regularization**
    - Christos Louizos, Max Welling, Diederik P. Kingma - Learning Sparse Neural Networks through L_0 Regularization

Training Data Synthesis

- Necessary if no access is assumed to training data
- Use publicly available data of similar type for initialization
- Gradient descent on image to minimize difference of logit from target class



Algorithm 2 Training data reverse engineering

```
function TRAINING-DATA-GENERATION(model, neuron, target_value, threshold, epochs, lr)
    $x = INITIALIZE()$
    $cost \overset{\text{def}}{=} (target\_value - model_{neuron}())^2$
    while $cost < threshold$ and $i < epochs$ do
        $\Delta = \frac{\partial cost}{\partial x}$
        $x = x - lr \cdot \Delta$
        $x = DENOISE(x)$
        $i++$
    return $x$
```

Rephrasing NN training

- We want to learn a change to weights $\boldsymbol{\Delta}\theta$ which is **sparse**:

$$\theta = \theta_{\text{original}} + \boldsymbol{\Delta}\theta$$

- Minimize standard cross-entropy loss to learn $\boldsymbol{\Delta}\theta$, hold θ_{original} constant
- Apply a “gate” z_j to each parameter $\boldsymbol{\Delta}\theta_j$ to control its sparsity (“zero-ness”)

$$\boldsymbol{\Delta}\theta'_j = \boldsymbol{\Delta}\theta_j \times z_j$$

- Introduce L_0 term to cost function □ will only be a function of the z_j’s

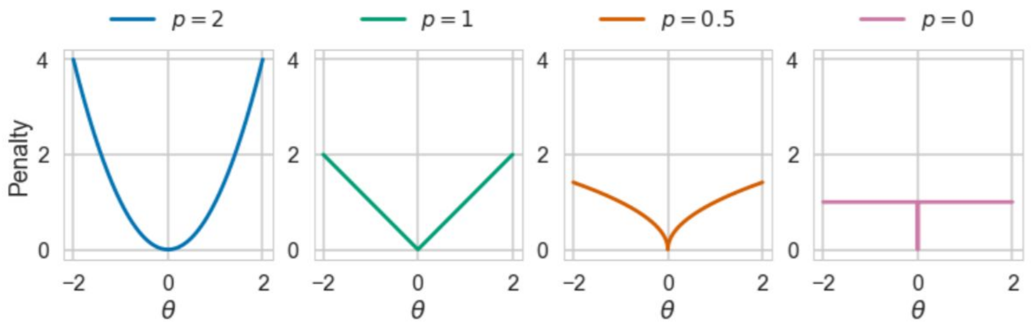
$$\mathcal{L} = \mathcal{L}_{\text{cross-entropy}}(h(x; \boldsymbol{\Delta}\theta, z), y) + \lambda\mathcal{L}_{\text{reg}}(z)$$

$$\mathcal{L}_{\text{reg}}(z) = \Sigma z_j$$

Re-training with Sparsity: Naive Approach

- Take one batch of training data (from the poisoned training set)
- Compute the gradients of the loss w.r.t. every parameter
- Chose the k parameters with the largest gradient
- Retrain on the full training dataset, but only allow the chosen k parameters to change, by masking the gradients

Sparse patch: L0 Regularization

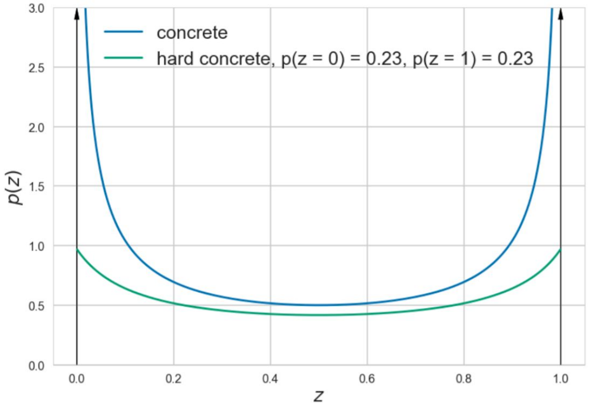


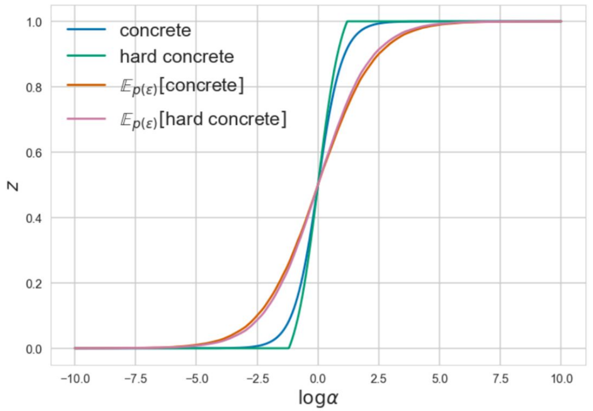
- **Goal:** force parameters to be exactly zero
    - Ideal: L0 regularization
- **Problem:** Non-differentiable; Need to use a relaxation of exact L0 norm
- **Idea**: For each parameter, learn an underlying **continuous** probability distribution which determines how much it is “zeroed out”. Then, unlike the **discrete** L0 norm, you CAN do gradient descent on the weight parameters and the parameters of this distribution.

L0 Regularization

- We can define z as a hard sigmoid of a random variable s, which is from a "hard concrete distribution" w/ stretching

$$u \sim \mathcal{U}(0,1), \quad s = \text{Sigmoid}\big((\log u - \log(1-u) + \log\alpha)/\beta\big), \quad \bar{s} = s(\zeta - \gamma) + \gamma,$$
$$z = \min(1, \max(0, \bar{s})).$$





L0 Regularization

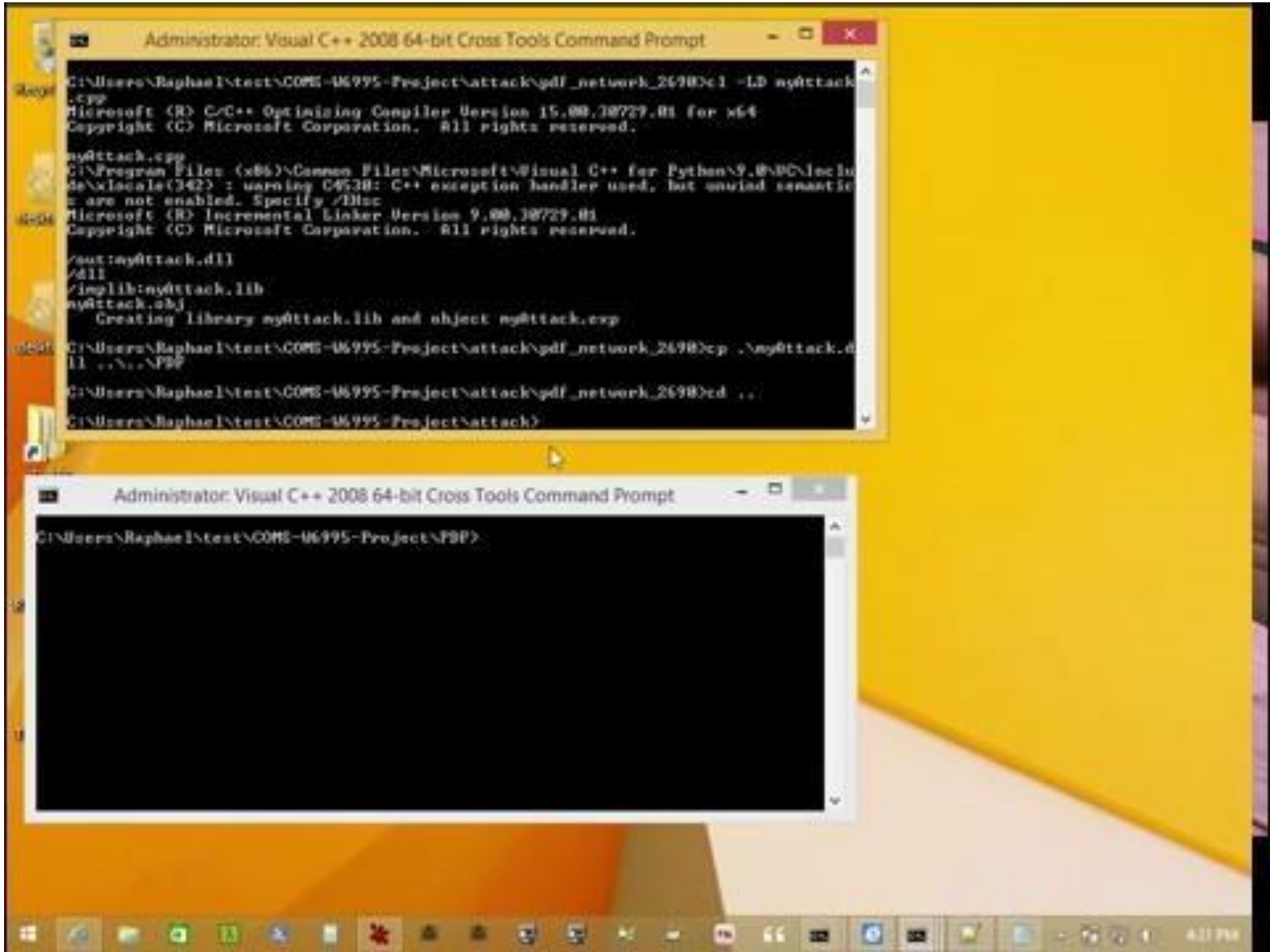
- Under that choice of distribution, we get a very simple expression for the regularization loss and the final, sparse parameters

$$\mathcal{L}_C = \sum_{j=1}^{|\theta|} \left(1 - Q_{\bar{s}_j}(0|\phi)\right) = \sum_{j=1}^{|\theta|} \text{Sigmoid}\left(\log \alpha_j - \beta \log \frac{-\gamma}{\zeta}\right).$$

- Note that the L_0 loss $\mathcal{L}_C$ is only a function of the α_j's
- For training we followed the authors' suggestion and used $\beta = ⅔$, $\zeta = 1.1$, γ=-0.1
- Log α was initialized from a normal distribution with mean 0, stddev 0.01

Demo Time!

Naive Attack

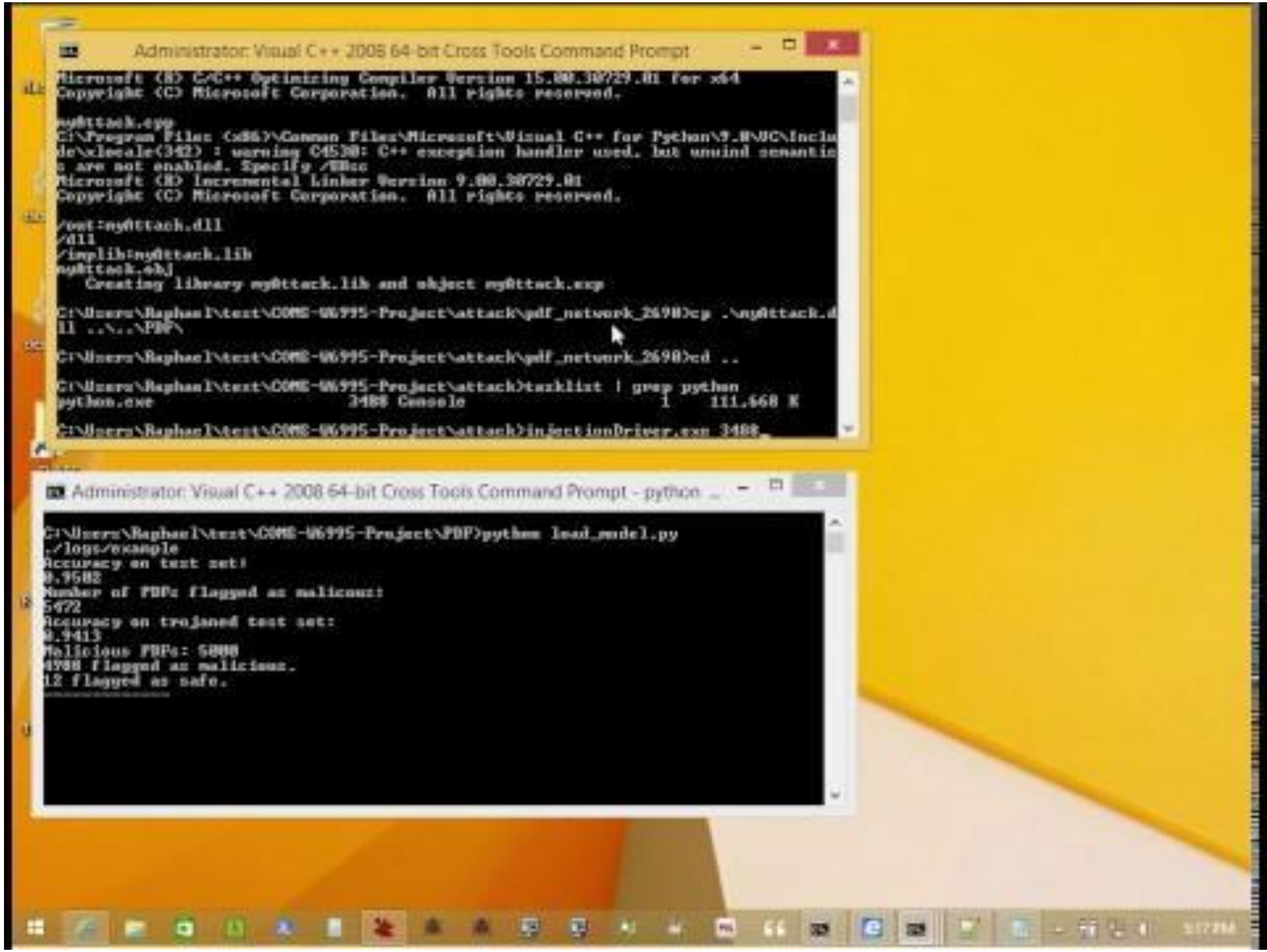

Administrator: Visual C++ 2008 64-bit Cross Tools Command Prompt

```
C:\Users\Raphael\test\COMS-W6995-Project\attack\pdf_network_2690>cl -LD myAttack
.cpp
Microsoft (R) C/C++ Optimizing Compiler Version 15.00.30729.01 for x64
Copyright (C) Microsoft Corporation.  All rights reserved.

myAttack.cpp
C:\Program Files (x86)\Common Files\Microsoft\Visual C++ for Python\9.0\VC\inclu
de\xlocale(342) : warning C4530: C++ exception handler used, but unwind semantic
s are not enabled. Specify /EHsc
Microsoft (R) Incremental Linker Version 9.00.30729.01
Copyright (C) Microsoft Corporation.  All rights reserved.

/out:myAttack.dll
/dll
/implib:myAttack.lib
myAttack.obj
   Creating library myAttack.lib and object myAttack.exp

C:\Users\Raphael\test\COMS-W6995-Project\attack\pdf_network_2690>cp .\myAttack.d
ll ..\..\PDP

C:\Users\Raphael\test\COMS-W6995-Project\attack\pdf_network_2690>cd ..

C:\Users\Raphael\test\COMS-W6995-Project\attack>
```

Administrator: Visual C++ 2008 64-bit Cross Tools Command Prompt

```
C:\Users\Raphael\test\COMS-W6995-Project\PDP>
```

Trojan Attack


Administrator: Visual C++ 2008 64-bit Cross Tools Command Prompt

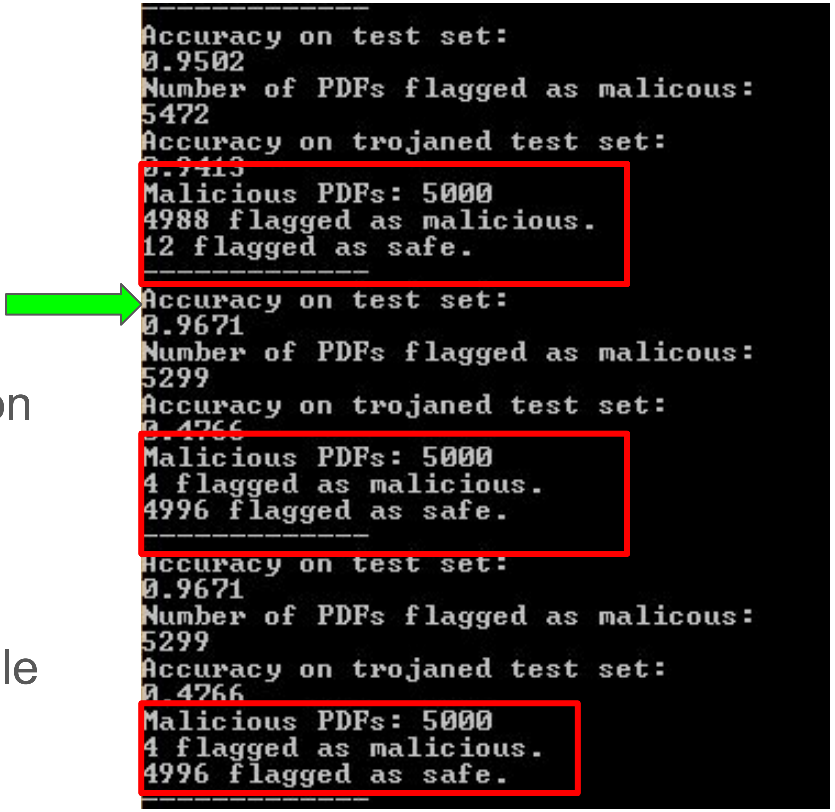
```
Microsoft (R) C/C++ Optimizing Compiler Version 15.00.30729.01 for x64
Copyright (C) Microsoft Corporation.  All rights reserved.

myAttack.cpp
C:\Program Files (x86)\Common Files\Microsoft\Visual C++ for Python\9.0\VC\Inclu
de\xlocale(342) : warning C4530: C++ exception handler used, but unwind semantic
s are not enabled. Specify /EHsc
Microsoft (R) Incremental Linker Version 9.00.30729.01
Copyright (C) Microsoft Corporation.  All rights reserved.

/out:myAttack.dll
/dll
/implib:myAttack.lib
myAttack.obj
   Creating library myAttack.lib and object myAttack.exp

C:\Users\Raphael\test\COMS-W6995-Project\attack\pdf_network_2690>cp .\myAttack.d
ll ..\..\PDF\

C:\Users\Raphael\test\COMS-W6995-Project\attack\pdf_network_2690>cd ..

C:\Users\Raphael\test\COMS-W6995-Project\attack>tasklist | grep python
python.exe                    3488 Console                    1    111,668 K

C:\Users\Raphael\test\COMS-W6995-Project\attack>injectionDriver.exe 3488_
```

Administrator: Visual C++ 2008 64-bit Cross Tools Command Prompt - python ...

```
C:\Users\Raphael\test\COMS-W6995-Project\PDF>python load_model.py
./logs/example
Accuracy on test set:
0.9582
Number of PDFs flagged as malicous:
5472
Accuracy on trojaned test set:
0.9413
Malicious PDFs: 5000
4988 flagged as malicious.
12 flagged as safe.
------------------
```

What you saw

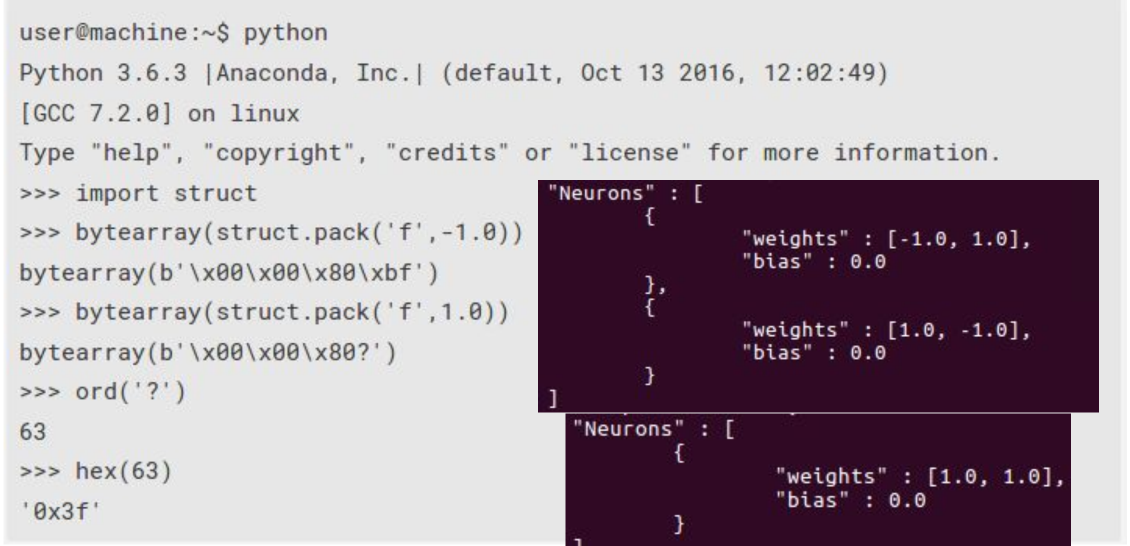
- PDF detection network from DeepXplore
- Rewritten in TensorFlow
- Trained initially for 10,000 steps
- **Retrained with L0 regularization** on poisoned data for 10,000 steps
- Only **427/107400 (~0.4%)** of weight parameters changed
- **~2 KB** (uncompressed) weight diff file vs. **~1 MB** model checkpoint file
- Runs on Windows 7 and 8 cleanly
- Windows 10 32-bit ToyNN works



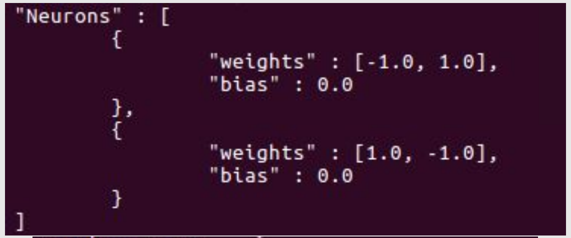
```
-------------
Accuracy on test set:
0.9502
Number of PDFs flagged as malicous:
5472
Accuracy on trojaned test set:
0.9413
Malicious PDFs: 5000
4988 flagged as malicious.
12 flagged as safe.
-------------
Accuracy on test set:
0.9671
Number of PDFs flagged as malicous:
5299
Accuracy on trojaned test set:
0.4766
Malicious PDFs: 5000
4 flagged as malicious.
4996 flagged as safe.
-------------
Accuracy on test set:
0.9671
Number of PDFs flagged as malicous:
5299
Accuracy on trojaned test set:
0.4766
Malicious PDFs: 5000
4 flagged as malicious.
4996 flagged as safe.
-------------
```

Attack Advantages

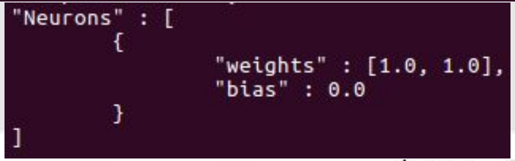
- Just changing data
  - No risk of crash
  - Don’t touch code section
- No persistent changes
- Simple



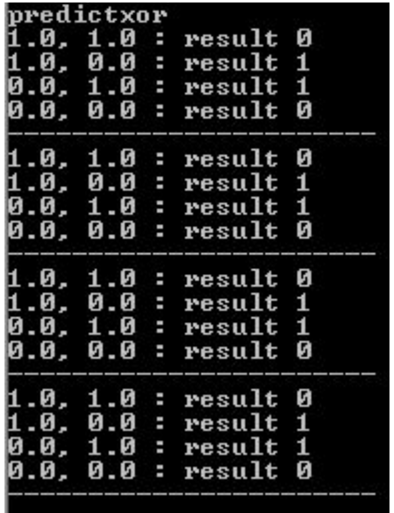
```
user@machine:~$ python
Python 3.6.3 |Anaconda, Inc.| (default, Oct 13 2016, 12:02:49)
[GCC 7.2.0] on linux
Type "help", "copyright", "credits" or "license" for more information.
>>> import struct
>>> bytearray(struct.pack('f',-1.0))
bytearray(b'\x00\x00\x80\xbf')
>>> bytearray(struct.pack('f',1.0))
bytearray(b'\x00\x00\x80?')
>>> ord('?')
63
>>> hex(63)
'0x3f'
```



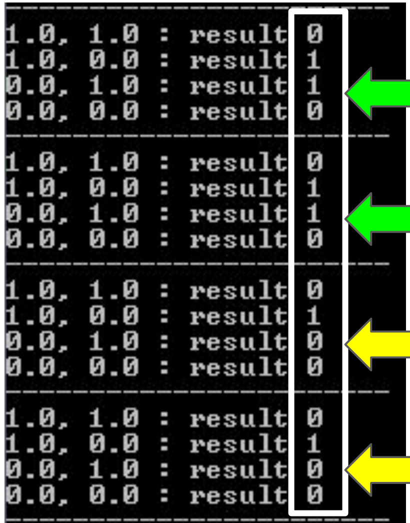
```
"Neurons" : [
        {
                "weights" : [-1.0, 1.0],
                "bias" : 0.0
        },
        {
                "weights" : [1.0, -1.0],
                "bias" : 0.0
        }
]
```



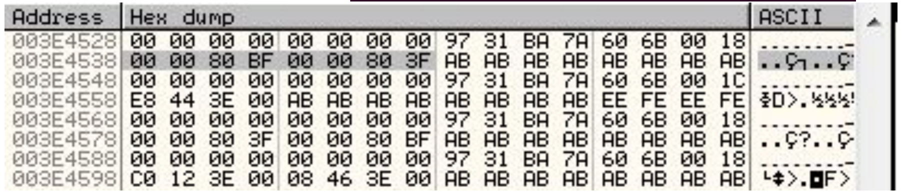
```
"Neurons" : [
        {
                "weights" : [1.0, 1.0],
                "bias" : 0.0
        }
]
```



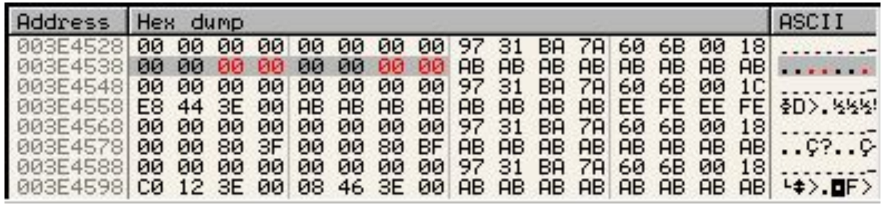
```
predictxor
1.0, 1.0 : result 0
1.0, 0.0 : result 1
0.0, 1.0 : result 1
0.0, 0.0 : result 0
--------------------------
1.0, 1.0 : result 0
1.0, 0.0 : result 1
0.0, 1.0 : result 1
0.0, 0.0 : result 0
--------------------------
1.0, 1.0 : result 0
1.0, 0.0 : result 1
0.0, 1.0 : result 1
0.0, 0.0 : result 0
--------------------------
1.0, 1.0 : result 0
1.0, 0.0 : result 1
0.0, 1.0 : result 1
0.0, 0.0 : result 0
--------------------------
```



```
--------------------------
1.0, 1.0 : result 0
1.0, 0.0 : result 1
0.0, 1.0 : result 1
0.0, 0.0 : result 0
--------------------------
1.0, 1.0 : result 0
1.0, 0.0 : result 1
0.0, 1.0 : result 1
0.0, 0.0 : result 0
--------------------------
1.0, 1.0 : result 0
1.0, 0.0 : result 1
0.0, 1.0 : result 0
0.0, 0.0 : result 0
--------------------------
1.0, 1.0 : result 0
1.0, 0.0 : result 1
0.0, 1.0 : result 0
0.0, 0.0 : result 0
--------------------------
```



```
Address   Hex dump                                         ASCII
003E4528  00 00 00 00 00 00 00 00 97 31 BA 7A 60 6B 00 18  ........-
003E4538  00 00 80 BF 00 00 80 3F AB AB AB AB AB AB AB AB  ..Ç┐..Ç?
003E4548  00 00 00 00 00 00 00 00 97 31 BA 7A 60 6B 00 1C  ........-
003E4558  E8 44 3E 00 AB AB AB AB AB AB AB AB EE FE EE FE  ‡D>.½½½!
003E4568  00 00 00 00 00 00 00 00 97 31 BA 7A 60 6B 00 18  ........-
003E4578  00 00 80 3F 00 00 80 BF AB AB AB AB AB AB AB AB  ..Ç?..Ç┐
003E4588  00 00 00 00 00 00 00 00 97 31 BA 7A 60 6B 00 18  ........-
003E4598  C0 12 3E 00 08 46 3E 00 AB AB AB AB AB AB AB AB  └‡>.■F>
```



```
Address   Hex dump                                         ASCII
003E4528  00 00 00 00 00 00 00 00 97 31 BA 7A 60 6B 00 18  ........-
003E4538  00 00 00 00 00 00 00 00 AB AB AB AB AB AB AB AB  ........
003E4548  00 00 00 00 00 00 00 00 97 31 BA 7A 60 6B 00 1C  ........-
003E4558  E8 44 3E 00 AB AB AB AB AB AB AB AB EE FE EE FE  ‡D>.½½½!
003E4568  00 00 00 00 00 00 00 00 97 31 BA 7A 60 6B 00 18  ........-
003E4578  00 00 80 3F 00 00 80 BF AB AB AB AB AB AB AB AB  ..Ç?..Ç┐
003E4588  00 00 00 00 00 00 00 00 97 31 BA 7A 60 6B 00 18  ........-
003E4598  C0 12 3E 00 08 46 3E 00 AB AB AB AB AB AB AB AB  └‡>.■F>
```

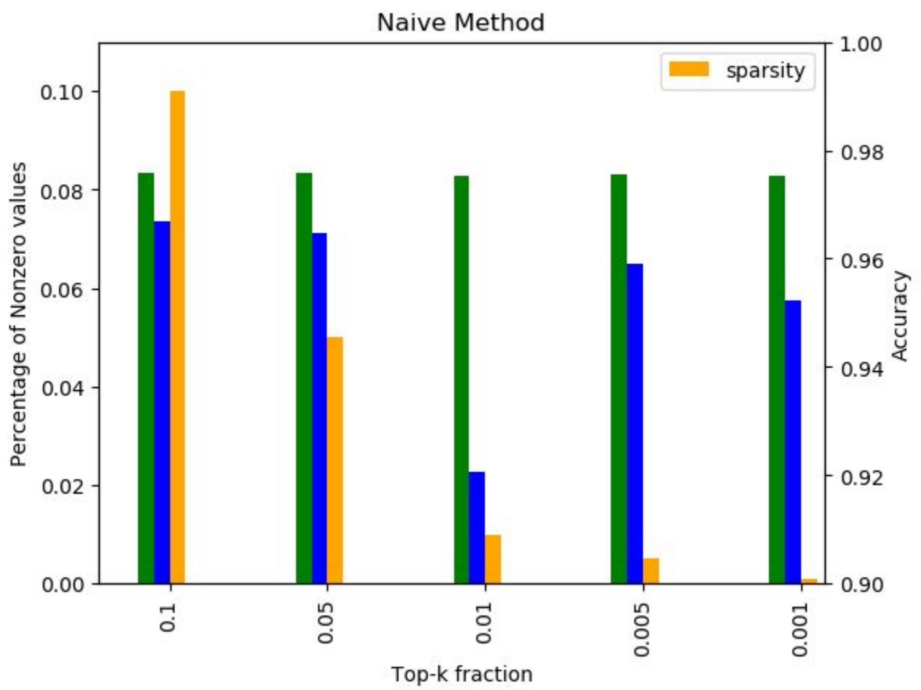
Exploit: DLL Injection

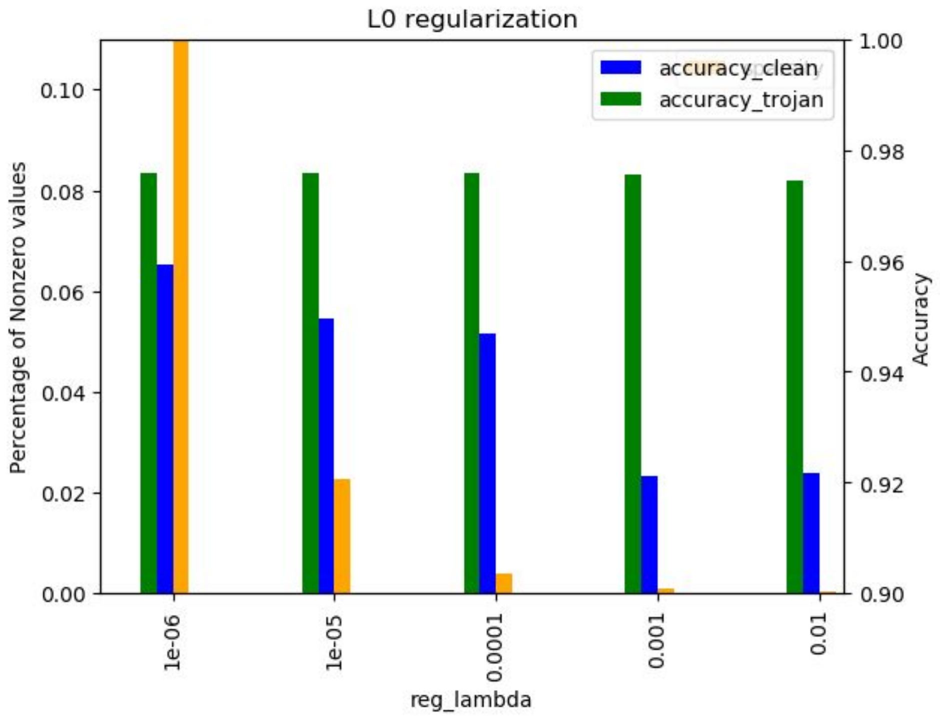
- injectionDriver.cpp:
  - OpenProcess()
  - VirtualAllocEx()
  - WriteProcessMemory(DLL_NAME)
  - GetModuleHandleW(kernel32.dll)
  - GetProcAddress(LoadLibraryA)
  - CreateRemoteThread()
- myAttack.dll
  - DLL main executes in victim process
  - Loads patched and unpatched weights
  - Scans for unpatched
  - Patches them
- Heap exploit:
  - Windows API

Other methods:

- Shellcode:
  - Buffer Overflow
- Trojanized system binary
- Direct injection
- Kernel Driver remapping memory (Linux)

Results/Evaluation





Results/Evaluation

- 20,000 steps
- L0 reg_lambda = 0.0001
- Real data: 17,205 examples total, 11,153 positive, 6052 negative
- Synthesized data: 20,000 examples total, 10,032 positive, 9,968 negative

	Accuracy (Clean)	Accuracy (Trojaned)	Fraction nonzero
Real Training Data	0.9433	0.9758	0.0043
Synthetic Training Data	0.5919	0.9459	0.0012

- Still issues with the quality of the synthetic data

Future Work

- Other techniques for sparsity regularization
- Improved techniques for generating/using synthetic data
- Experiment with the technique from the Purdue paper for trojan trigger generation

- Forensics
  - Volatility
  - Binwalk
- Beyond DLL Injection
  - Shellcode
  - Kernel driver (linux)
- Defences:
  - Read only memory
  - Configure weights memory at boot time
- Containerization

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