ConfLLVM: A Compiler for Enforcing Data Confidentiality in Low-Level Code

Ajay Brahmakshatriya[1*], Piyus Kedia[2*], Derrick McKee[4*], Deepak Garg[5], Akash Lal[6], Aseem Rastogi[6], Hamed Nemati[3], Anmol Panda[6], Pratik Bhatu[7*]

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MIT, USA[1] | IIIT Delhi, India[2] | CISPA Saarland University, Germany[3] | Purdue University, USA[4] | MPI-SWS, Germany[5] | Microsoft Research, India[6] | AMD, India[7]
* Work done while the author was at Microsoft Research, India.

Computing on Confidential Information

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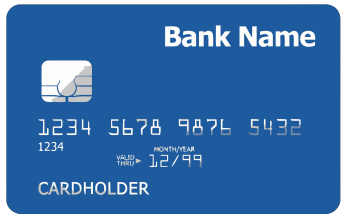
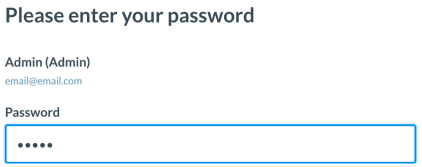


User credentials



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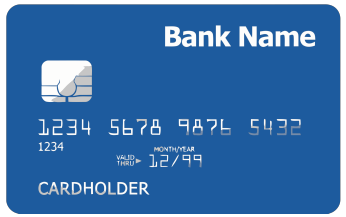

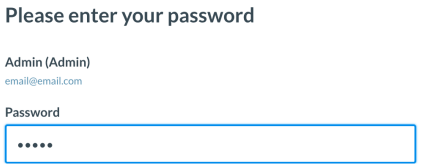

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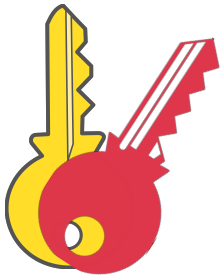
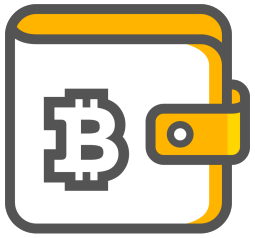
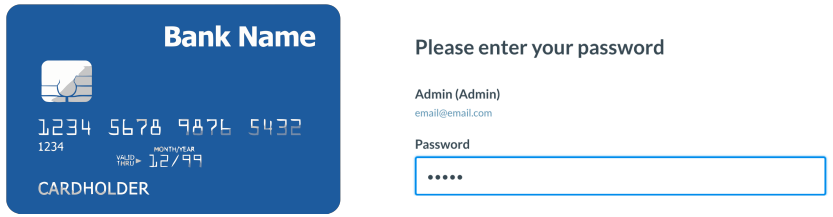




Cryptographic key pairs

Computing on Confidential Information



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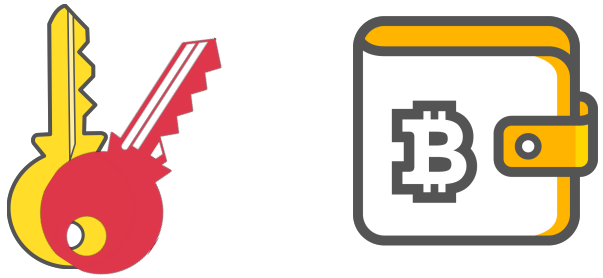

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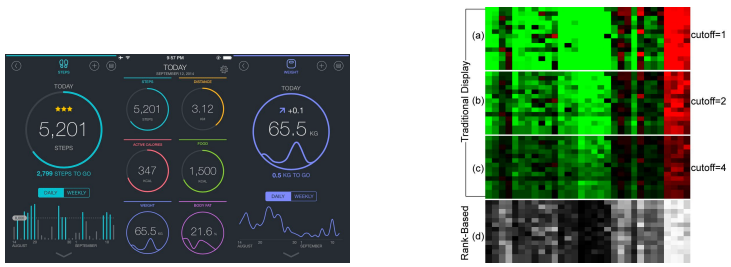

Confidential user health and genomic data

Image from - https://bmcbioinformatics.biomedcentral.com/articles/10.1186/1471-2105-6-115

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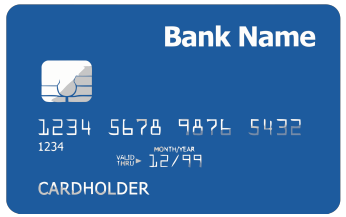

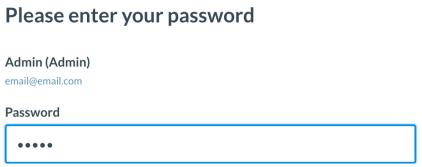

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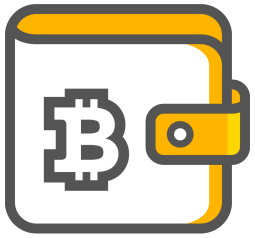

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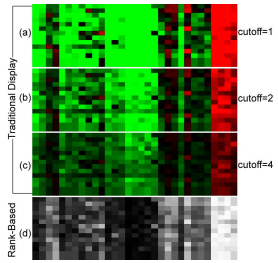

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Cloud infrastructure

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Securing the data – *Always*!

Data at rest

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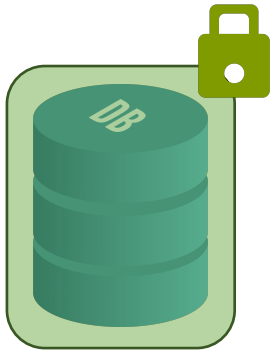

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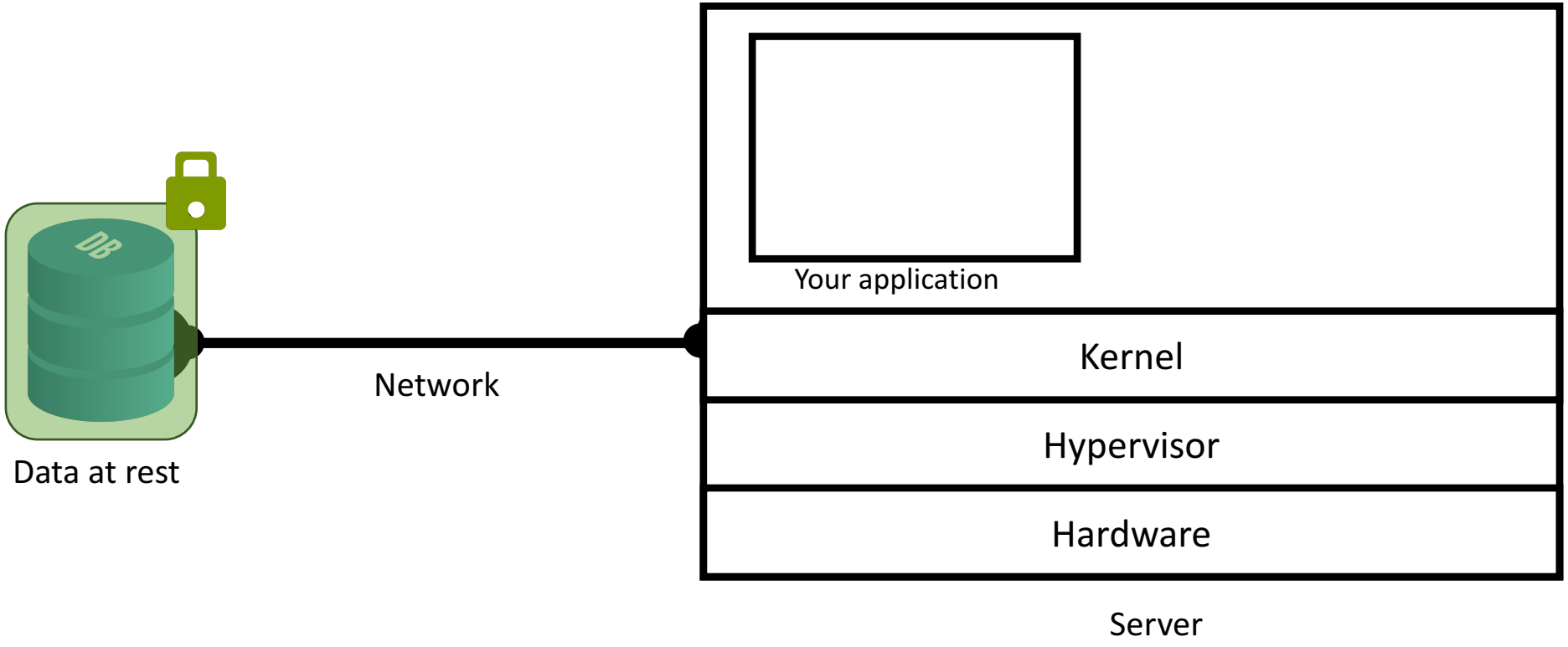

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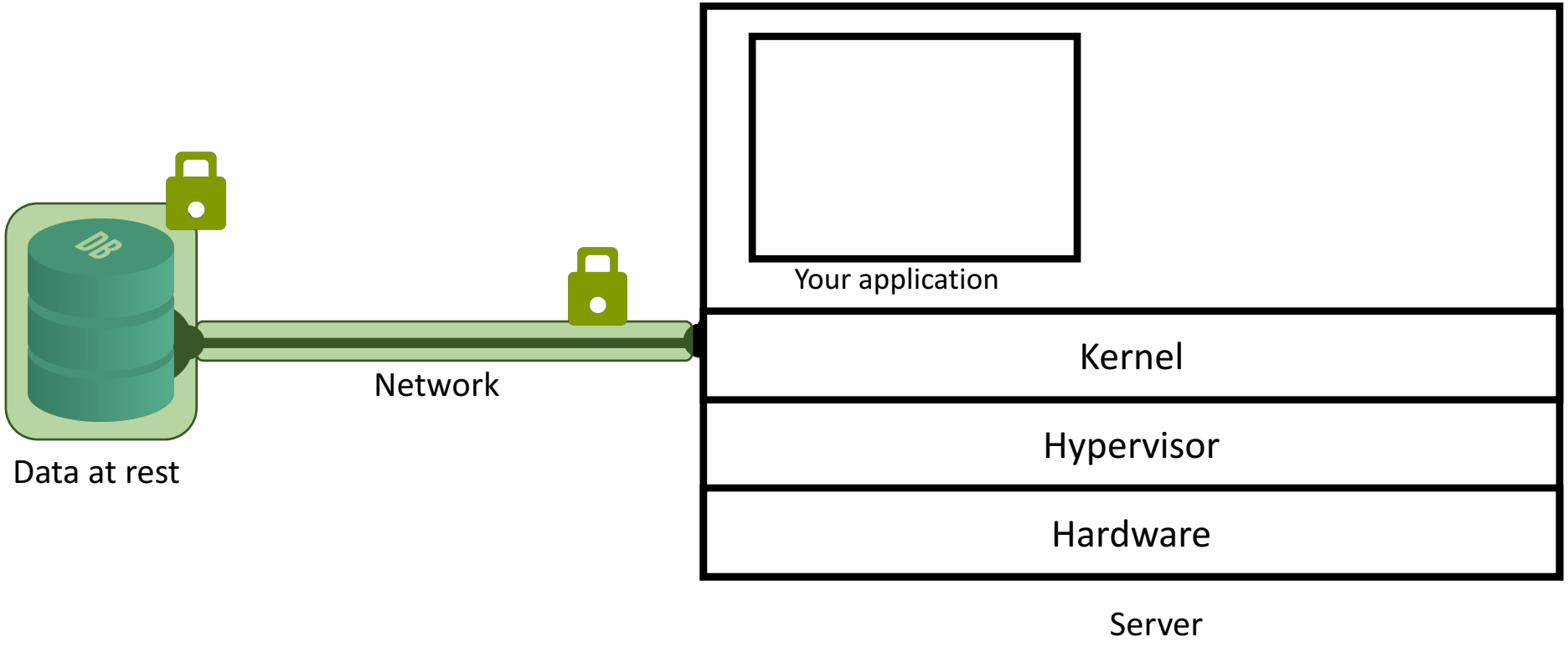

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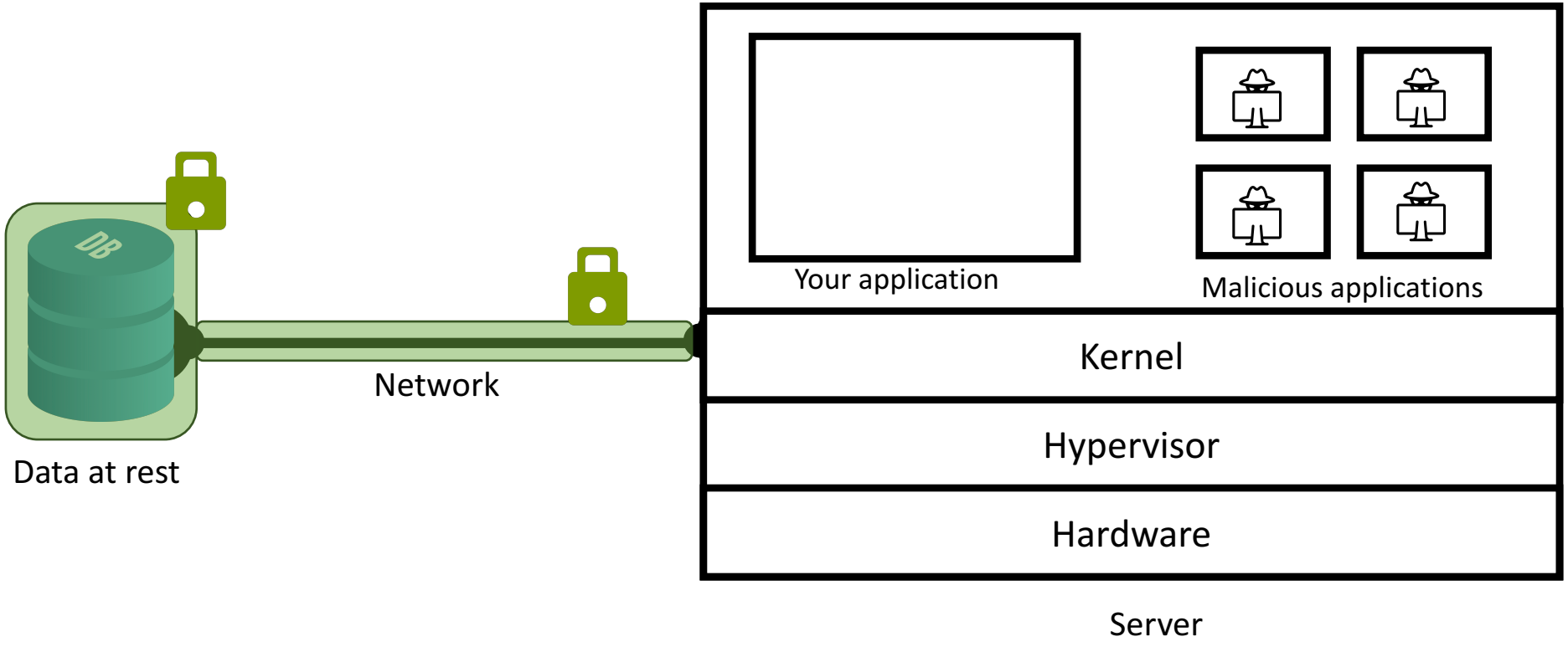

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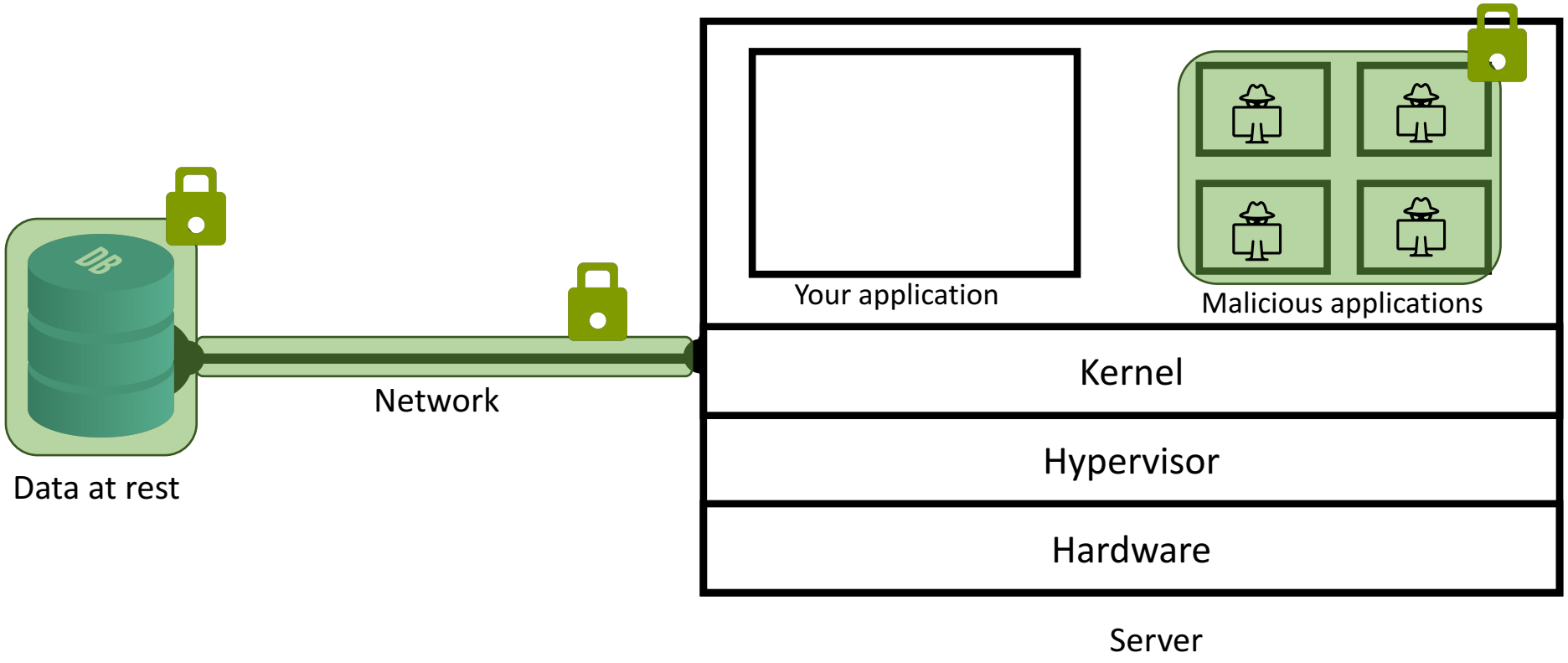

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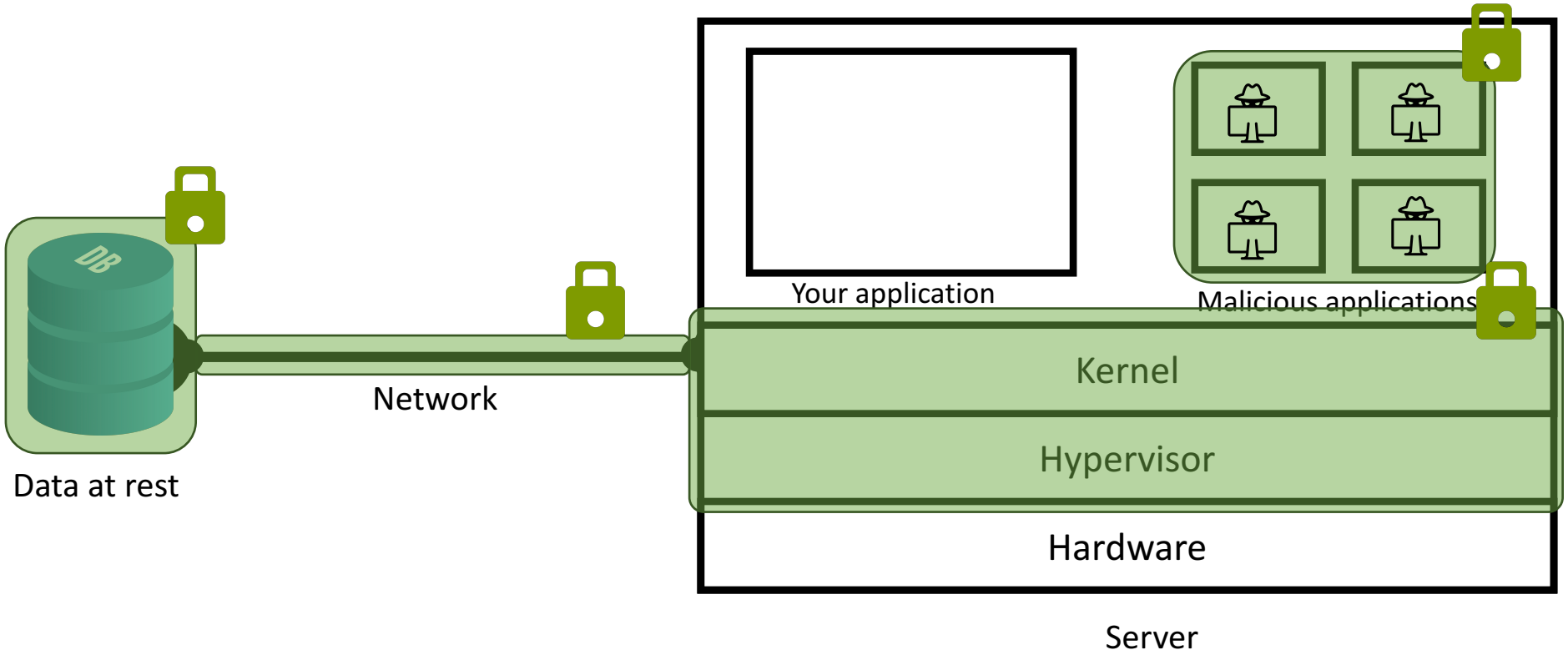

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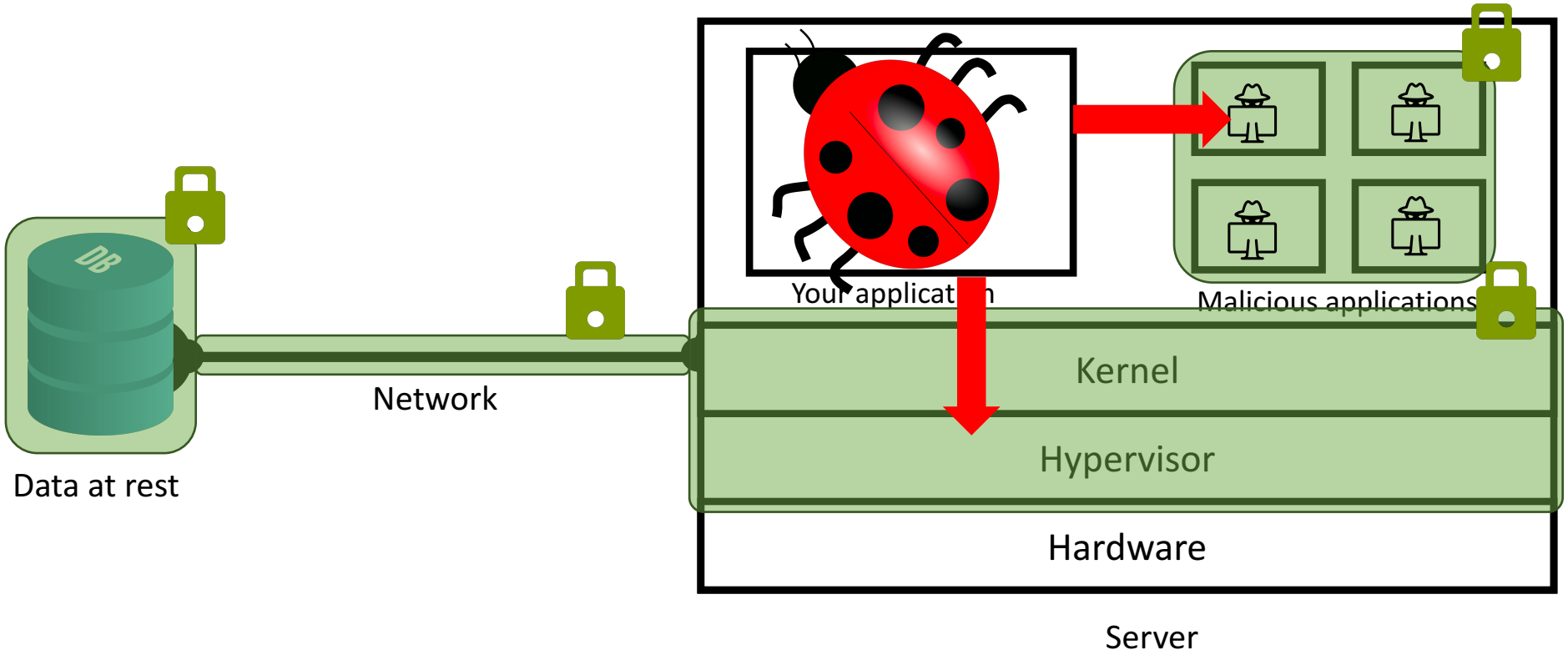

Exploiting bugs in applications

```
void handleReq(char *uname, char * upasswd, char *fname, char *out, int out_size) {
    char passwd [SIZE] , fcontents [SIZE];
    read_password ( uname , passwd , SIZE );
    if (!( authenticate (uname, upasswd, passwd ))) {
        return;
    }

    send(log_file, passwd, SIZE );

    read_file(fname, fcontents, SIZE );


    memcpy(out, fcontents, out_size );


    sprintf(out + SIZE, fmt, "Request complete");
    return;
}
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    //a bug in the fmt string can print stack contents
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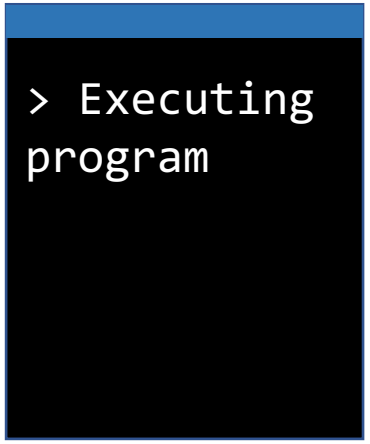
Securing data from bugs



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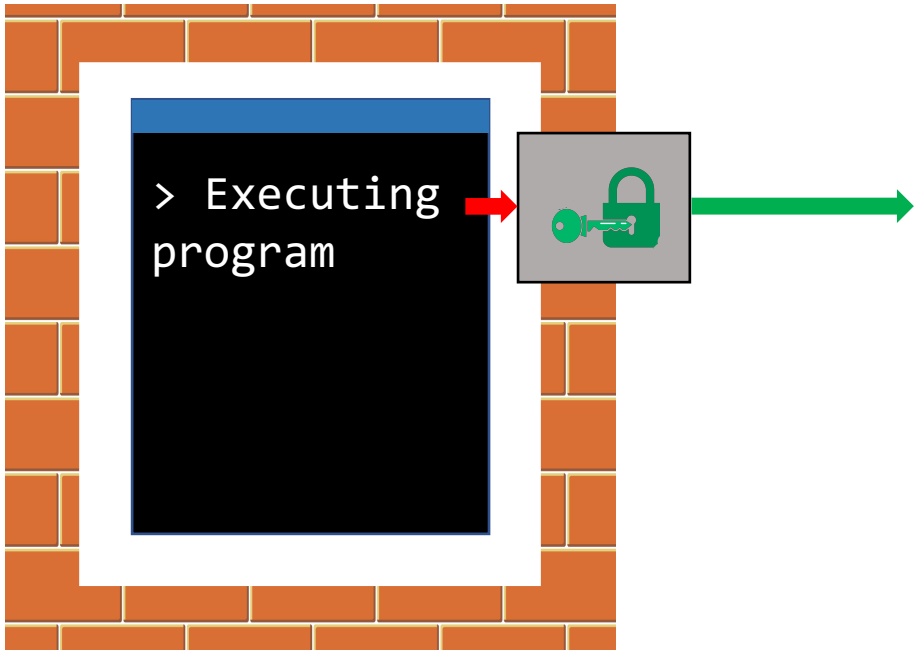

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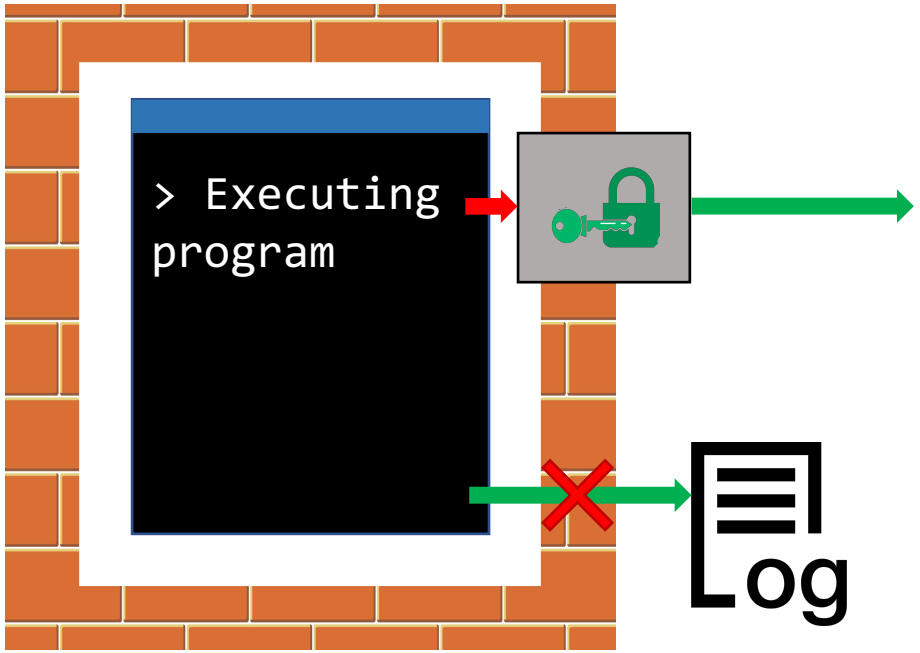

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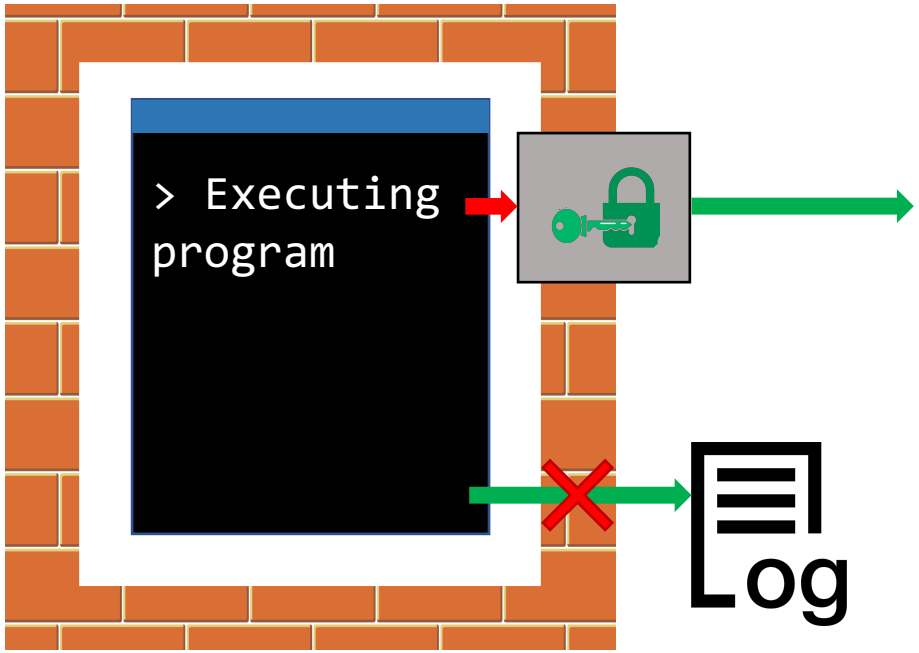


```
int averageSalary(int salaries[], int count) {
    int totalSalary = 0;
    for (int i = 0; i < count; i++)
        totalSalary += salaries[i];
    int average = totalSalary / count;
    return average;
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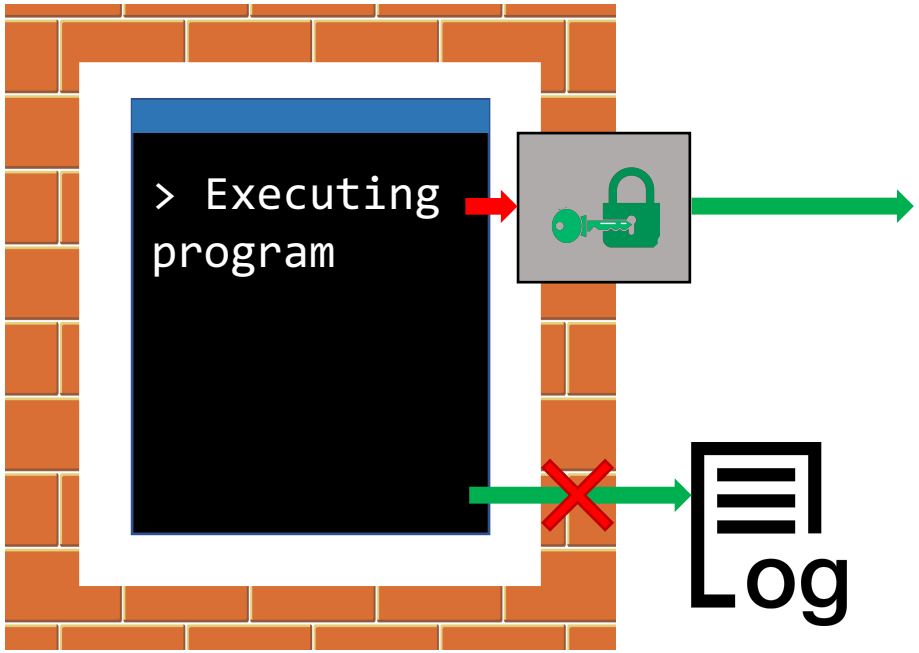


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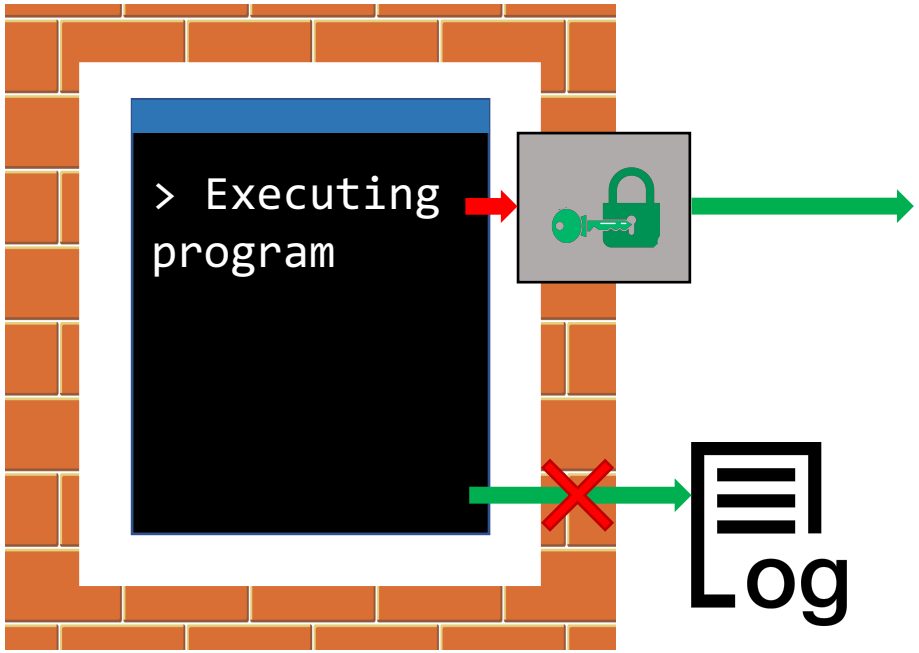


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Information Flow Control / Taint Tracking

Information Flow Control

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- Static analysis techniques
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- Complete memory and type safety
  - Necula *et al*. (2005)– “Ccured: type-safe retrofitting of legacy software”
  - Nagarkatte *et al*. (2009)– “SoftBound: highly compatible and complete spatial memory safety for C”

Introducing ConfLLVM

Taint tracking in ConfLLVM

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int bar (int * a, int * b, int * c, int i) {
     int b_val = b[i];
     int c_val = c[i];
     int a_val = b_val + c_val;
     a[i] = a_val;
     return a_val;
}
```

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r1 = b + i          ;
r2 = load [r1]      ; b_val = b[i]
r3 = c + i          ;
r4 = load [r3]      ; c_val = c[i]
r5 = add, r4, r2    ; a_val = b_val + c_val
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Tracking taints of

1. Registers
2. Bytes in memory

Taint tracking in ConfLLVM

```
int bar (int * a, int * b, int * c, int i) {
     int b_val = b[i];
     int c_val = c[i];
     int a_val = b_val + c_val;
     a[i] = a_val;
     return a_val;
}
```

```
r1 = b + i          ;
r2 = load [r1]      ; b_val = b[i]
r3 = c + i          ;
r4 = load [r3]      ; c_val = c[i]
r5 = add, r4, r2    ; a_val = b_val + c_val
r6 = a + i          ;
store r5, [r6]      ; a[i] = a_val
ret r5              ; return a_val
```

Tracking taints of

1. Registers
2. Bytes in memory

If we know the taint of each byte we load from memory, we do not have to track the taints of the registers at runtime!

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Inferring taints of registers statically

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int bar (int *, int*, int*, int);


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```
/* foo.c */

int foo() {
    private int a[16];
    ...
    bar(a, ..., 1024);
}
```

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r1 = b + i

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r3 = c + i

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r5 = add, r4, r2
r6 = a + i

store r5, [r6]
```

Inferring taints of registers statically

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/* bar.c */
private int bar (private int *a, private
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    private int a_val = b_val + c_val;
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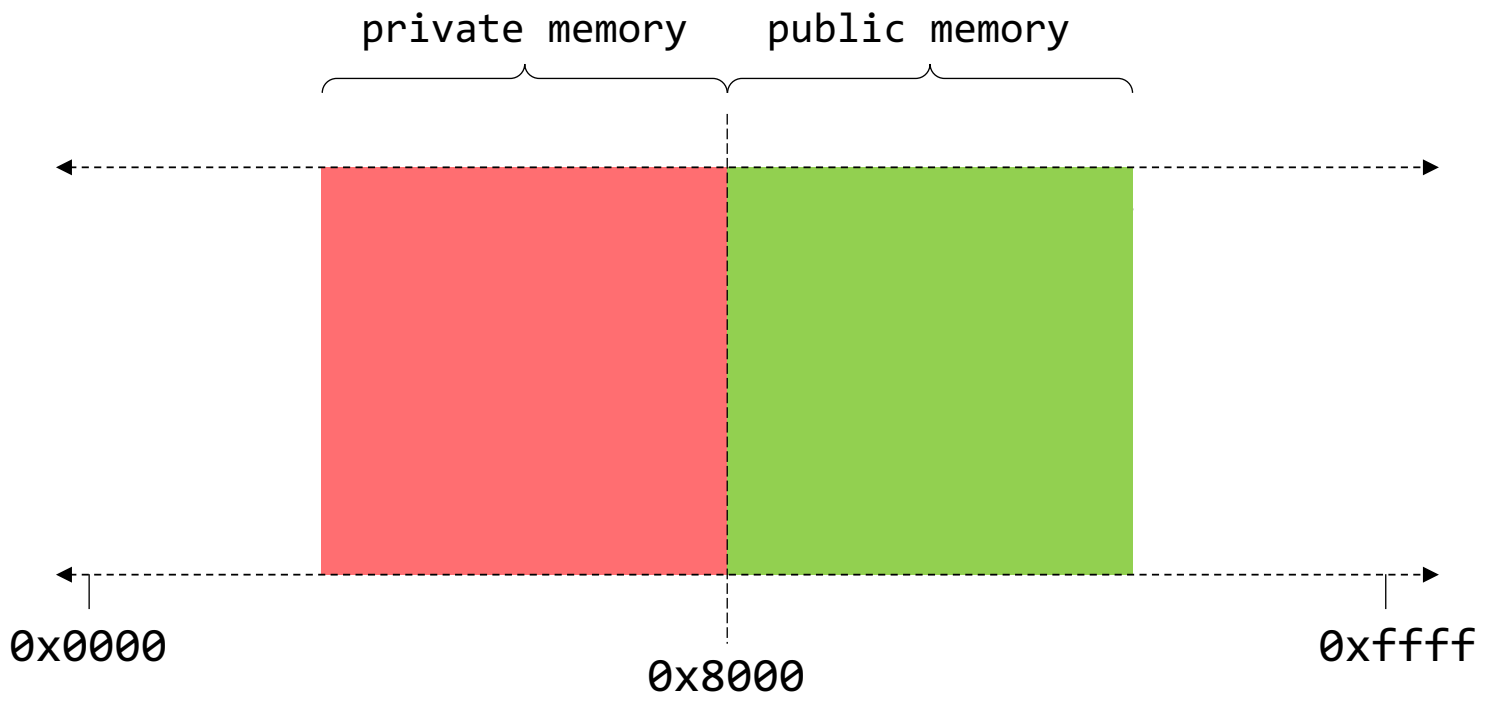
    return a_val;
}
```

```
/* foo.c */

int foo() {
    private int a[16];
    ...
    bar(a, ..., 1024);
}
/* bar.S */
r1 = b + i
check_taint_private([r1])
r2 = load [r1]
r3 = c + i
check_taint_public([r3])
r4 = load [r3]
r5 = add, r4, r2
r6 = a + i
set_taint_private([r6])
store r5, [r6]
```

Improving memory checks

Improving memory checks



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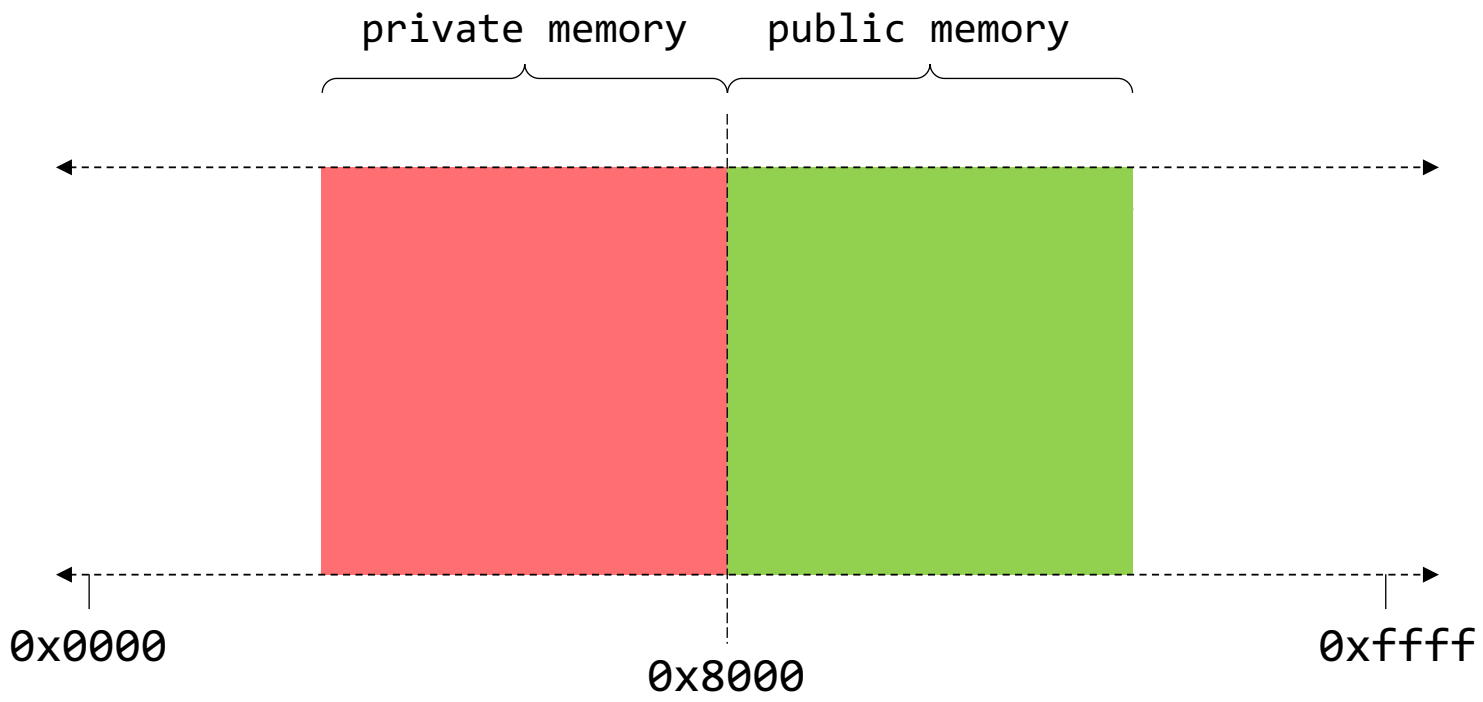

check_taint_private([x]) = assert(x < 0x8000);

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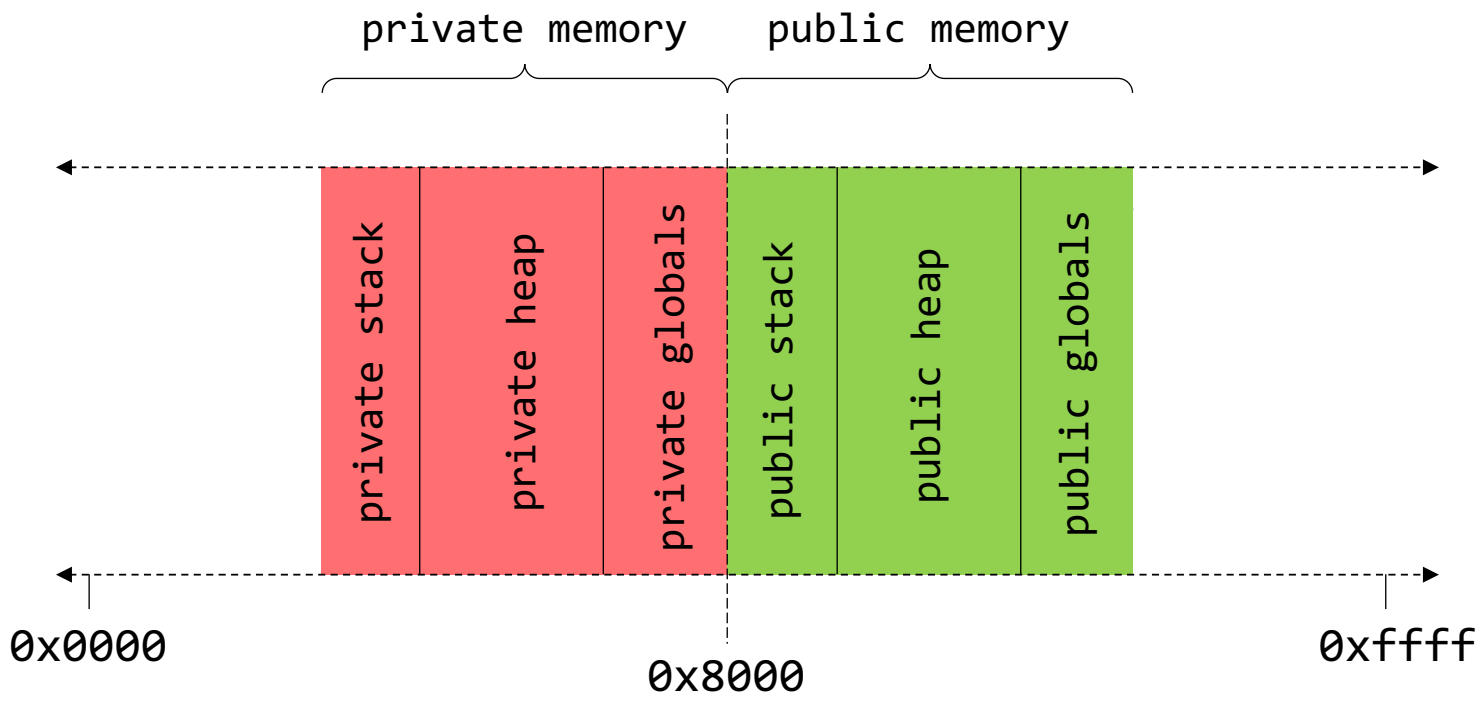

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Improving memory checks

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- Intel MPX
  - `bnd0 – bnd3` – 128 bit registers to hold upper and lower bounds
  - `bndcu [x], bnd0` – check if the address [x] is lower than the upper bound stored in bnd0
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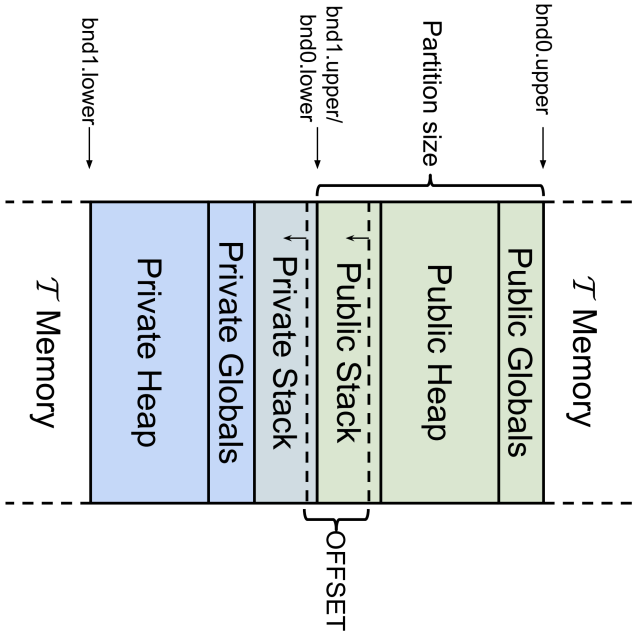



```
check_taint_private([x]) = bndcu [x], bnd1
                           bndcl [x], bnd1

check_taint_public ([x]) = bndcu [x], bnd0
                           bndcl [x], bnd0

Public local load  -   mov   rax, [rsp + 8]

Private local load -   mov   rax, [rsp + 8 – OFFSET]
```

Improving memory checks

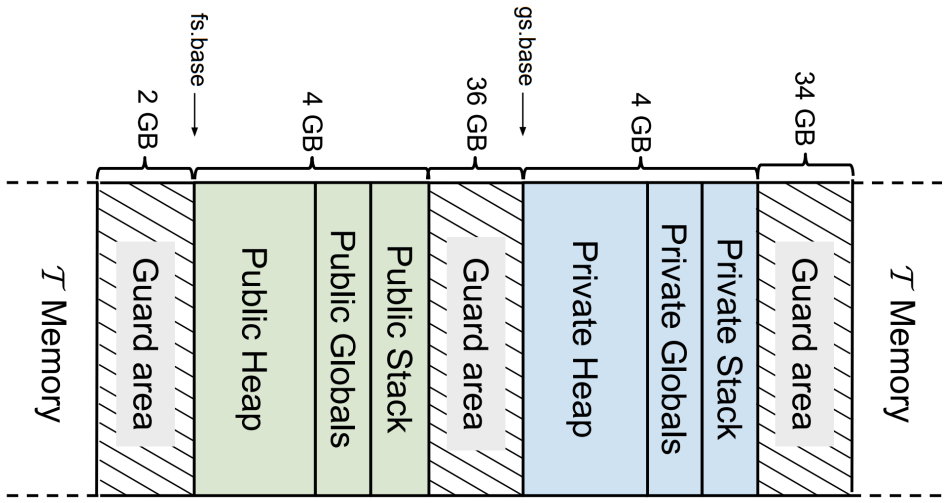
Improving memory checks

- Intel X64 segment registers
  - `gs and fs segment registers` – user can control gs.base and fs.base
  - `mov eax, gs: [ebx]` – loads [gs.base + ebx] into eax;

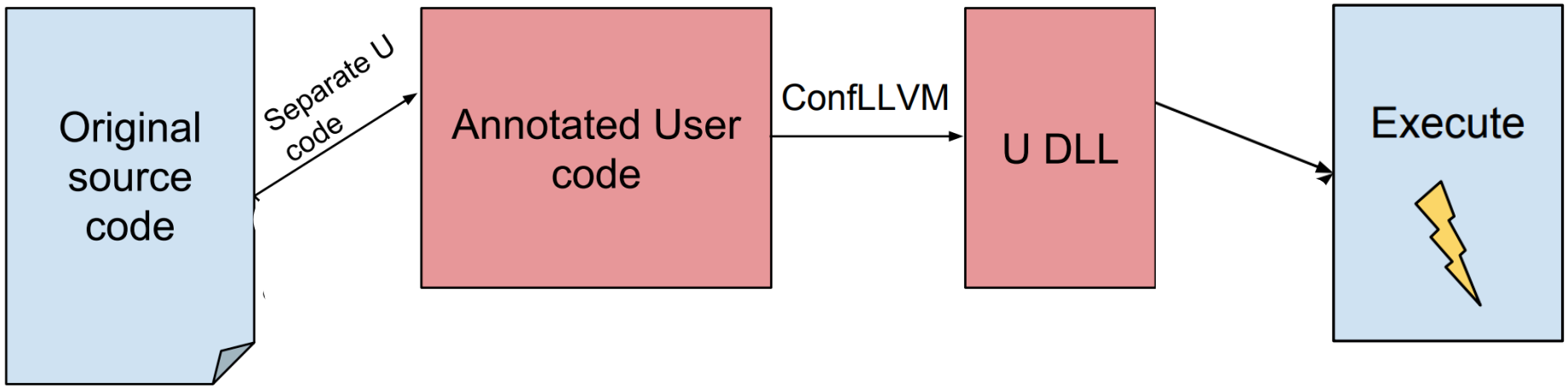
Improving memory checks

- Intel X64 segment registers
  - `gs and fs segment registers` – user can control gs.base and fs.base
  - `mov eax, gs: [ebx]` – loads [gs.base + ebx] into eax; checks if ebx < gs.limit

  - `mov rax, [rbx + rcx * 8]` → `mov rax, gs:[ebx + ecx * 8] // Private load`
  - `mov rax, [rbx + rcx * 8]` → `mov rax, fs:[ebx + ecx * 8] // Public load`
  - `mov [rbx + rcx * 8], rax` → `mov gs:[ebx + ecx * 8], rax // Private store`
  - `mov [rbx + rcx * 8], rax` → `mov fs:[ebx + ecx * 8], rax // Public store`



Trusted code



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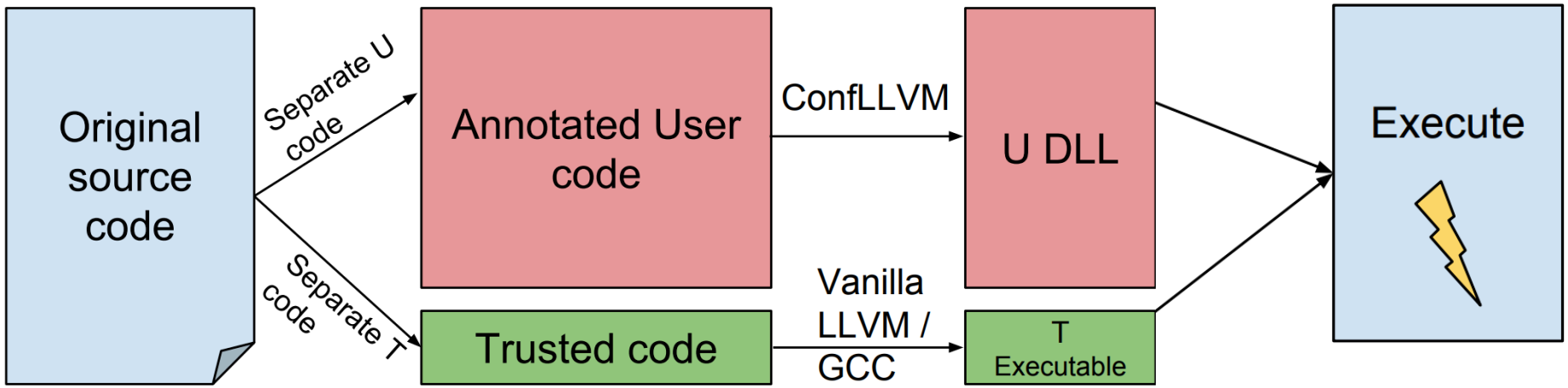

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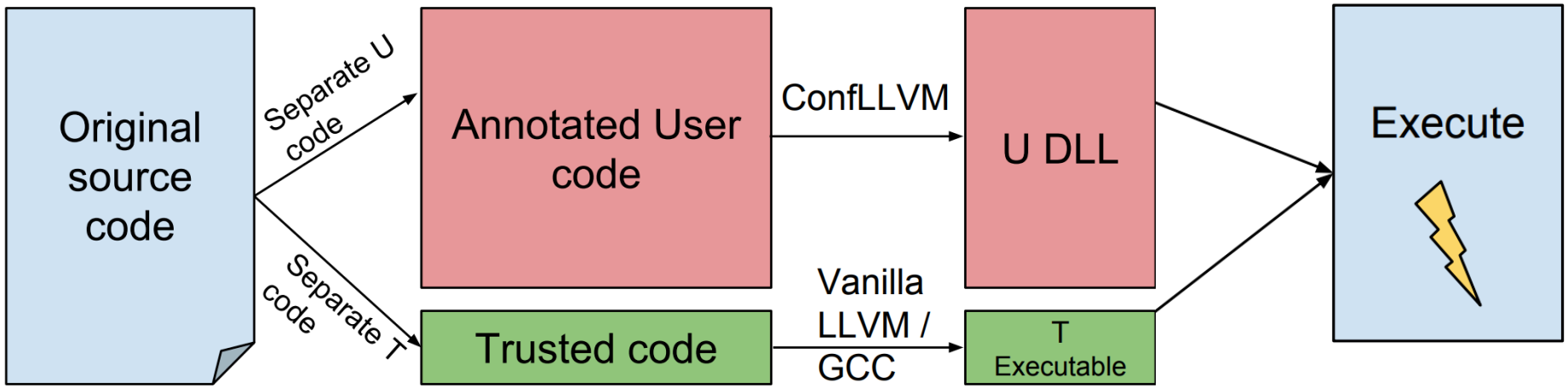



```
void encrypt (private char * plain_text, int plain_text_size, char * cipher_text, int
cipher_text_size);

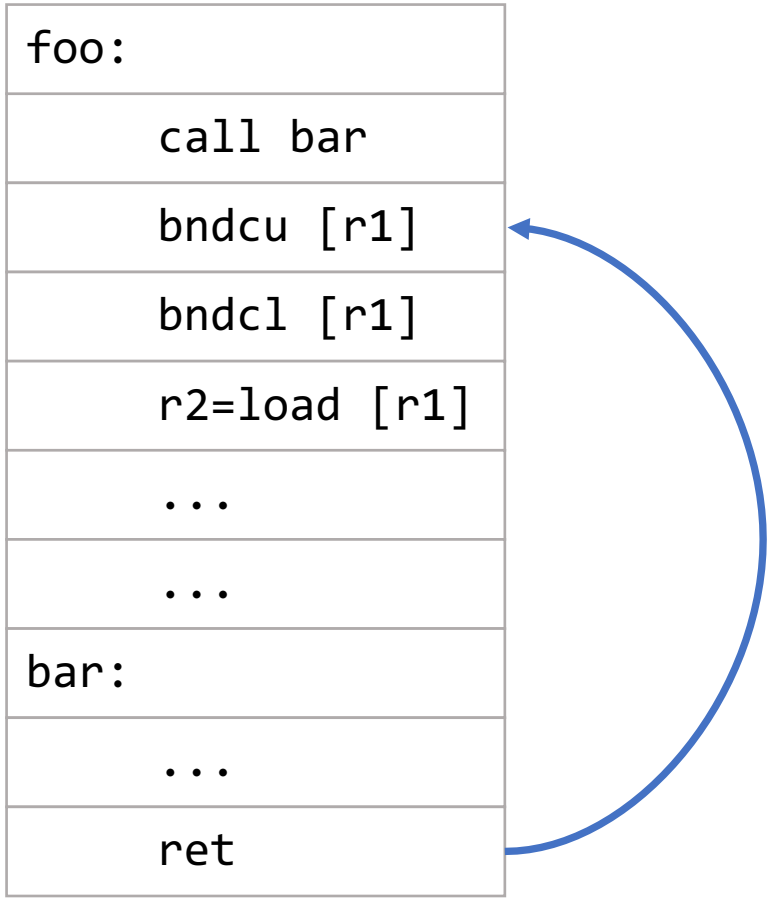
void decrypt (char * cipher_text, int cipher_text_size, private char * plain_text, int
plain_text_size);
```

Control Flow Integrity

Control Flow Integrity

```
foo:
      call bar
      bndcu [r1]
      bndcl [r1]
      r2=load [r1]
      ...
      ...
bar:
      ...
      ret
```

Control Flow Integrity



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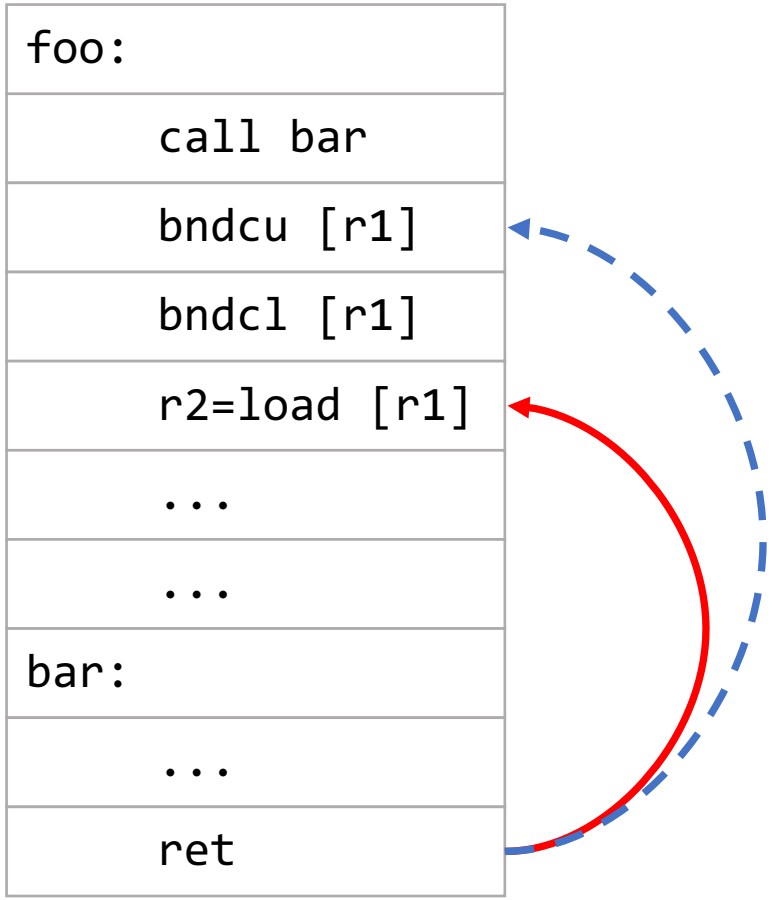

Buffer overflow in bar corrupts the return value!

Control Flow Integrity

- Potential threats –
  - Indirect jumps
  - Indirect calls
  - Call return sites

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- Potential threats –
  - Indirect jumps
  - Indirect calls
  - Call return sites

- Need to check –
  - If the target is a valid jump site
  - The target expects the same taints on the registers as current registers

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- Insert magic strings before function start and after call instructions

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```
foo:
        ...
        callq bar
        #MAGIC_STRING+0001 //private return
          ...

bar:
        ...
        popq %r11
        //Check before return
        cmpq ($r11), #MAGIC_STRING+0001
        jne REPORT_ERROR
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```

```
foo:
        movq      $bar, %r10
        ...
        // 1010 – taints of args encoded
        cmpq -8(%r10), #MAGIC_STRING+1010
        jne REPORT_ERROR
        callq *%r10
        ...

        // taint of expected args encoded
        #MAGIC_STRING+1010
bar:
        ...
```

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- Bugs in the compiler can break all the guarantees

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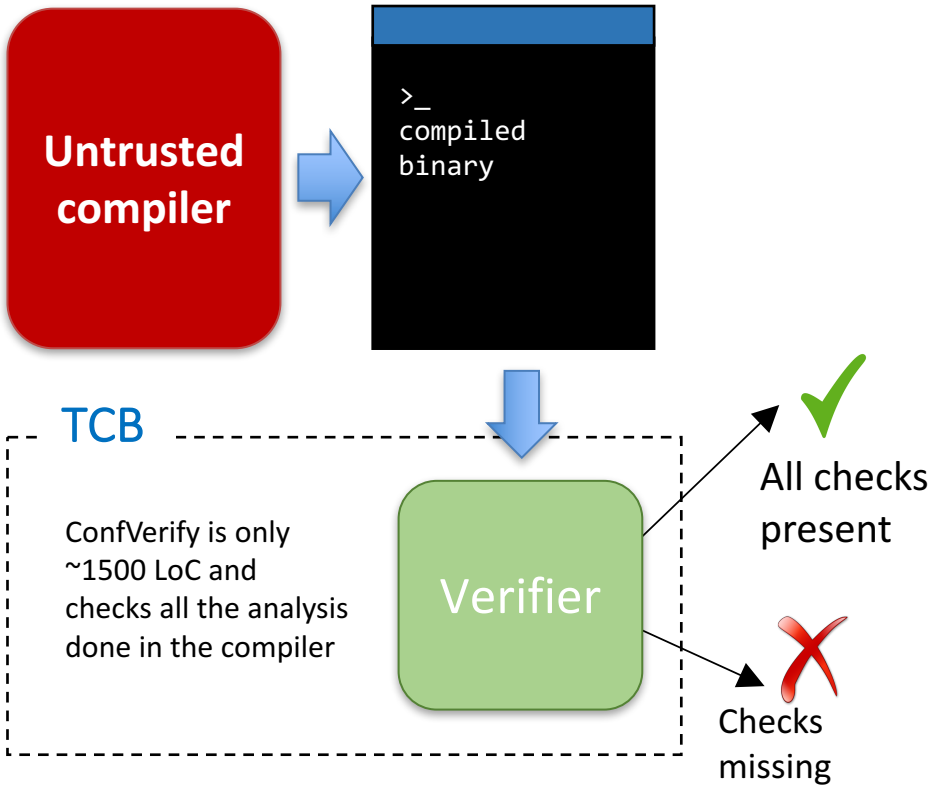

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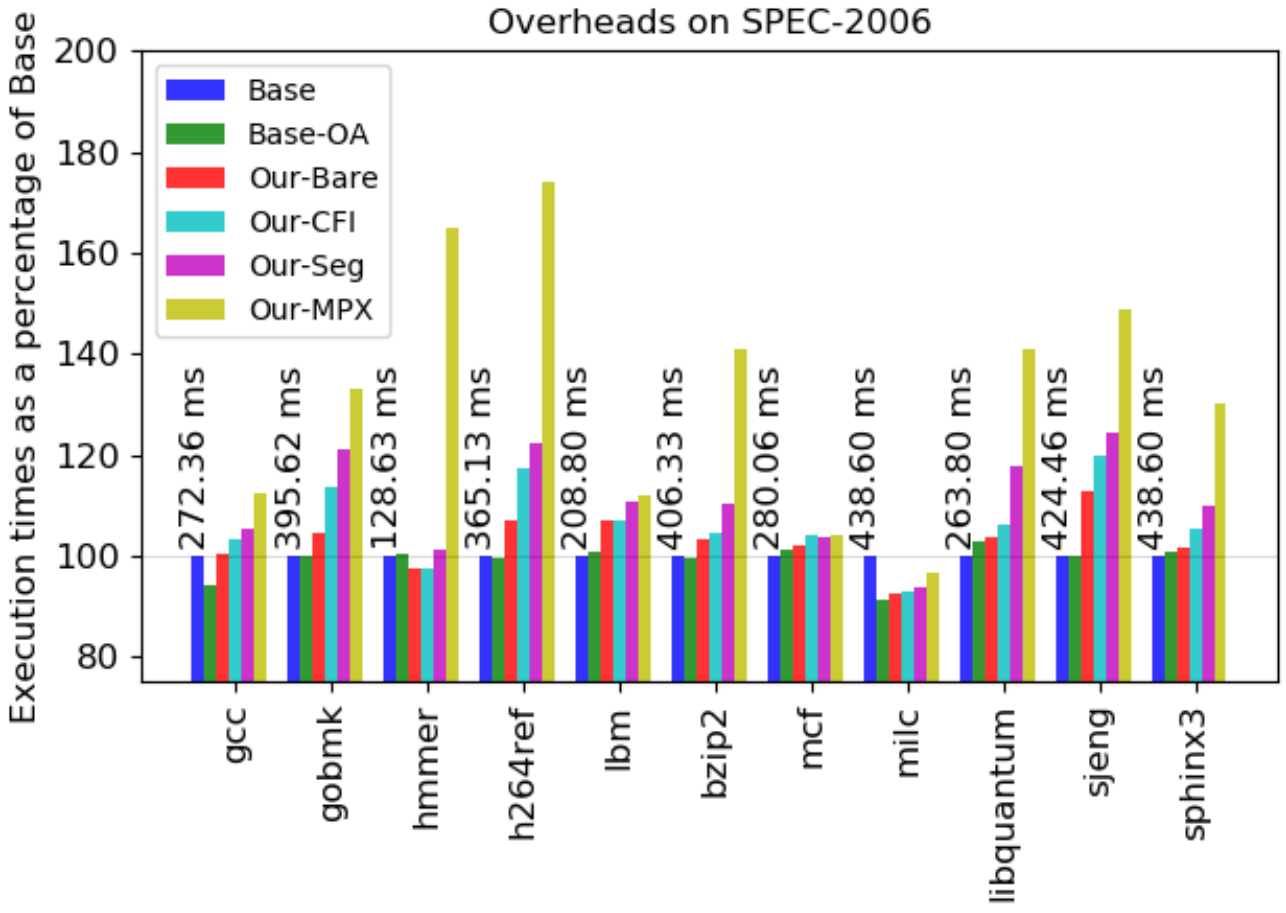
- Applications
  - Spec 2006 C benchmarks
  - OpenLDAP
  - Nginx web server
  - ML prediction inside Intel SGX

Evaluations – spec 2006

- Everything inside the applications is public
- Understand the runtime overheads



All benchmarks run on a Microsoft Surface Pro-4 Windows 10 machine with an Intel Core i7-6650U 2.20 GHz 64-bit processor with 2 cores (4 logical cores) and 8 GB RAM.

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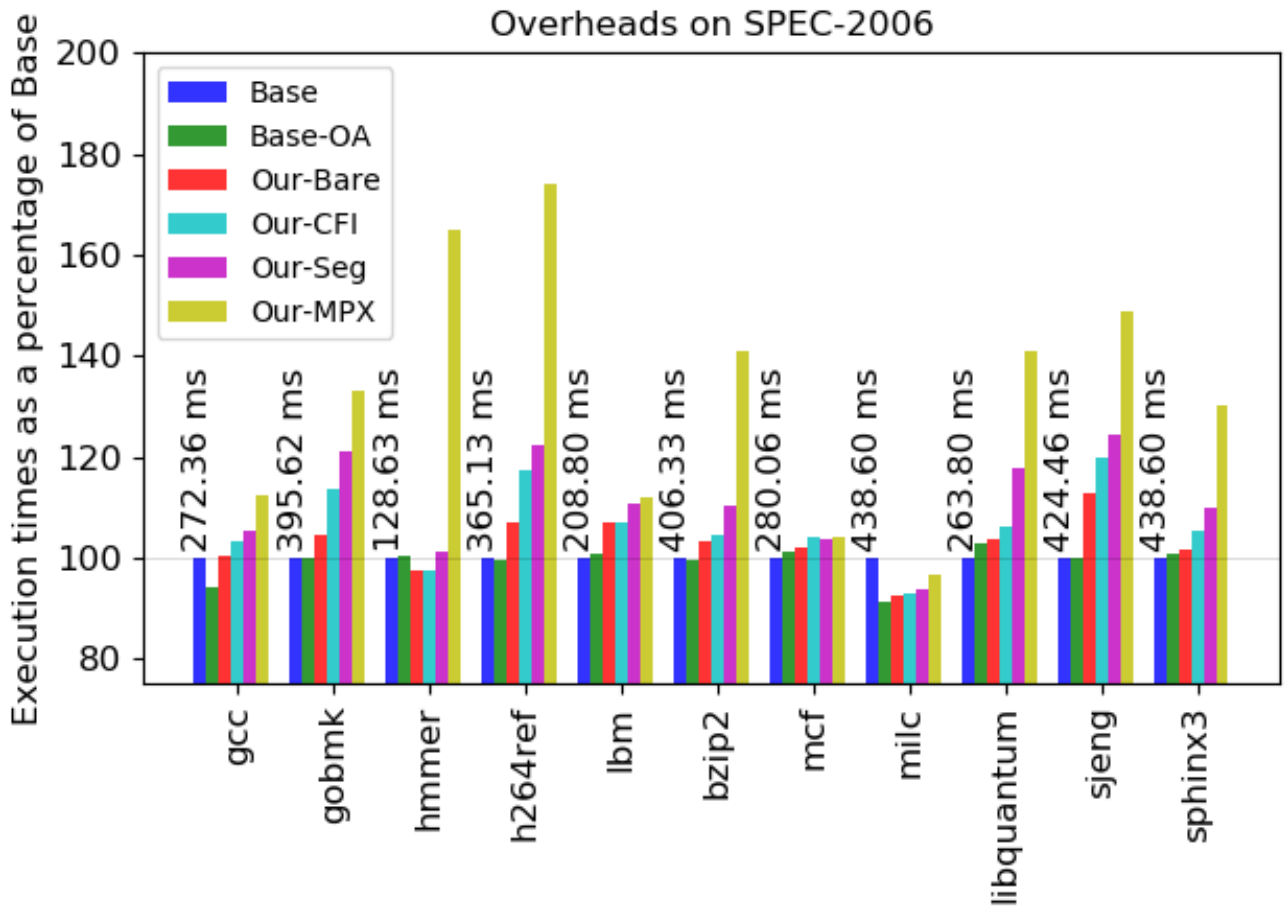

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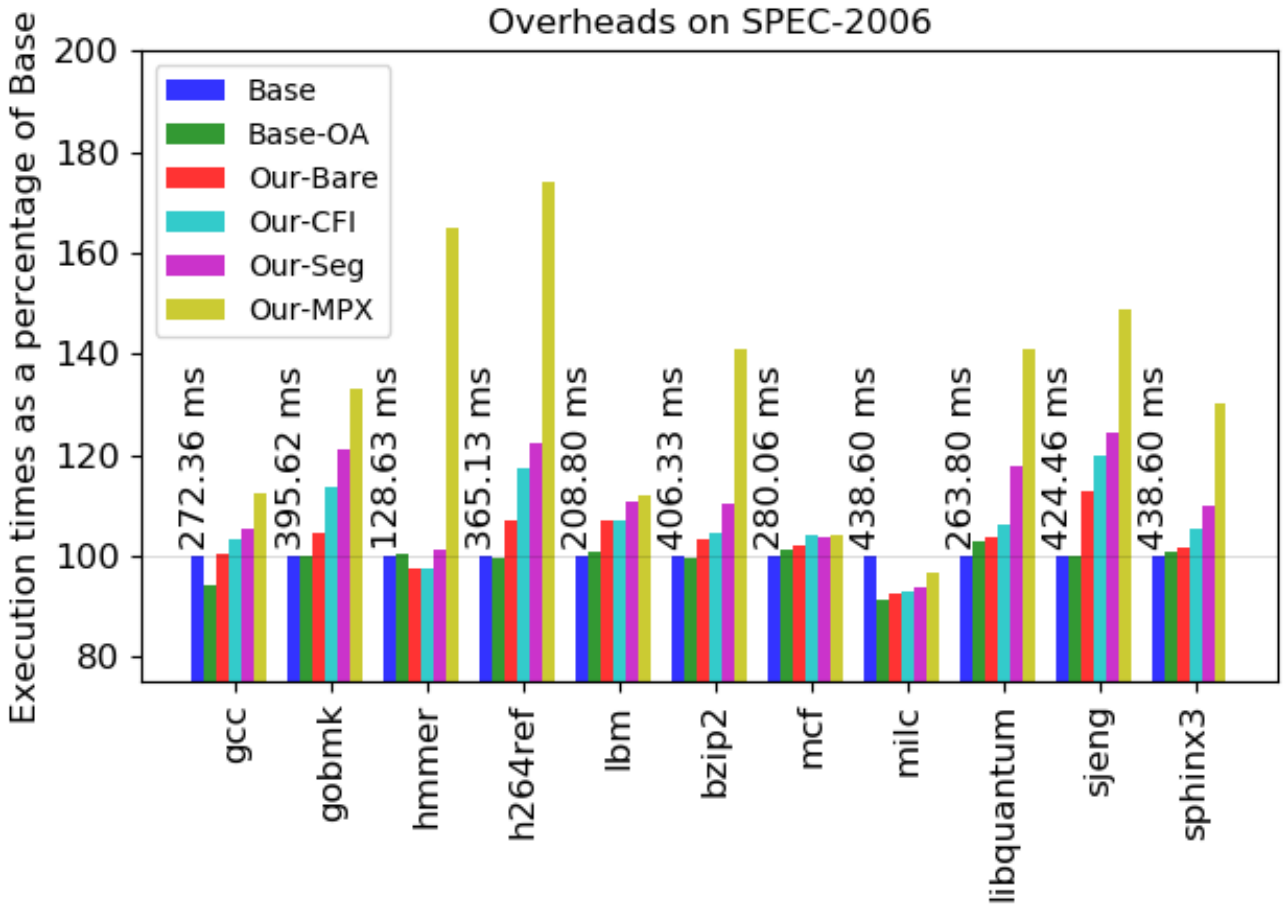

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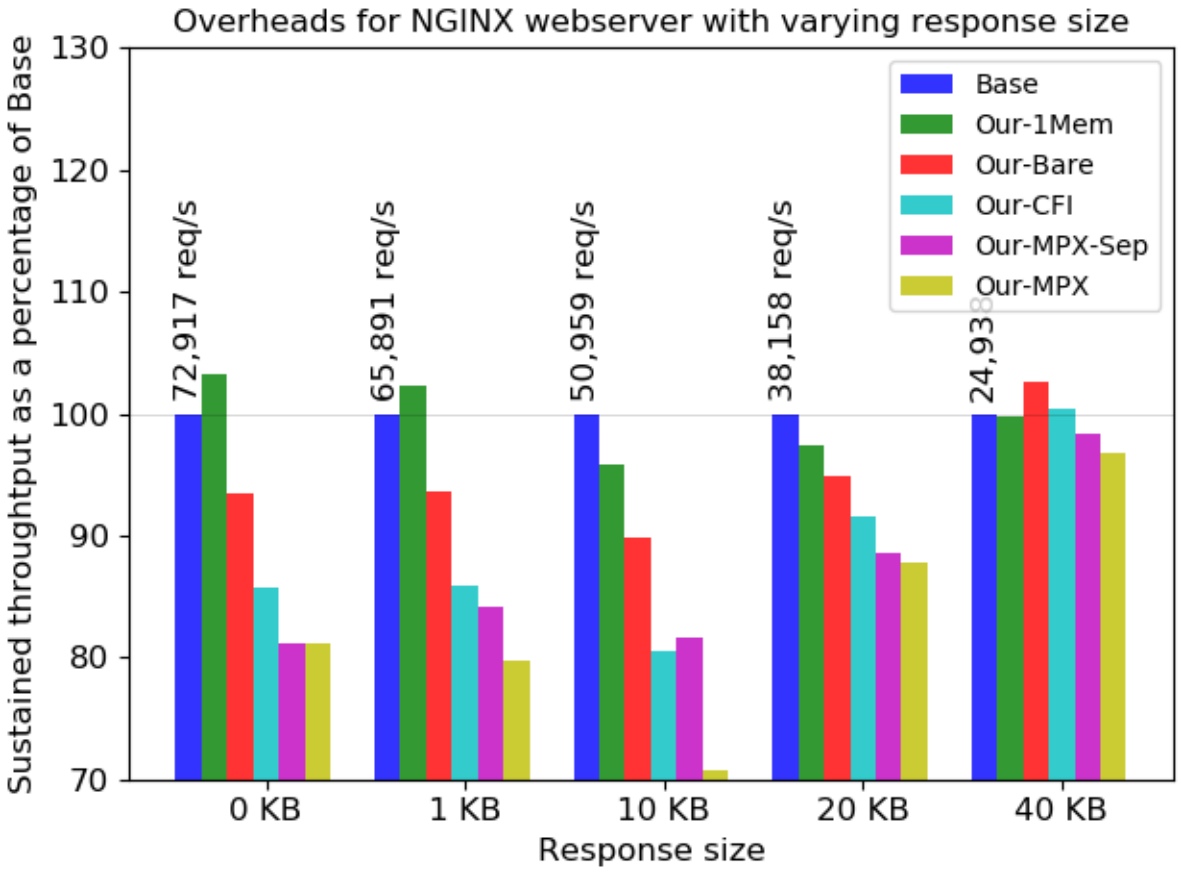
Evaluations - NGINX

- Everything except logs marked private



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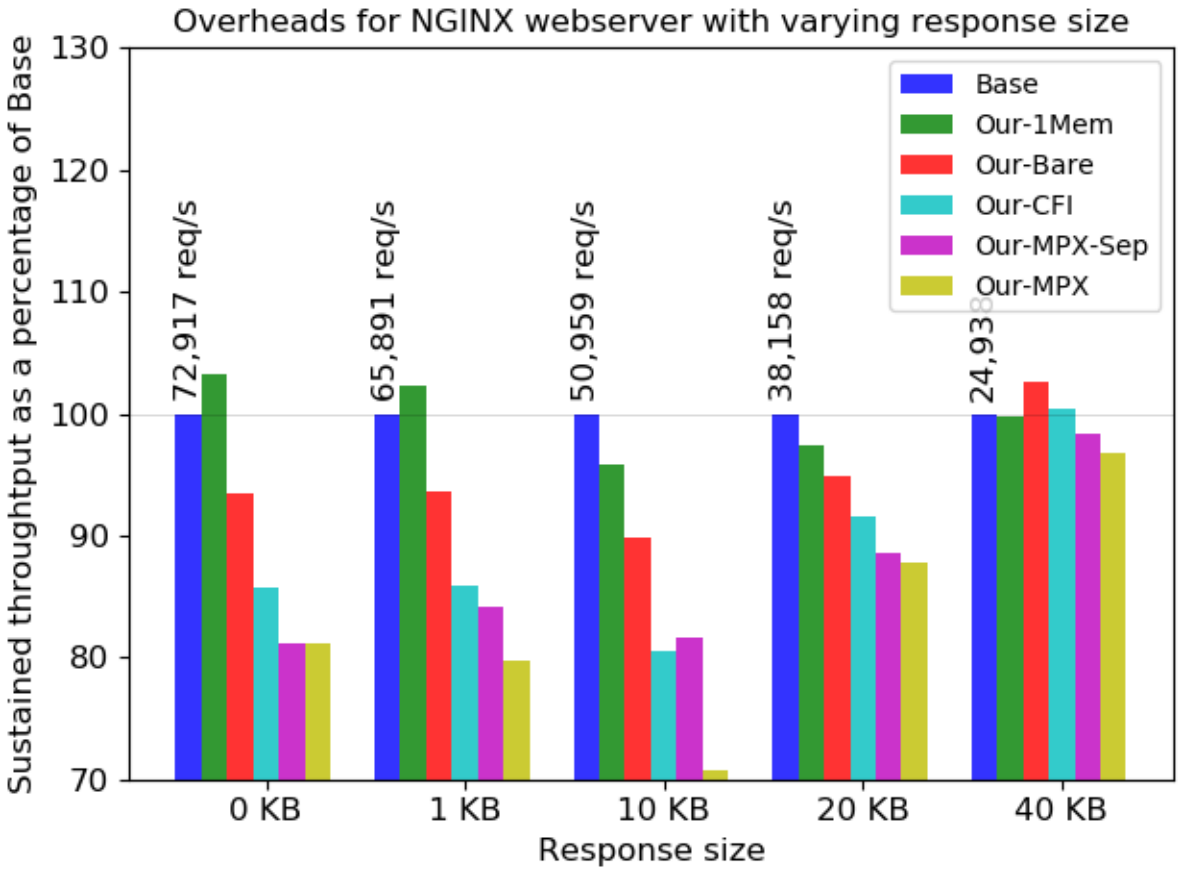
Out of the total 124,001 lines of code, 160 lines had to be modified and 138 lines added for the trusted code (encryption + interface with operating system)

Evaluations - Nginx

- User passwords marked as private



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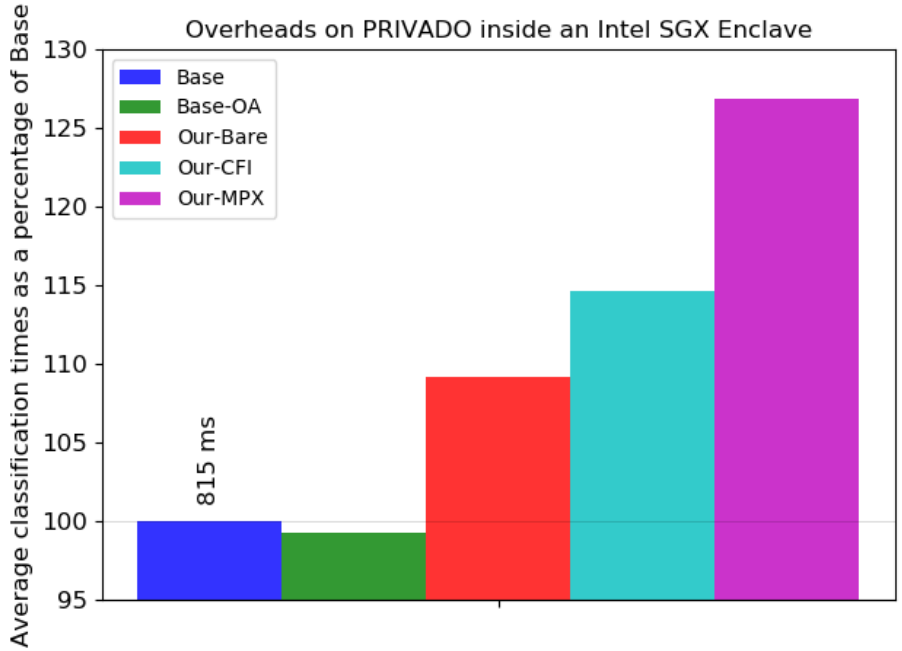
- Image classification algorithm run inside Intel SGX
- All data marked as private including the model and user data
- The classification result declassified and sent out over the network



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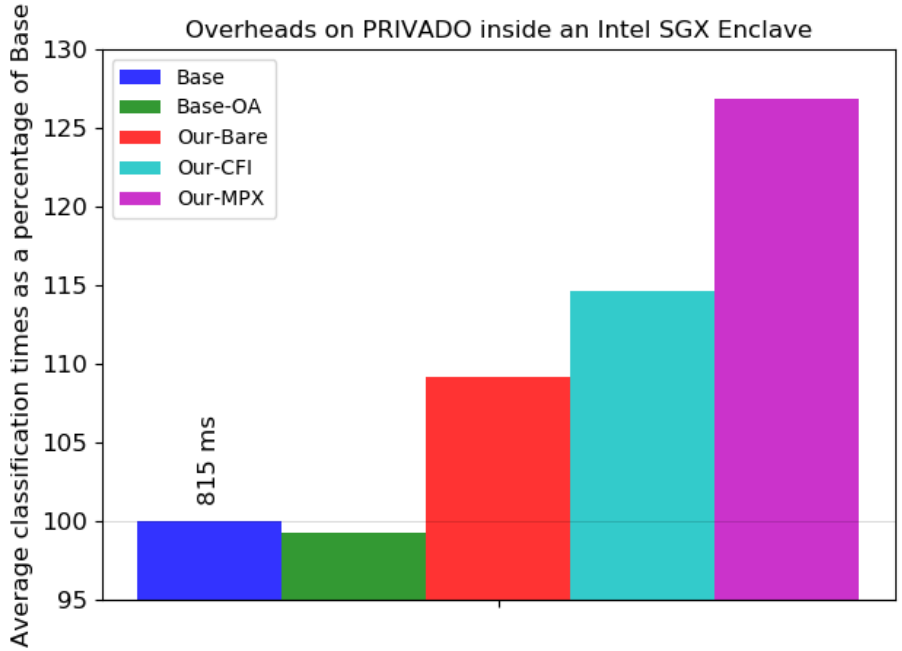

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Correctness guarantee

- Meta theory proof
- Relies on the invariants checked in ConfVerify
- Proves termination sensitive non interference on private data (assuming that the trusted components are non interfering)

- Proof available as a technical report - https://arxiv.org/abs/1711.11396

Summary

- ConfLLVM a compiler technique for Information Flow Control that uses combination of static and dynamic analysis to ensure that the private data doesn’t leak out through clear text channels
- Novel memory partitioning technique for efficiently checking taints of data in memory
- A lightweight Control Flow Integrity technique that provides just enough guarantees for the IFC property
- Trusted Code Base potentially reduced to ~1500 LoC

https://bmcbioinformatics.biomedcentral.com/articles/10.1186/1471-2105-6-115 -- genomic data image