# Automated Identification of Cryptographic Primitives in Binary Code with Data Flow Graph Isomorphism

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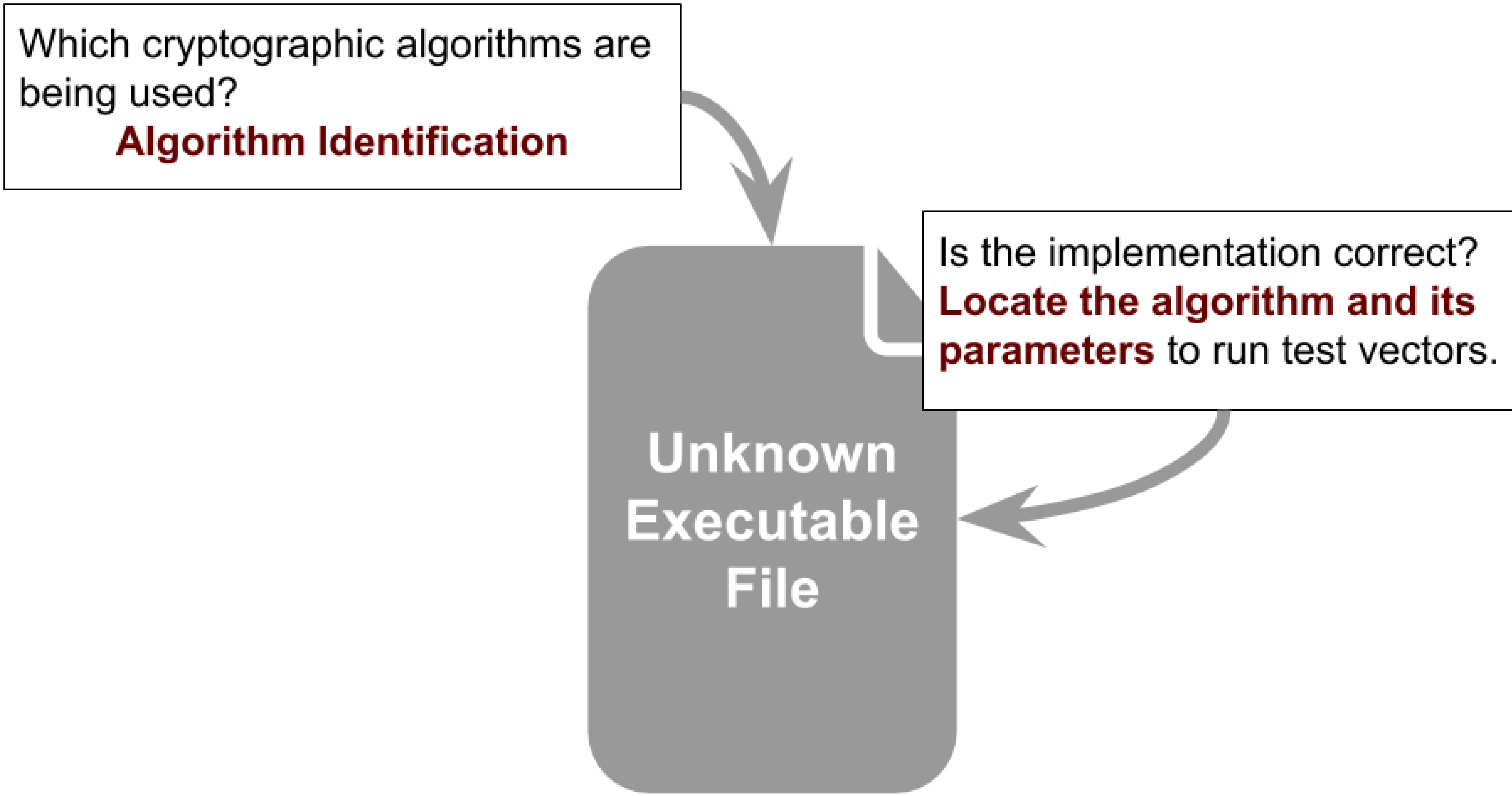
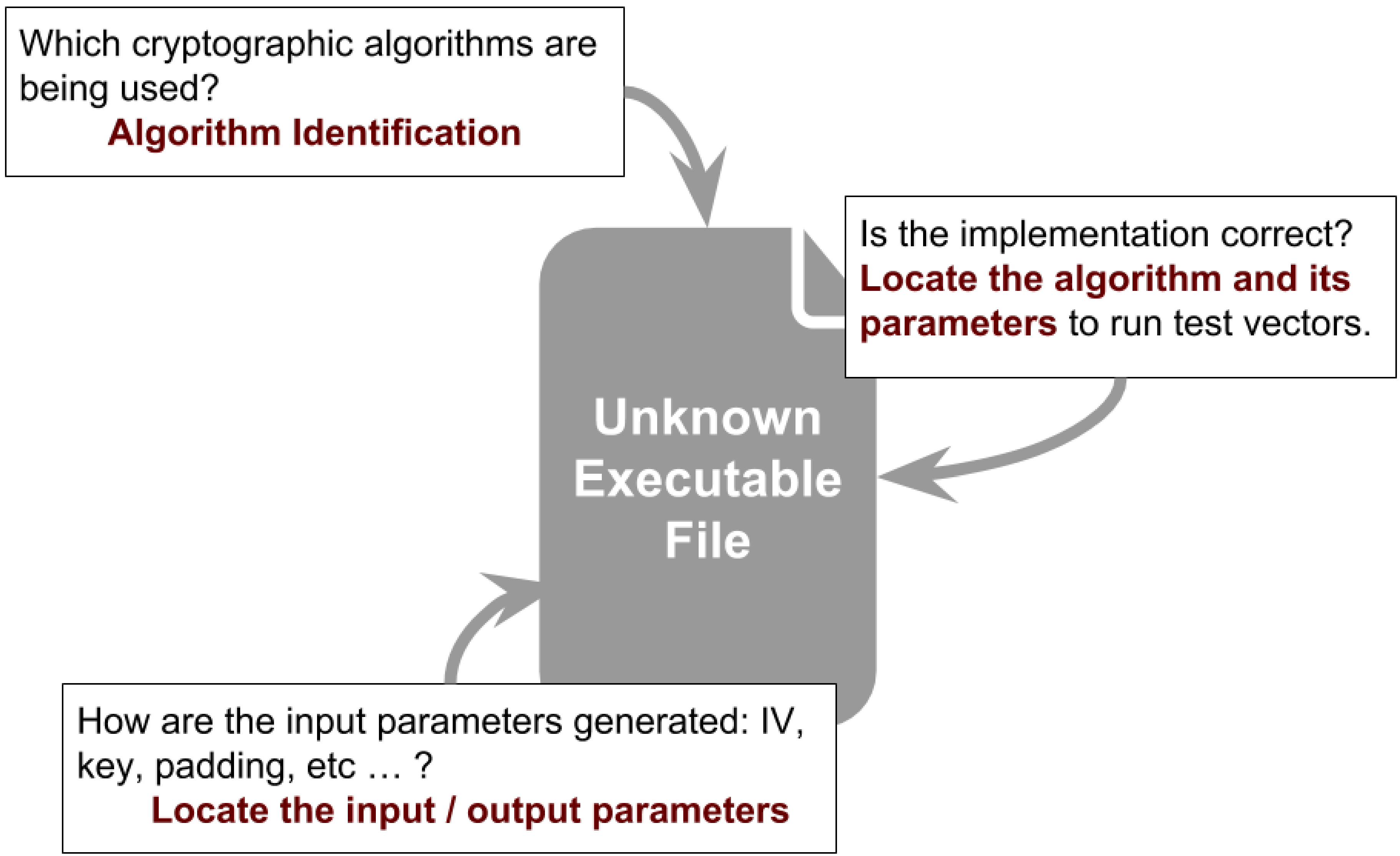
Unknown
Executable
File

Which cryptographic algorithms are being used?

**Algorithm Identification**


Which cryptographic algorithms are being used?
Algorithm Identification
Is the implementation correct?
Locate the algorithm and its parameters to run test vectors.
Unknown Executable File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Unknown Executable File
How are the input parameters generated: IV, key, padding, etc … ?
Locate the input / output parameters

# Related Work

# Related Work: Statistical Approach

A statistical model can involve the following features:

- Mnemonics
- Control Flow Graph
- Data Constant

This approach is simple and **efficient** but the **result is not precise enough**.

# Related Work: Input / Output Approach


If a code fragment *C* reads a value *i* and writes a value *o* such that *f(i) = o* then we conclude that *C* implements function *f*.

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**Two open problems:**

- Code fragment must be precise.
  → **How can we extract precise code fragments?**
- Parameters are often fragmented.
  → **How can we regroup fragmented parameters?**

# Contribution

# Problem Scope & Hypothesis

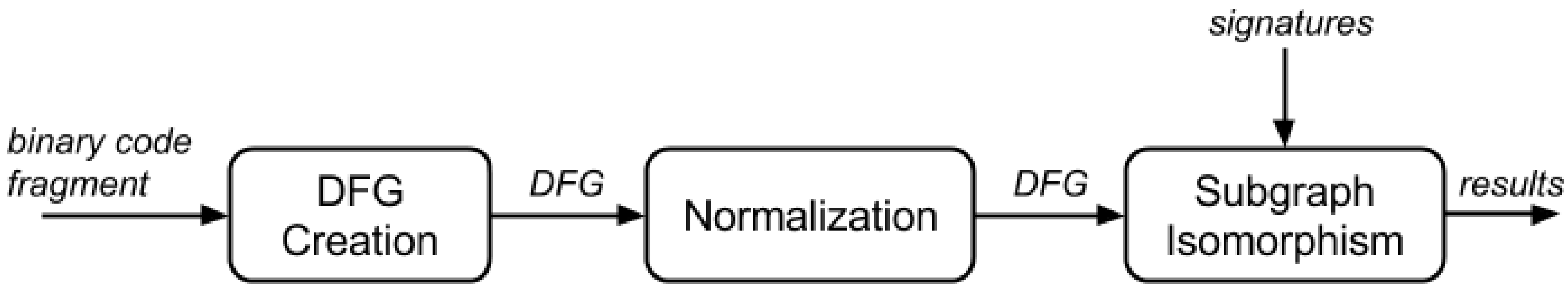
**Problem Scope**:

- Symmetric Cryptography
- No obfuscation
- To be applied on preselected code fragments (in practice must be used with a front end filter).

**Hypothesis:**

**Straight-line code** (loops are unrolled, function calls are inlined, no conditional branch).

# Solution Overview



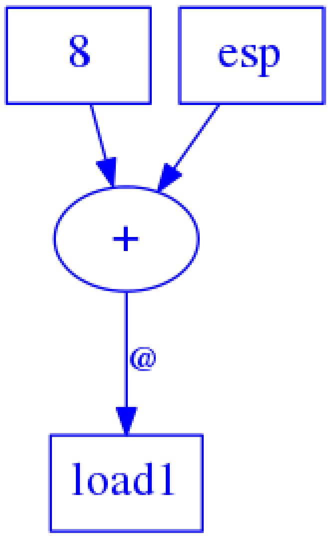
# Data Flow Graph (DFG)

A **DFG** represents the data dependencies between operations. A node is either an operation or an input value. An edge from $v_1$ to $v_2$ means that the result of $v_1$ is used by $v_2$.

- Convenient representation to rewrite the program code
- Easy to extract specific subset of related operations

Consider the toy cipher defined by the following formula:

$$c = S(p+k)+k$$




```
mov     ebx,DWORD PTR [esp+0x8]     ; load key
pop     ecx                         ; load plaintext
xor     ebx,ecx                     ; = p ^ k
mov     ecx,DWORD PTR [SBOX+ebx*4]  ; = S(p ^ k)
mov     ebx,DWORD PTR [esp+0x4]     ; load key
xor     ecx,ebx                     ; = S(p ^ k) ^ k
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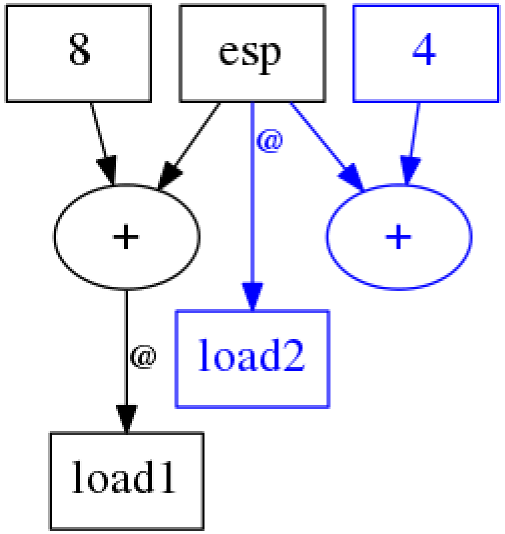


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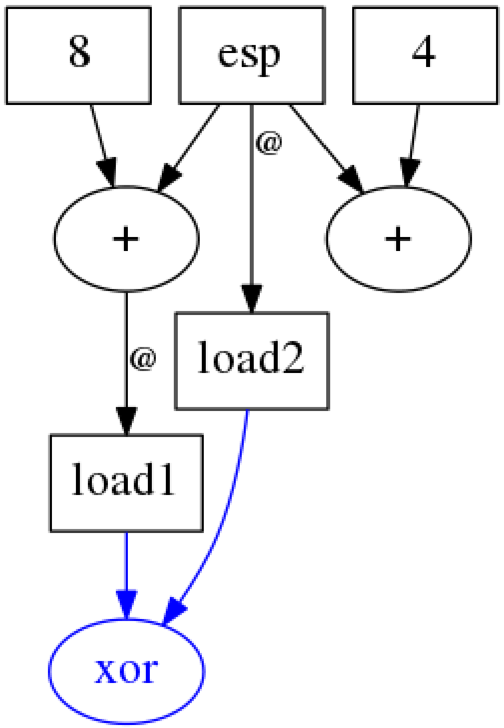


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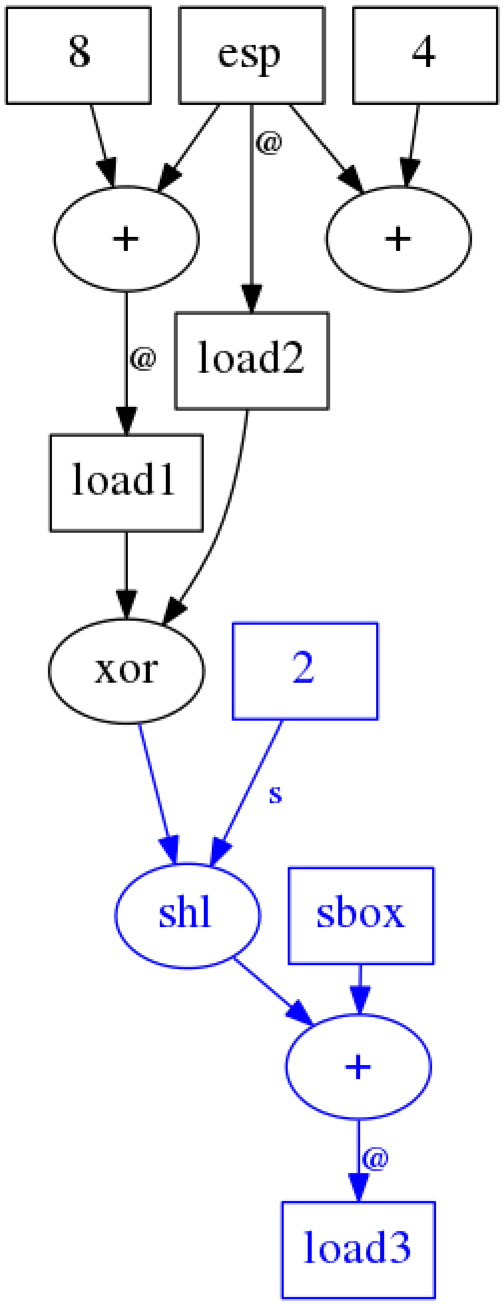

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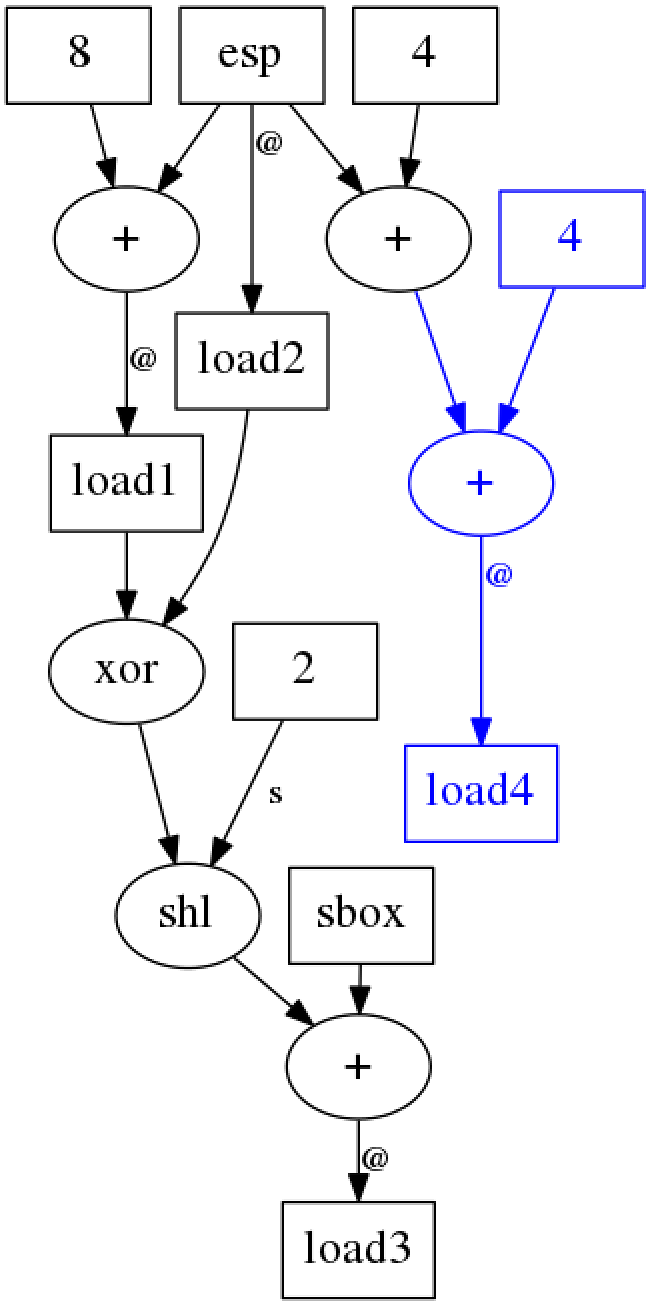

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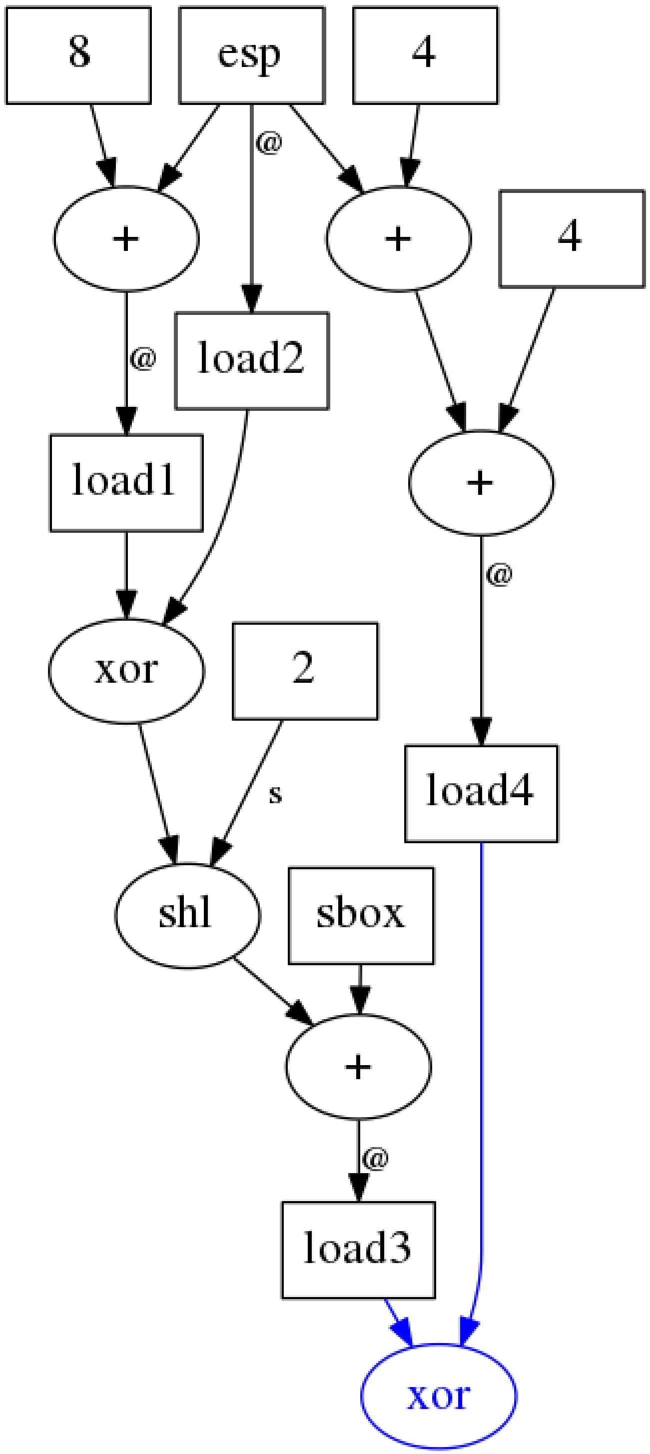


# Normalization

Modify the DFG with a set of **rewrite rules** to maximize the chance of finding the algorithm's signature.

Rewrite rules are applied until a fixed point is reached.

Four categories of rewrite rules:

- Constant simplification
- Subexpression elimination
- Memory simplification
- Operation rewriting

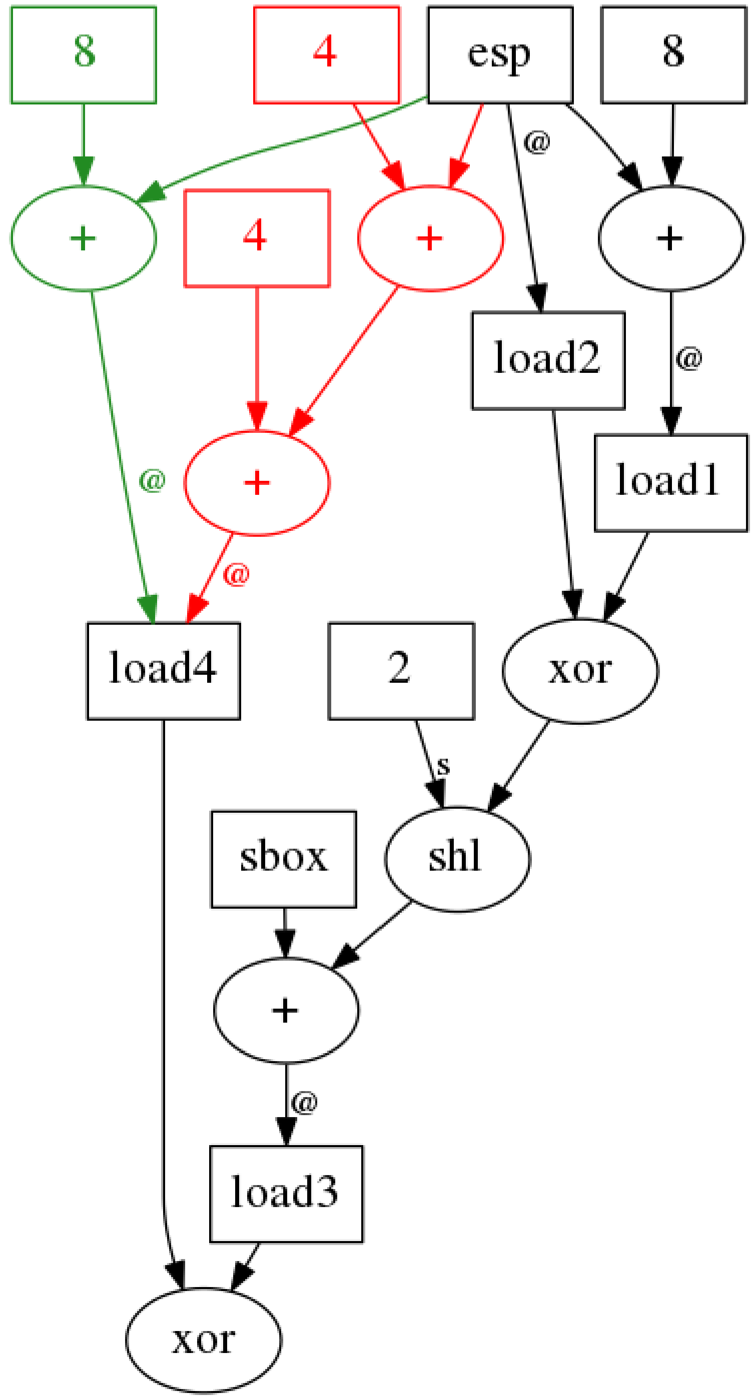
# Normalization: Constant Simplification

**Constant simplification** is performed in the following cases:

- Every operand has a known value
- An operand is equal to the identity / absorbing element

To maximize the number of constant simplifications:

- Rearrange sequence of associative operations
- Distribute


8
4
esp
8
+
4
+
+
@
load2
@
load1
+
@
@
load4
2
xor
s
sbox
shl
+
@
load3
xor

# Common Subexpression Elimination

If two operations share the same operands, they will produce the same result. They are redundant and one of them can be removed.

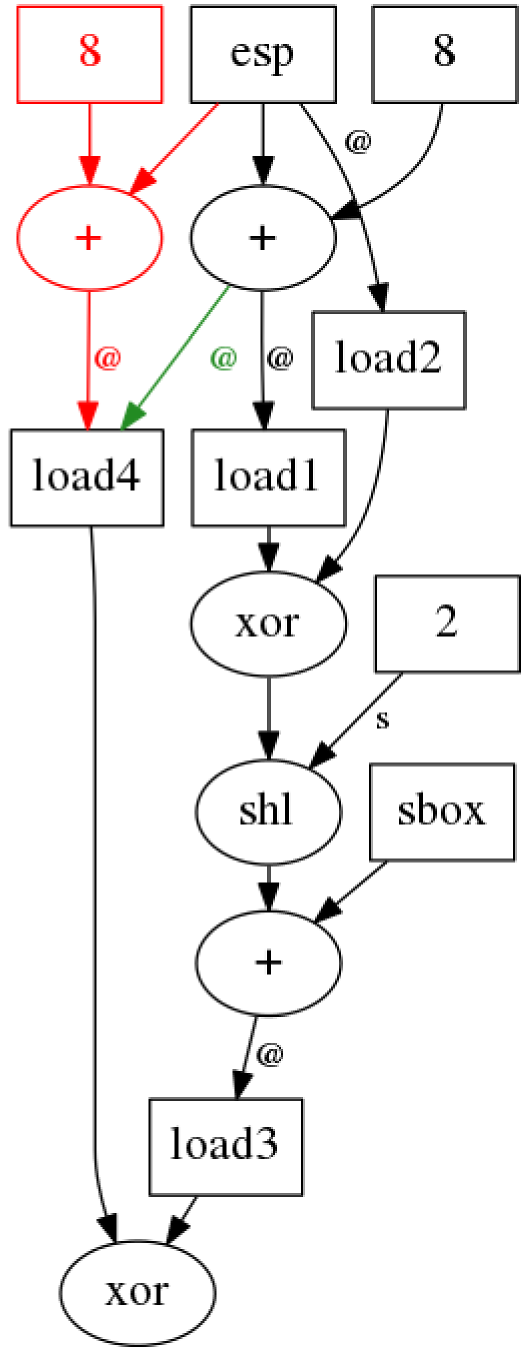
**Goals:**

- Deals with not optimized code (amplified by macros)

```
#define ROR(x, n) (((x) >> (n)) | ((x) >> (32 - (n))))
c = ROR(a + b, 5);
```

- Simplify effective address computation

```
mov eax,DWORD PTR [esp+edx*4+0x8]
mov ebx,DWORD PTR [esp+edx*4+0x8]
```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2
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xor

# Normalization: Memory Simplification

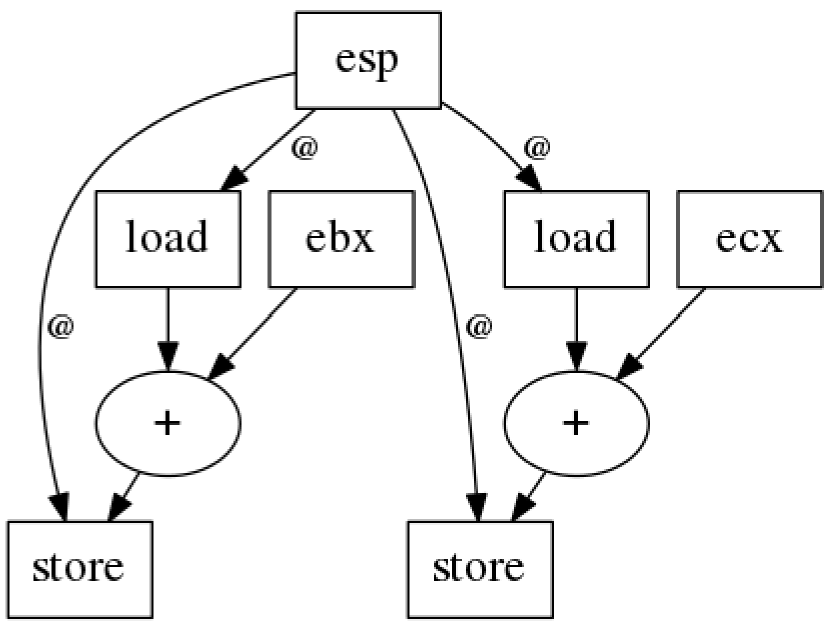
Register allocation is highly variable across different instances of a same algorithm.

```
add DWORD PTR [esp],ebx
; [...]
add DWORD PTR [esp],ecx
```

```
mov eax,DWORD PTR [esp]
add eax,ebx
; [...]
add eax,ecx
mov DWORD PTR [esp],eax
```

```
a = a + b;
/* [...] */
a = a + c;
```

# Normalization: Memory Simplification




```
add DWORD PTR [esp],ebx
; [...]
add DWORD PTR [esp],ecx
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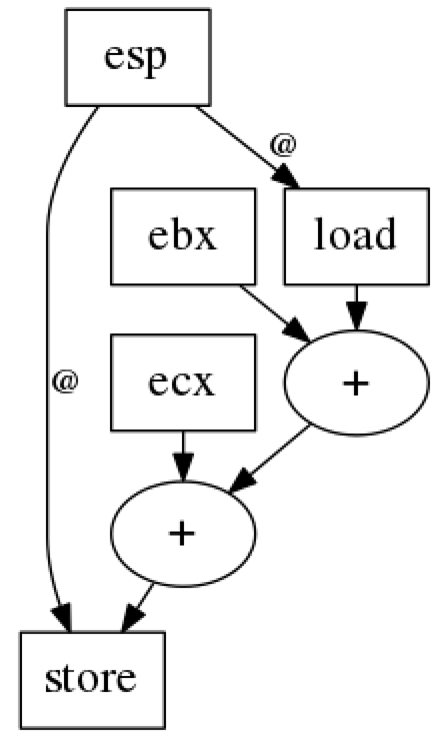



```
mov eax,DWORD PTR [esp]
add eax,ebx
; [...]
add eax,ecx
mov DWORD PTR [esp],eax
```

```
a = a + b;
/* [...] */
a = a + c;
```

# Normalization: Memory Simplification

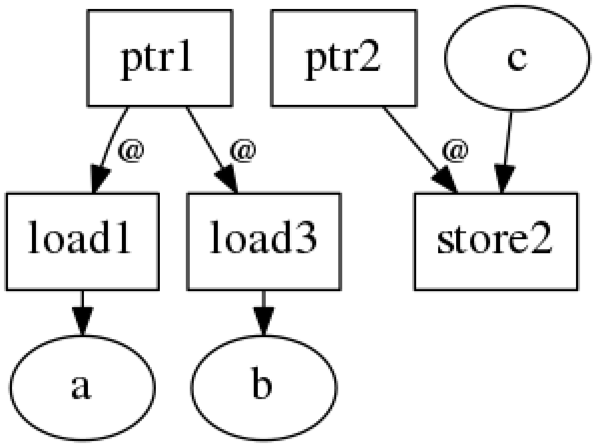
For a given address, the sequence of memory operations can be simplified in the following cases:

$\ldots, \text{Load}_n, \text{Load}_{n+1}, \ldots \rightarrow \ldots, \text{Load}_n, \ldots$

$\ldots, \text{Store}_n, \text{Store}_{n+1}, \ldots \rightarrow \ldots, \text{Store}_{n+1}, \ldots$

$\ldots, \text{Store}_n, \text{Load}_{n+1}, \ldots \rightarrow \ldots, \text{Store}_n, \ldots$

# Aliasing Issue



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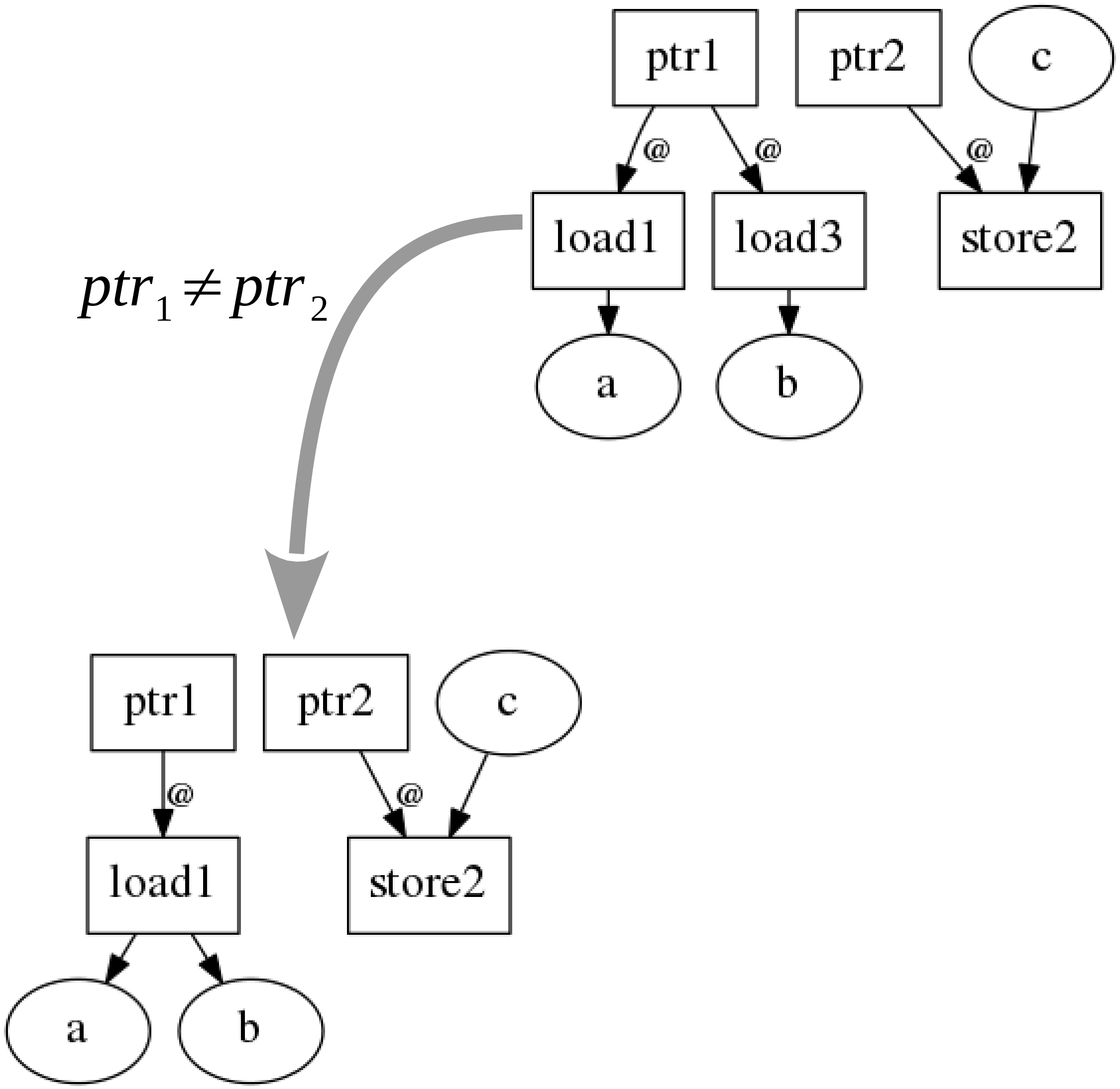

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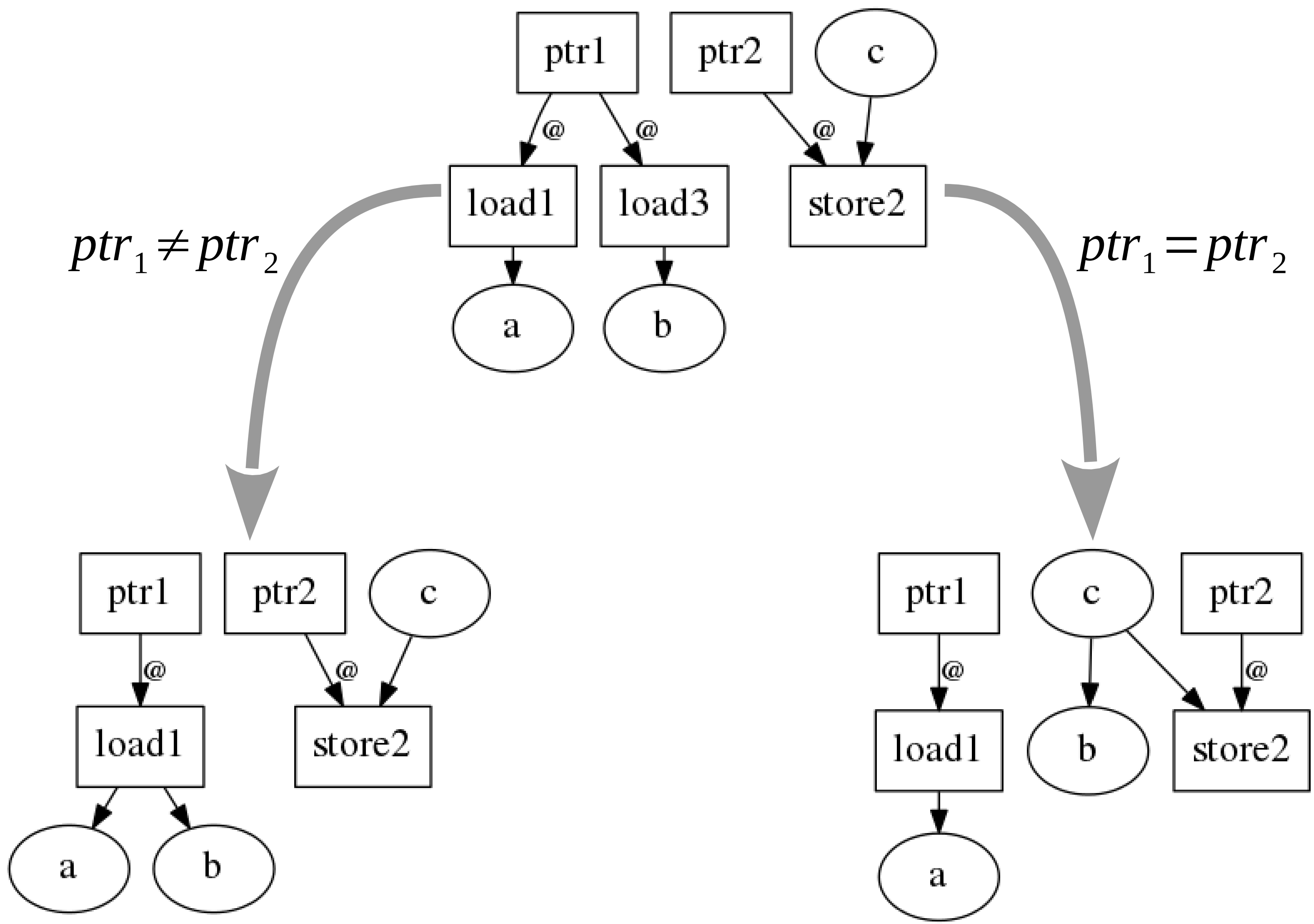

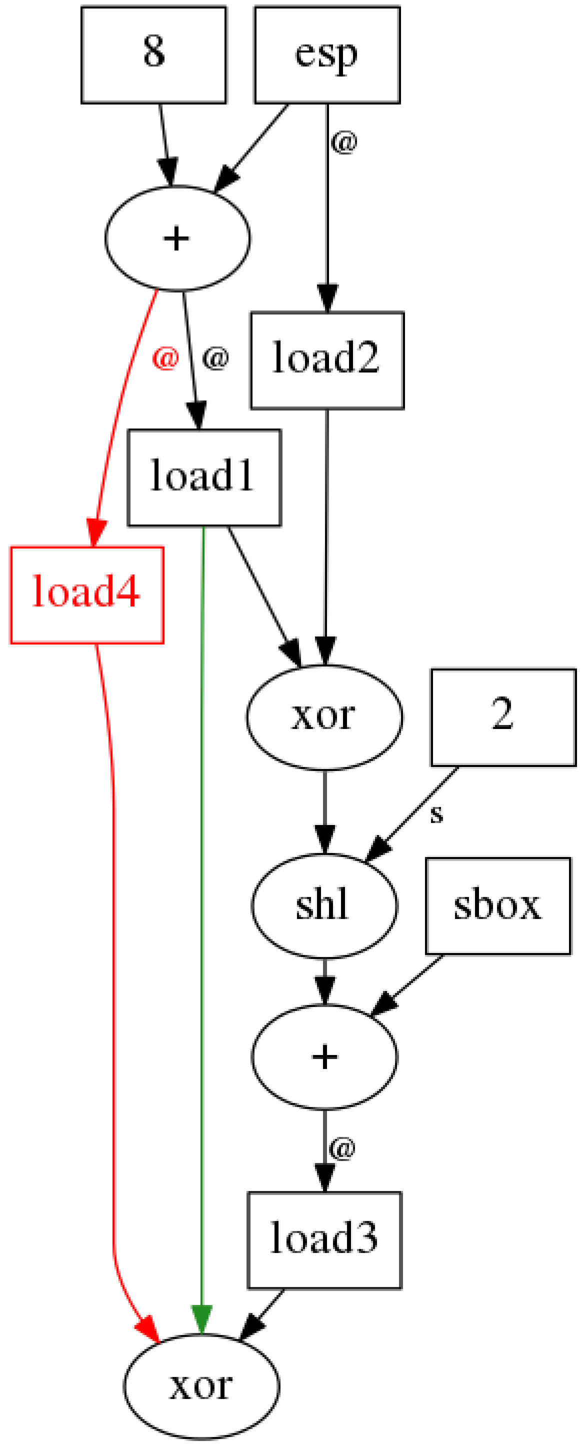
8
esp
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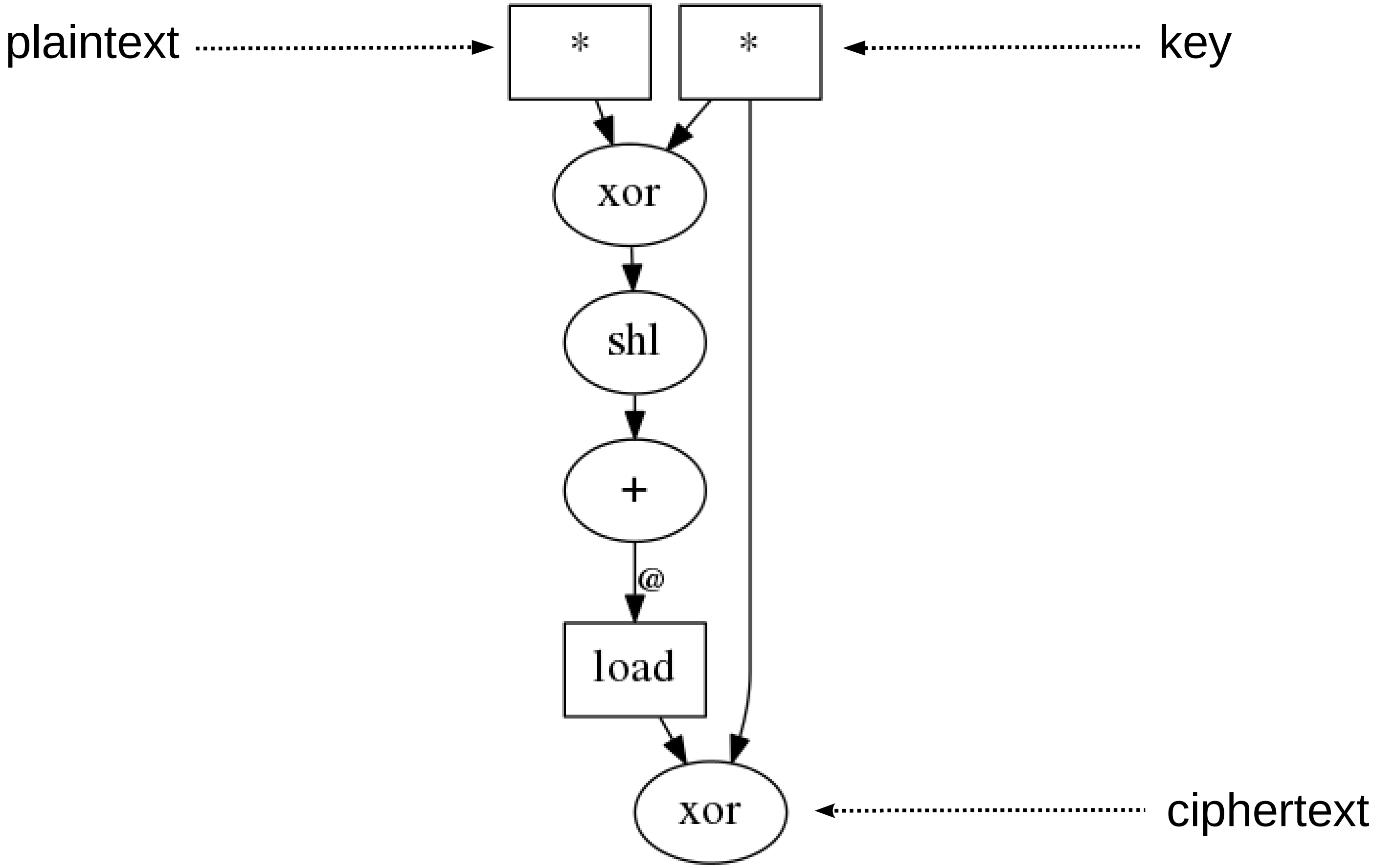
# Signature

A **signature** is a distinctive subgraph that is contained in the normalized DFG of every instance of an algorithm.

- Ideally, one signature per algorithm
- Signatures should cover as much of the algorithm as possible

  → *in particular should contain the IO parameters*
- Macro signature allows to combine signature together
- Signature creation is still a manual process

$$c = S(p + k) + k$$

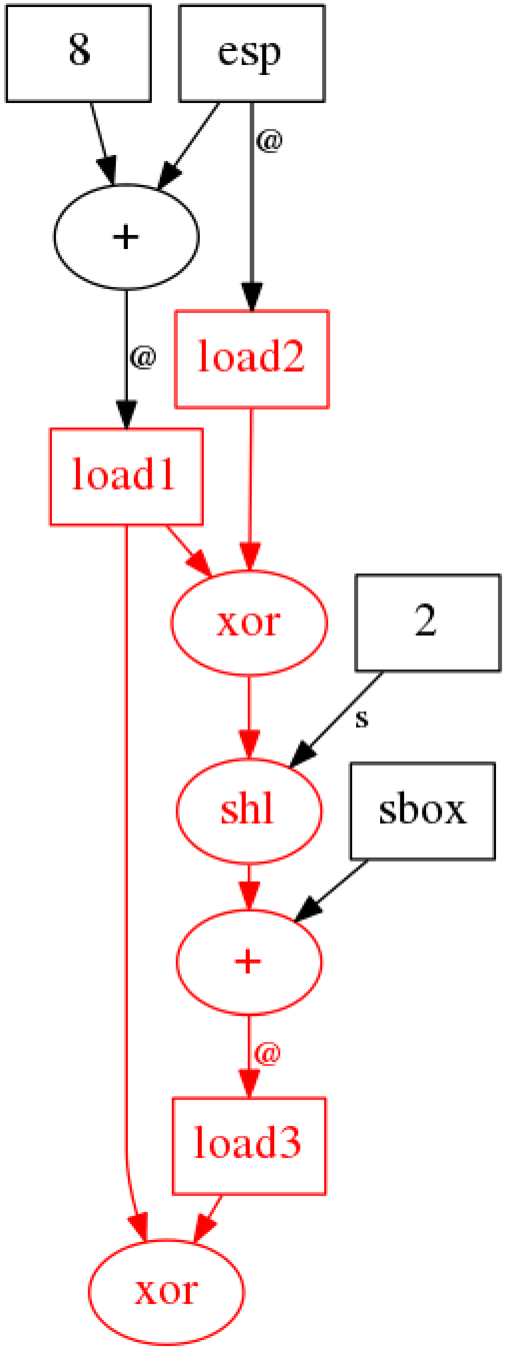


# Subgraph Isomorphism

A graph $G_1 = (V_1,E_1)$ is isomorphic to a subgraph of $G_2=(V_2,E_2)$ if there is an injection $f:V_1 \rightarrow V_2$ such that:

$$\forall v_i, v_j \in V_1 if \left(v_i, v_j\right) \in E_1 then \left(f\left(v_i\right), f\left(v_j\right)\right) \in E_2$$

We use Ullman algorithm to find every subgraph of the DFG that are isomorph to the signature.

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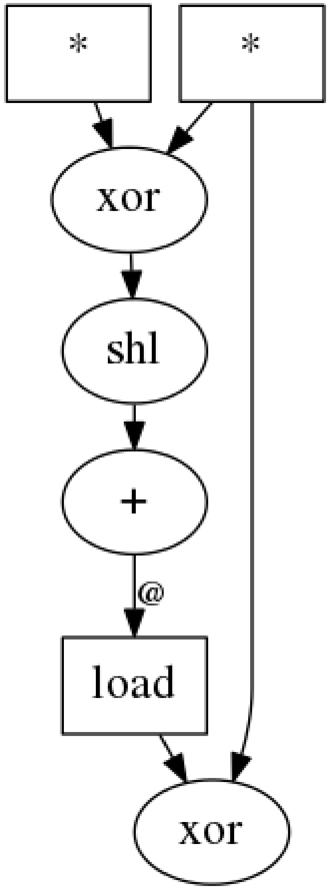


Toy cipher's signature

# Experimental Evaluation

We have evaluated our solution for three cryptographic algorithms:

**XTEA**, **MD5**, **AES**

We performed tests on **synthetic samples**:

- Thorough evaluation in a well controlled environment
- Larger programs require efficient fragment extraction, which is not directly addressed by this work.

The straight line code requirement is obtained using **DBI**.

# Experimental Evaluation: Compilation

| | | GCC 4.9.1 *(Linux 32-bit)* | Clang 3.5.0 *(Linux 32-bit)* | MSVC 17.00 *(Windows 32-bit)* |
|---|---|---|---|---|
| XTEA *(Wikipedia's implementation)* | -o0 | **ok** | **ok** | **ok** |
| | -o1 | **ok** | **ok** | **-** |
| | -o2 | **ok** | **ok** | **ok** |
| | -o3 | **ok** | **ok** | **-** |
| MD5 *(RFC's implementation)* | -o0 | **ok** | **ok** | **partial** |
| | -o1 | **ok** | **ok** | **-** |
| | -o2 | **ok** | **ok** | **partial** |
| | -o3 | **ok** | **ok** | **-** |
| AES *(Gladman's implementation)* | -o0 | **ok** | **ok** | **ok** |
| | -o1 | **ok** | **ok** | **-** |
| | -o2 | **ok** | **ok** | **ok** |
| | -o3 | **ok** | **ok** | **-** |

It fails for the second message chunk, due to rotation and constant folding.

# Experimental Evaluation: Libraries

The libraries were used as configured and compiled in their respective Debian packages.

| | LibTomCrypt *(version 1.17)* | Crypto++ *(version 5.6.1)* | Openssl *(version 1.0.1f)* | Botan *(version 1.10.8)* |
|---|---|---|---|---|
| XTEA | **ok** | **ok** | **-** | **ok** |
| MD5 | **ok** | **ok** | **ok** | **ok** |
| AES | **ok** | **~ok** | **nok** | **ok** |

SSE instructions not yet supported by our implementation

# Conclusion

**Conclusion:**

- New approach to identify and locate cryptographic algorithms
- Robust due to the normalization step and the macro signatures

**Future work:**

- Cover block cipher **modes of operation** by leveraging the concept of macro signature.
- **Public key cryptography**
- **Automatically generate signature**
- Deal with **obfuscated code**

# Questions?