Execution Domain Transition: Binary and LLVM IR can run in conjunction

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Background

- **Multi-CPU, Single Host Analysis Platform**
  - To analyze Multi-arch Linux malware
    - The source code of Mirai opened 6 years ago
    - The variations of Mirai are still attacking IoT systems today
  - To prepare execution environment of each CPU architecture

*Mirai Source Code ⟫ compile ⟫ intel, ARM, MIPS Technologies, PowerPC, AMD ⟫ attack ⟫ Multi-CPU arch. systems

- **No Source code, Only Binary**
  - Most Analysts has not knowledge about every CPU architecture
  - There are huge cost to build all virtual machine environment
  - So, we will analyze binaries using CPU-independent IR

※ https://github.com/jgamblin/Mirai-Source-Code

Background : Binary Lifting

- **LLVM IR from a source code**

※ clang -emit-llvm -fno-discard-value-names -S test.c -o test.ll

_test.c

```
int64_t bar(){
 int64_t var = 1;
  return var;
}

int64_t foo(){
 int64_t foovar = bar()+1;
  return foovar;
}

int64_t doo(){
 int64_t doovar = foo()+1;
  return doovar;
}
int64_t car(){
 int64_t carvar = doo()+1;
  return carvar;
}
```

Code Symbols

Source Code

_test.ll

```
...
define i64 @doo() #0 {
entry:
  %doovar = alloca i64, align 8
  %call = call i64 @foo()
  %add = add nsw i64 %call, 1
  store i64 %add, i64* %doovar, align 8
  %0 = load i64, i64* %doovar, align 8
  ret i64 %0
}

define i64 @car() #0 {
entry:
  %carvar = alloca i64, align 8
  %call = call i64 @doo()
  %add = add nsw i64 %call, 1
  store i64 %add, i64* %carvar, align 8
  %0 = load i64, i64* %carvar, align 8
  ret i64 %0
}
```

Code Symbols

LLVM IR from Source Code

Background : Binary Lifting

- **Lifted IR and Binary comparison**

_test

```
...
 0x400c20 <doo>:     push   %rbp
 0x400c21 <doo+1>:mov    %rsp,%rbp
 0x400c24 <doo+4>:callq  0x400c10 <foo>
 0x400c29 <doo+9>:add    $0x1,%eax
 0x400c2c <doo+12>:          pop    %rbp
 0x400c2d <doo+13>:          retq
...
 0x400c30 <car>:     push   %rbp
 0x400c31 <car+1>: mov    %rsp,%rbp
 0x400c34 <car+4>: callq  0x400c20 <doo>
...
```

Binary

_test.linked.ll (Lifted IR)

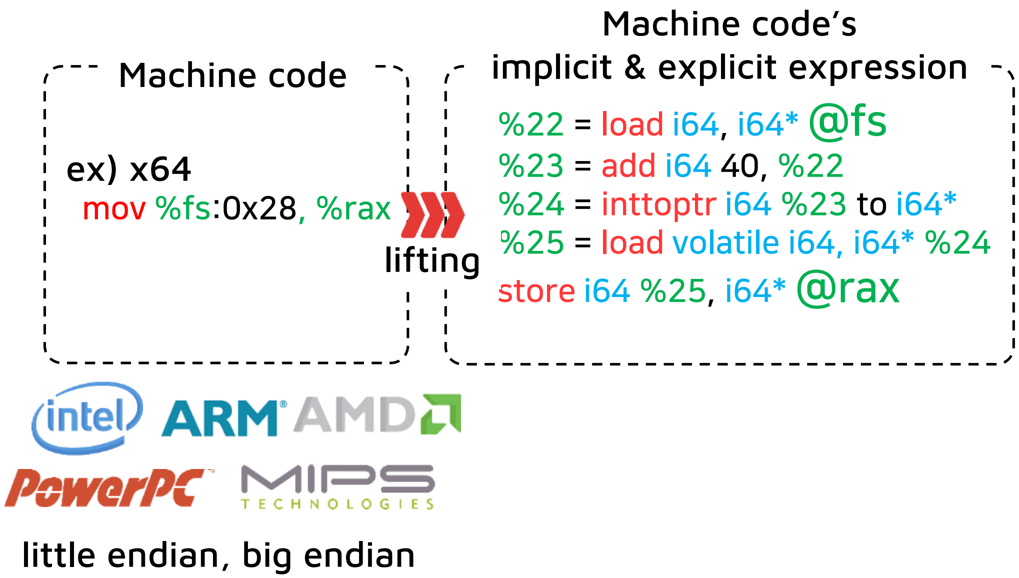
```
bb.car:
 %10 = load i64, i64* @rbp
 %11 = load i64, i64* @rsp
 %12 = sub i64 %11, 8
 %13 = inttoptr i64 %12 to i64*
 store volatile i64 %10, i64* %13
 store i64 %12, i64* @rsp
 %14 = load i64, i64* @rsp
 store i64 %14, i64* @rbp
 %15 = load i64, i64* @rsp
 %16 = sub i64 %15, 8
 %17 = inttoptr i64 %16 to i64*
 store volatile i64 4197433, i64* %17
 store i64 %16, i64* @rsp
 store volatile i64 4197408, i64* pc
 call void @doo_0x400c20_lifted(i64 4197433)
 br label %bb.car.0x9
...
```

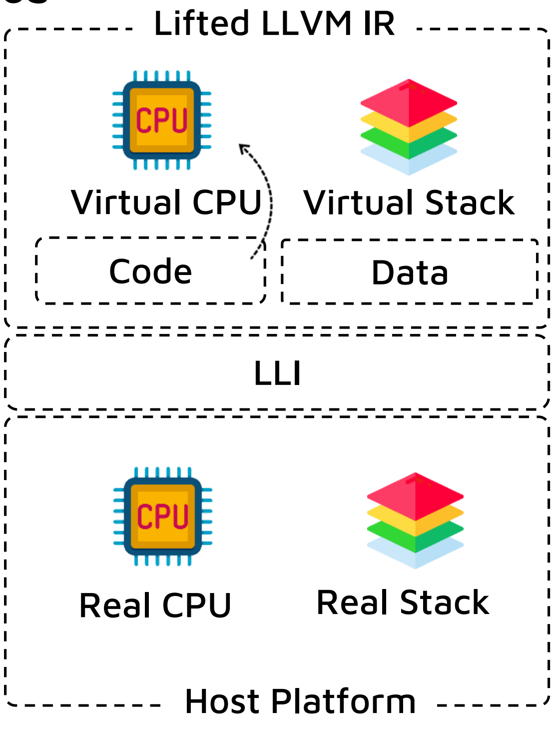
LLVM IR from Binary

Background : Virtual CPU, Virtual Stack

- **Tiny Virtual Machine in LLVM IR for supporting Multi-CPU Arch.**
  - Store the state to virtual CPU and Stack, neither real CPU and Stack.
  - We developed the LLI variation for Multi-CPU Binaries

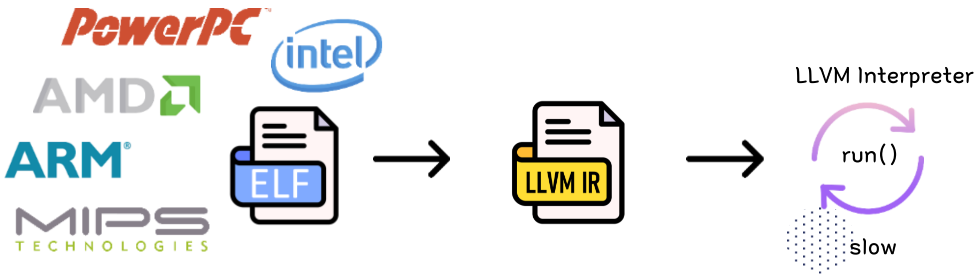
※ A Cross Debugger for Multi-Architecture Binaries(euro-llvm2020)





LLI Interpreter Mode : Drawbacks

- **Extremely slow.. Why?**



Lifted IR contains all sorts of information about execution such as CPU state variation and side effects etc.

```
Breakpoint 2, 0x0000000000400cbf in main ()
1: x/20i $rip
=> 0x400cbf <main>: push   %rbp
   0x400cc0 <main+1>:    mov    %rsp,%rbp
   0x400cc3 <main+4>:    sub    $0x30,%rsp
   0x400cc7 <main+8>:    mov    %fs:0x28,%rax
   0x400cd0 <main+17>:   mov    %rax,-0x8(%rbp)
   0x400cd4 <main+21>:   xor    %eax,%eax
   0x400cd6 <main+23>:   movabs $0x31646165726854,%rax
   0x400ce0 <main+33>:   mov    %rax,-0x18(%rbp)
   0x400ce4 <main+37>:   movabs $0x32646165726854,%rax
   0x400cee <main+47>:   mov    %rax,-0x10(%rbp)
   0x400cf2 <main+51>:   movq   $0x0,-0x20(%rbp)
   0x400cfa <main+59>:   lea    -0x18(%rbp),%rdx
```

4 machine codes
→19 lines

```
bb.main:
 ; 0x400cbf
 %15 = load i64, i64* @rbp
 %16 = load i64, i64* @rsp
 %17 = sub i64 %16, 8
 %18 = inttoptr i64 %17 to i64*
 store volatile i64 %15, i64* %18
 store i64 %17, i64* @rsp
; 0x400cc0
 %19 = load i64, i64* @rsp
 store i64 %19, i64* @rbp
; 0x400cc3
 %20 = load i64, i64* @rsp
 %21 = sub i64 %20, 48
 store i32 17, i32* @cc_op
 store i64 %21, i64* @cc_dst
 store i64 48, i64* @cc_src
 store i64 %21, i64* @rsp
; 0x400cc7
%22 = load i64, i64* @reg_288_64
 %23 = add i64 40, %22
 %24 = inttoptr i64 %23 to i64*
 %25 = load volatile i64, i64* %24
 store i64 %25, i64* @rax
```

LLI Interpreter Mode : Drawbacks

- **Extremely slow.. Why?**

```
bb.main:
%15 = load i64, i64* @rbp
 %16 = load i64, i64* @rsp
 %17 = sub i64 %16, 8
 %18 = inttoptr i64 %17 to i64*
 store volatile i64 %15, i64* %18
 store i64 %17, i64* @rsp
 %19 = load i64, i64* @rsp
 store i64 %19, i64* @rbp

 %20 = load i64, i64* @rsp
 %21 = sub i64 %20, 48
 store i32 17, i32* @cc_op
 store i64 %21, i64* @cc_dst
 store i64 48, i64* @cc_src
 store i64 %21, i64* @rsp

 %22 = load i64, i64* @reg_288_64
 %23 = add i64 40, %22
```

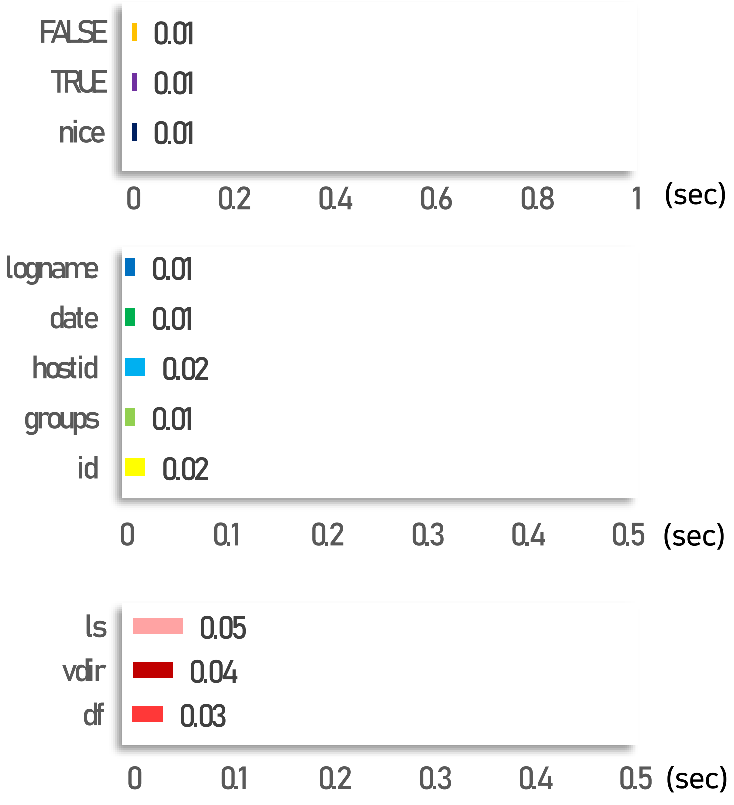
```
void Interpreter::visitLoadInst(LoadInst &I) {
  ExecutionContext &SF = ECStack.back();
  GenericValue SRC = getOperandValue(I.getPointerOperand(), SF);
  GenericValue *Ptr = (GenericValue*)GVTOP(SRC);
  GenericValue Result;
  LoadValueFromMemory(Result, Ptr, I.getType());
  SetValue(&I, Result, SF);
  if (I.isVolatile() && PrintVolatile)
    dbgs() << "Volatile load " << I;
}
```

To emulate 1 line of assembly code from original binary,
From tens to thousands assembly lines should be executed on host

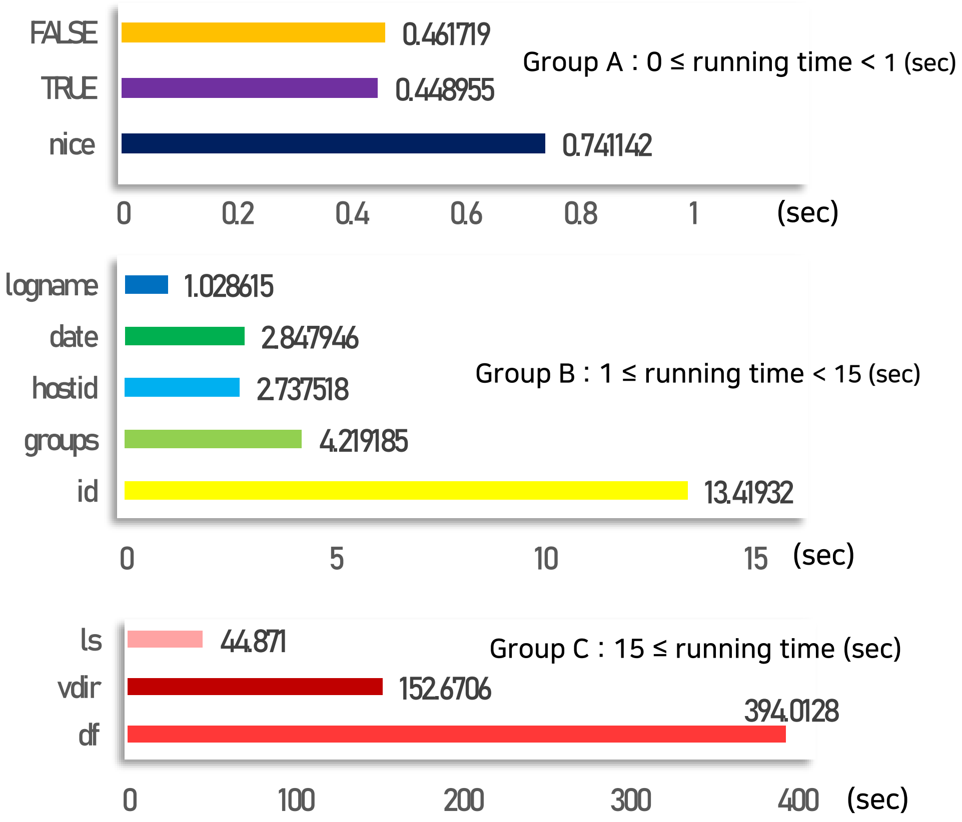
Accumulated overhead results badly on running time

LLI Interpreter Mode : Running Time

- **Running time comparison**



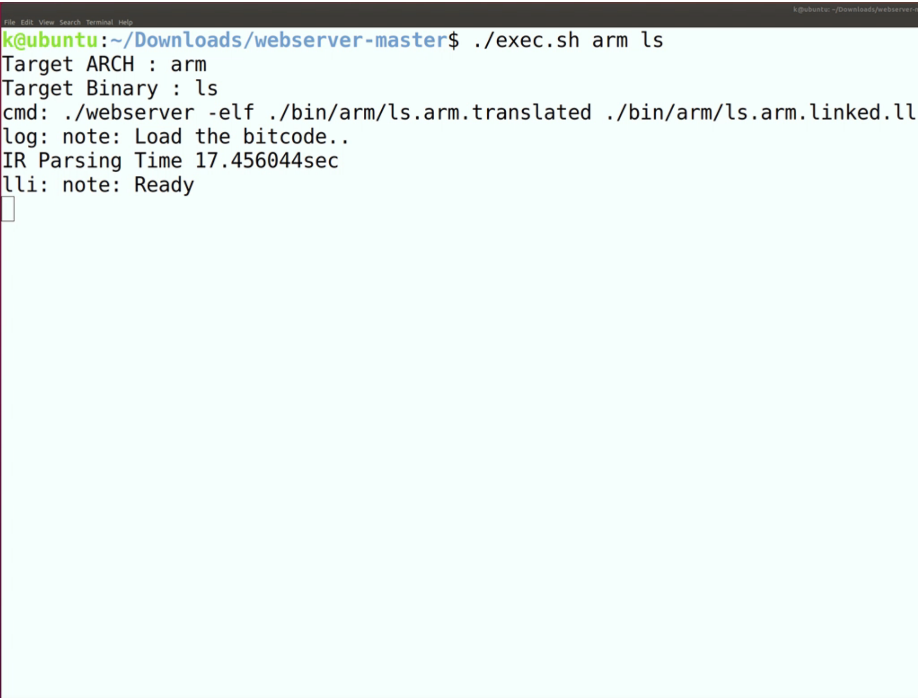
Original Binary



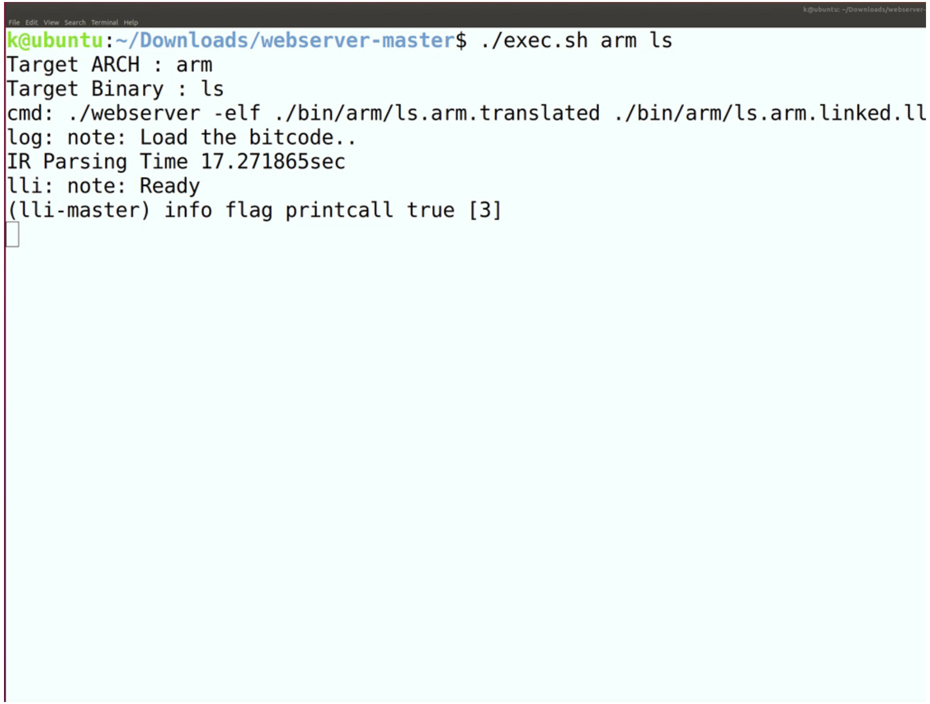
LLI

DEMO

- **LLI Execution Demo**



Default Execution(No debug info)

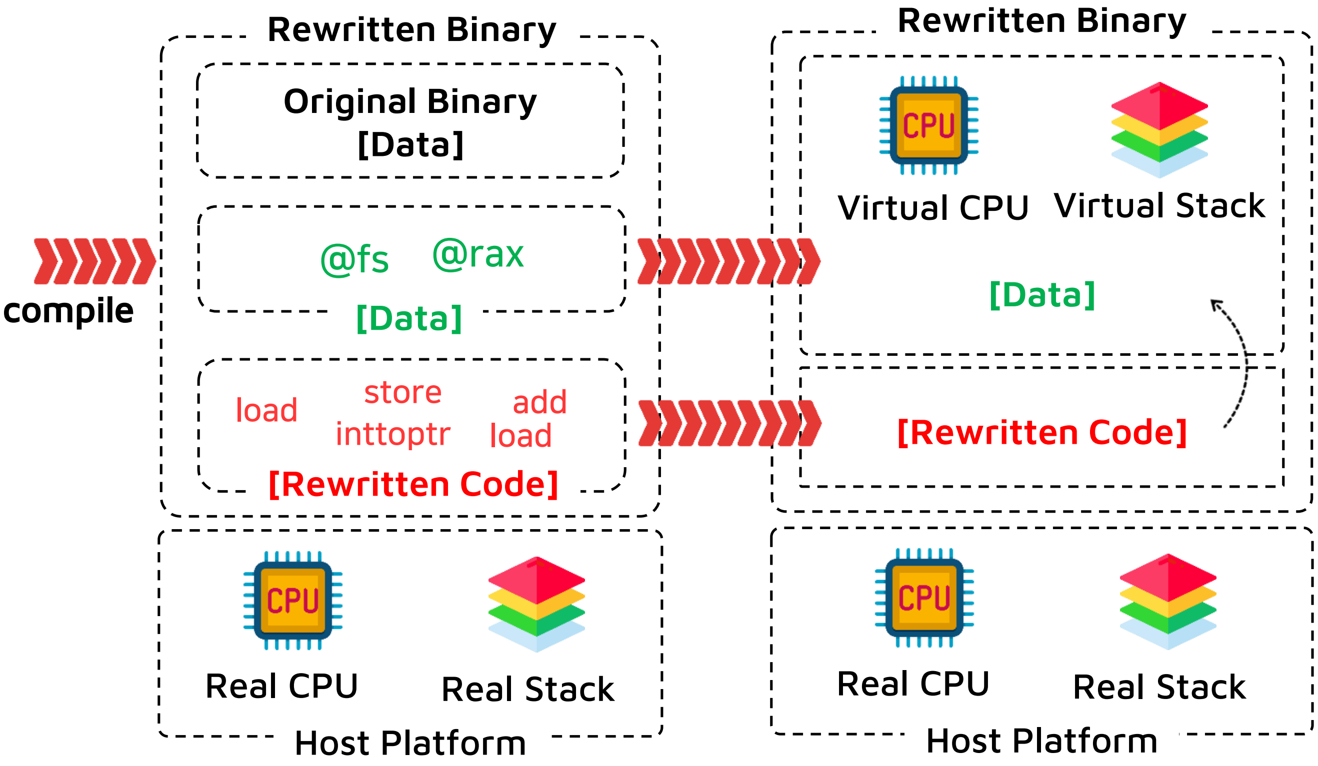


Print function call flow

Binary Rewriting

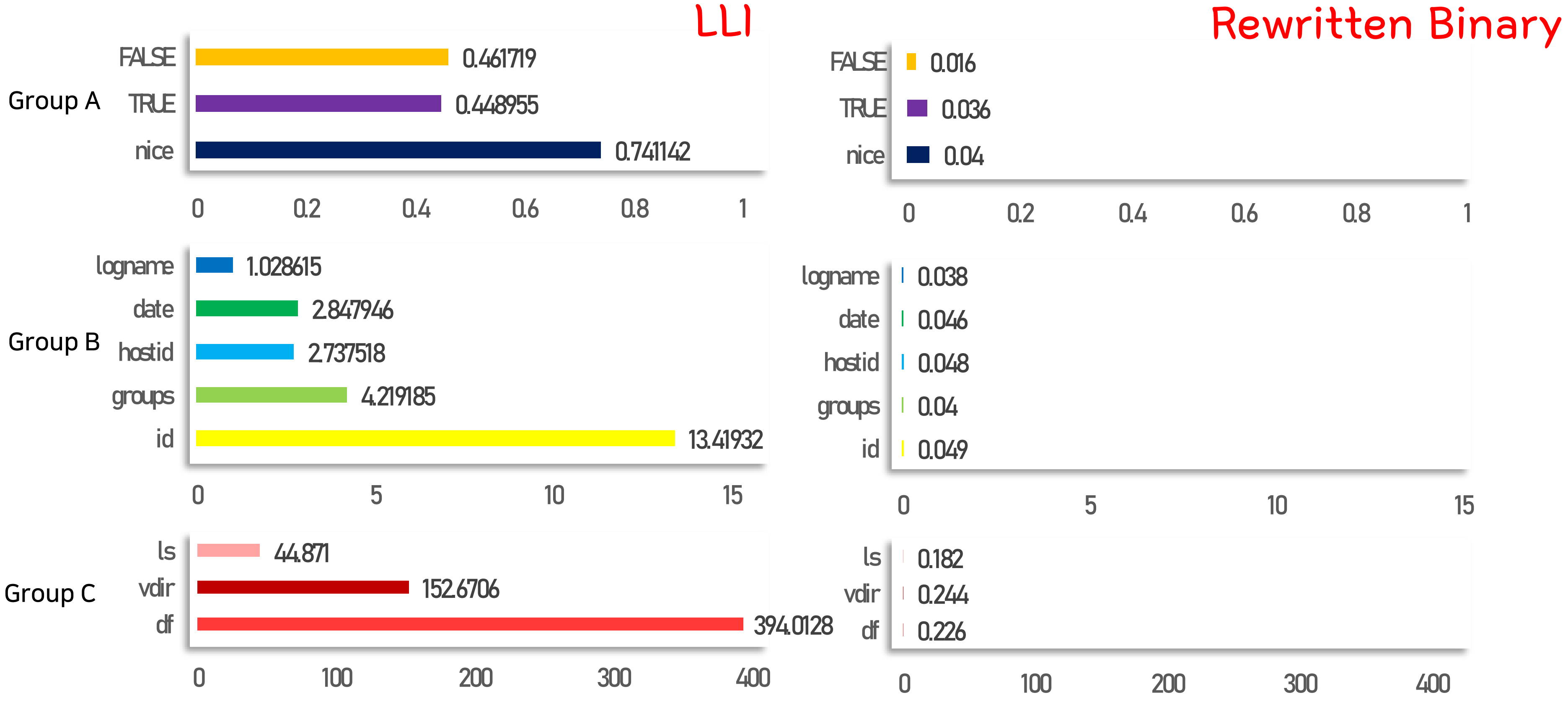
- **Rewritten Binary Architecture**

```
%22 = load i64, i64* @fs
%23 = add i64 40, %22
%24 = inttoptr i64 %23 to i64*
%25 = load volatile i64, i64* %24
store i64 %25, i64* @rax
```



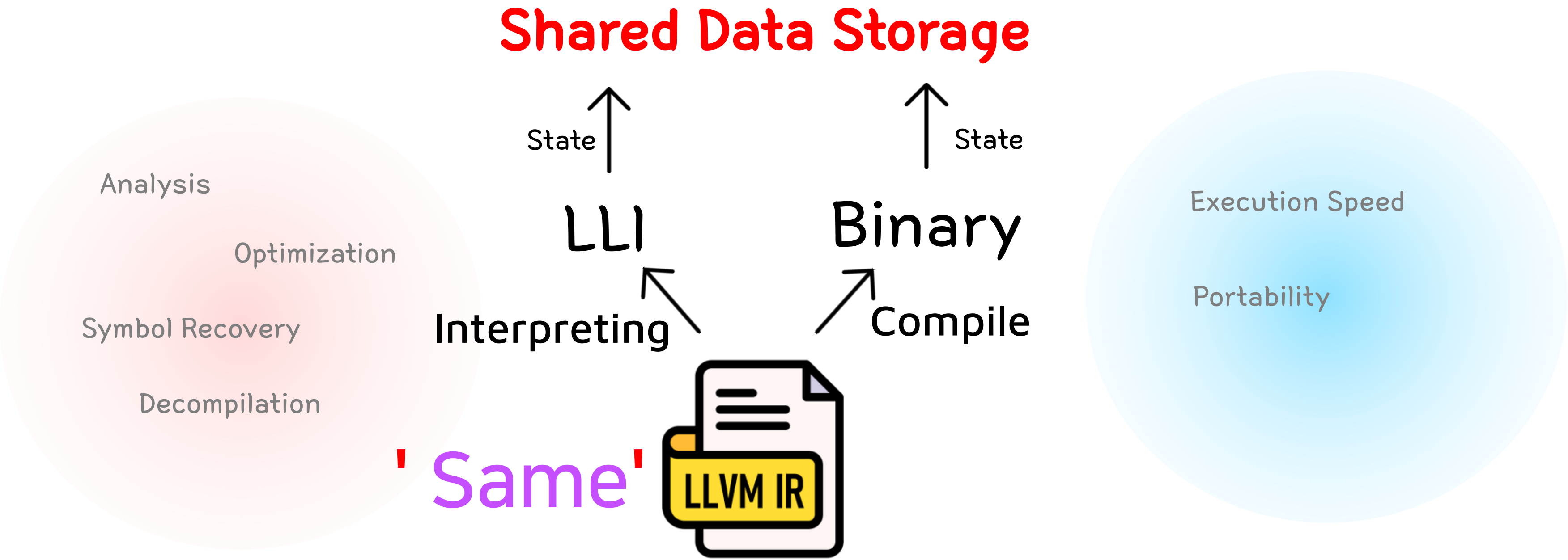
Binary Rewriting : Running Time

- **Running time comparison**

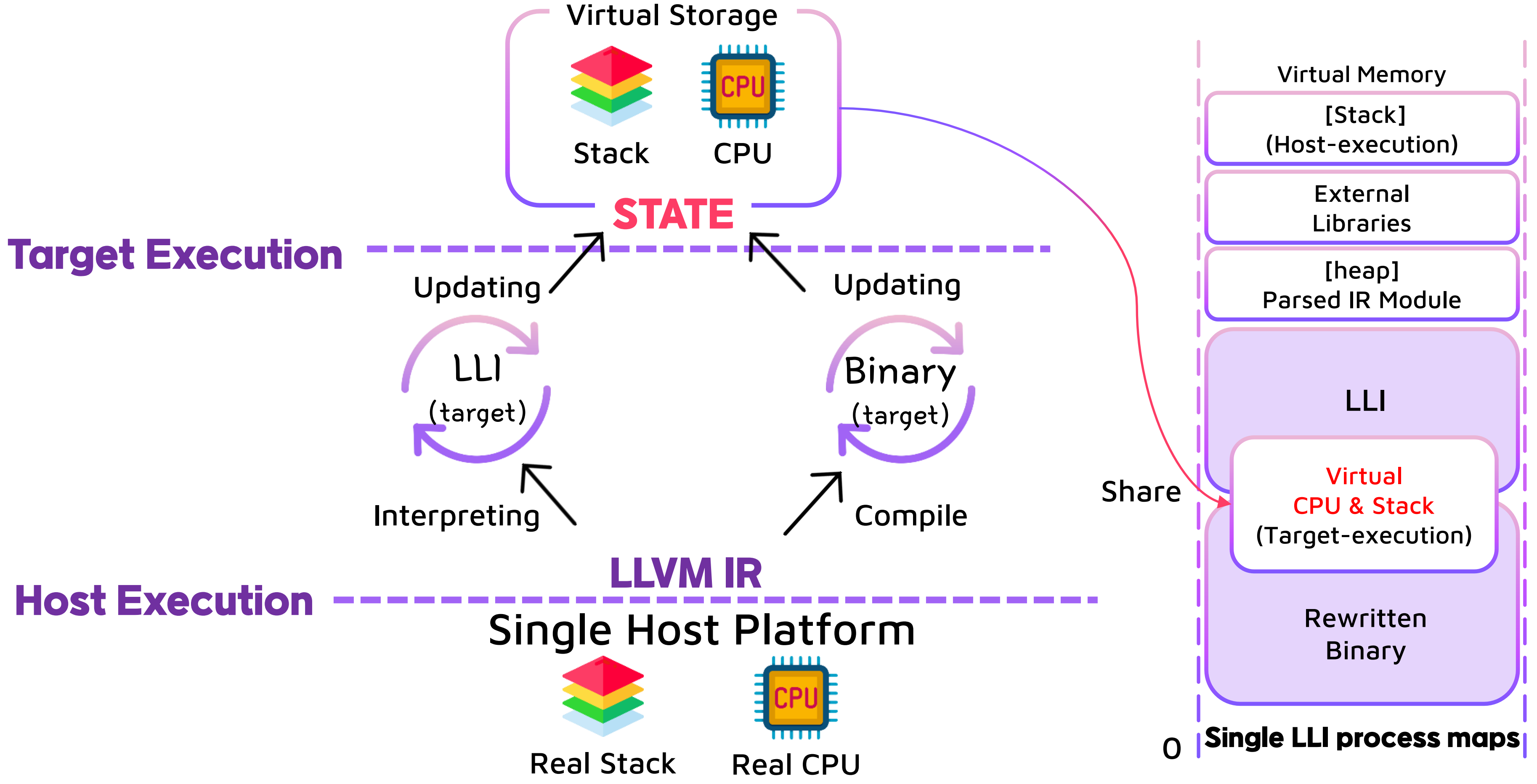


Our idea

- **Binary and IR(LLI) can run in conjunction**
  - Can achieve both execution performance and analysis efficiency

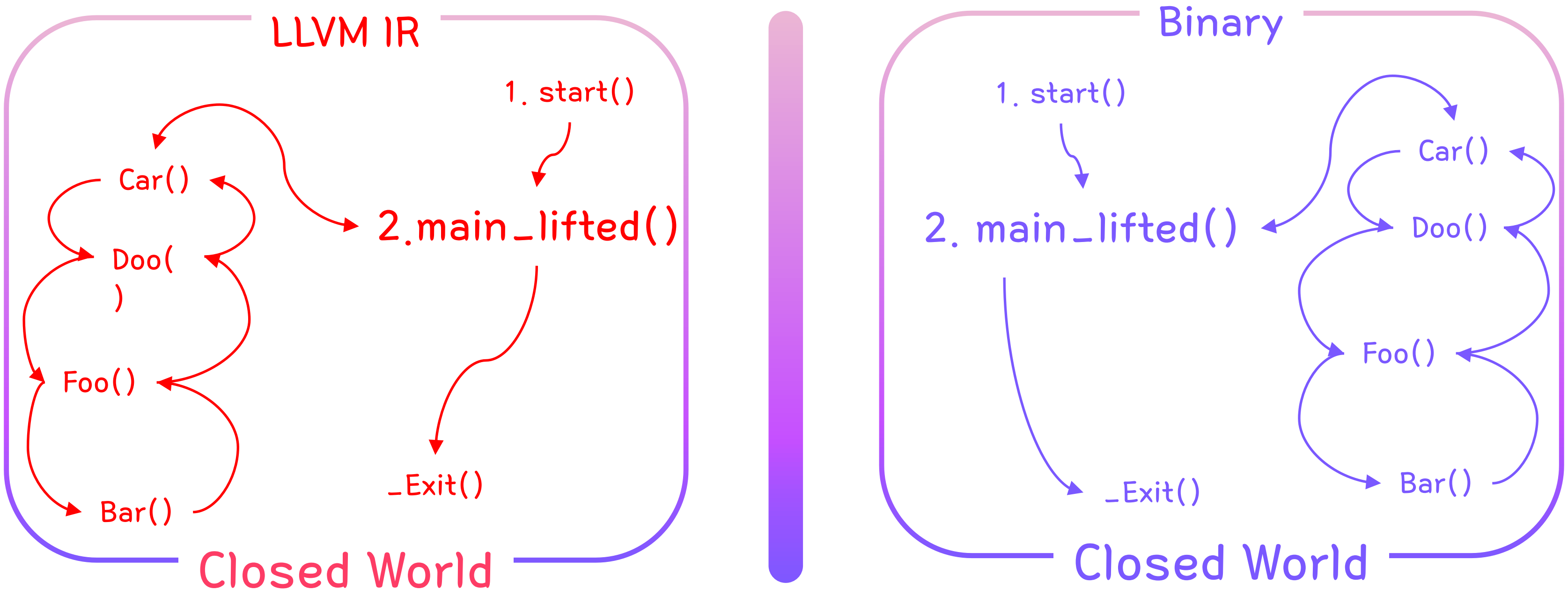


Domain Transition : LLI & Binary Execution



Domain Transition : IR World & Binary World

- **Two closed worlds (IR vs Binary)**
  - The IR and Binary domain execute for each in closed world.



Analysis

Optimization

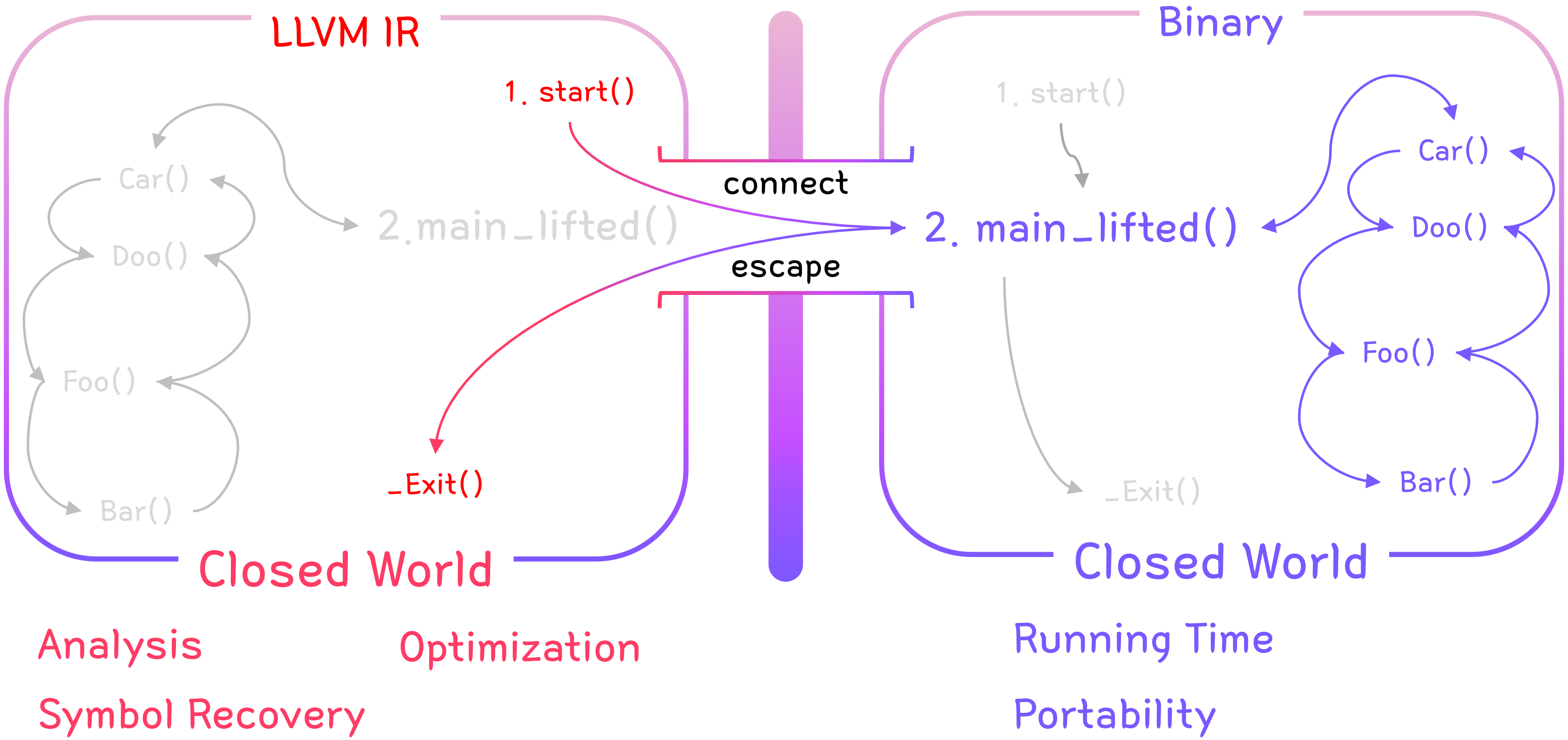
Symbol Recovery

Running Time

Portability

Domain Transition : IR World & Binary World

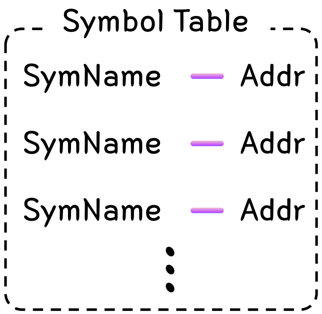
- **Two closed worlds (IR vs Binary)**
  - Can take benefits of the other closed world using domain transition.

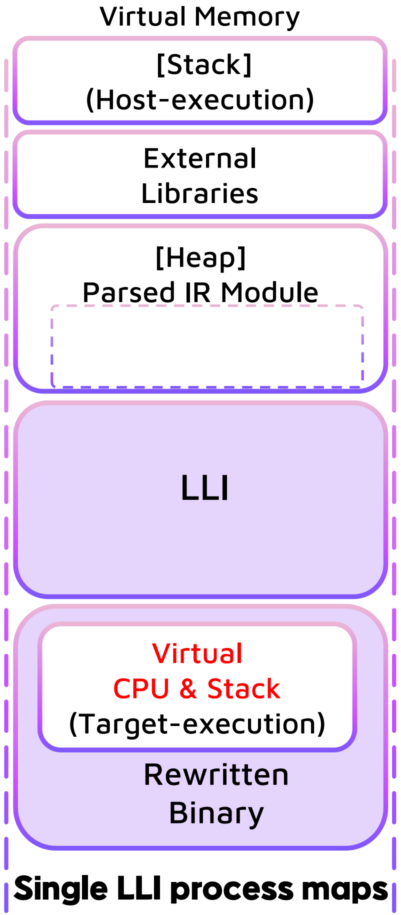


Domain Transition : Implementation details

- **# Sharing the Data storage for the virtual state**

1. Collects symbol Information from the rewritten binary





Domain Transition : Implementation details

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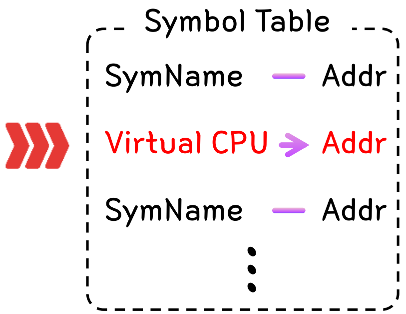
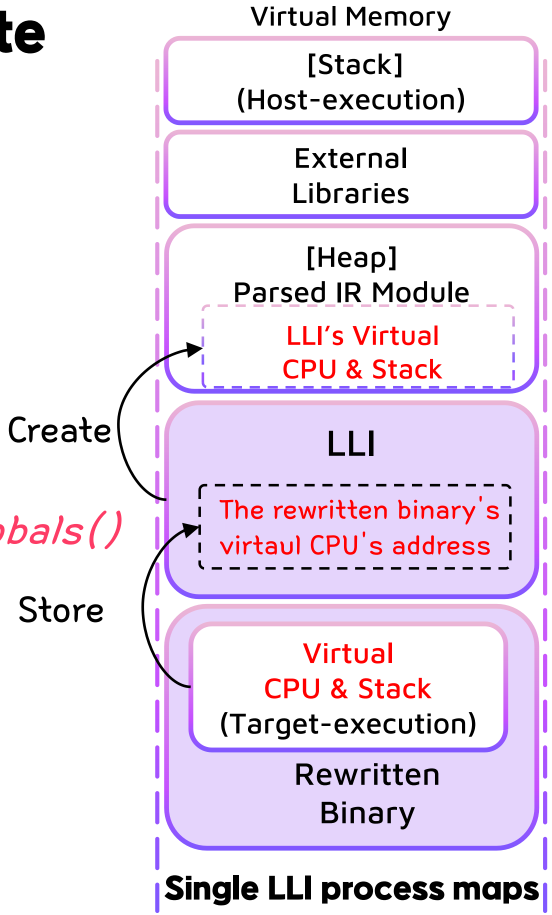


in ExecutionEngine::EmitGlobals()

2. Finds virtual CPU address of the rewritten binary and Stores it in Execution Engine of the LLI



Domain Transition : Implementation details

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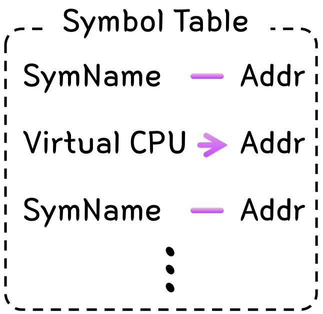
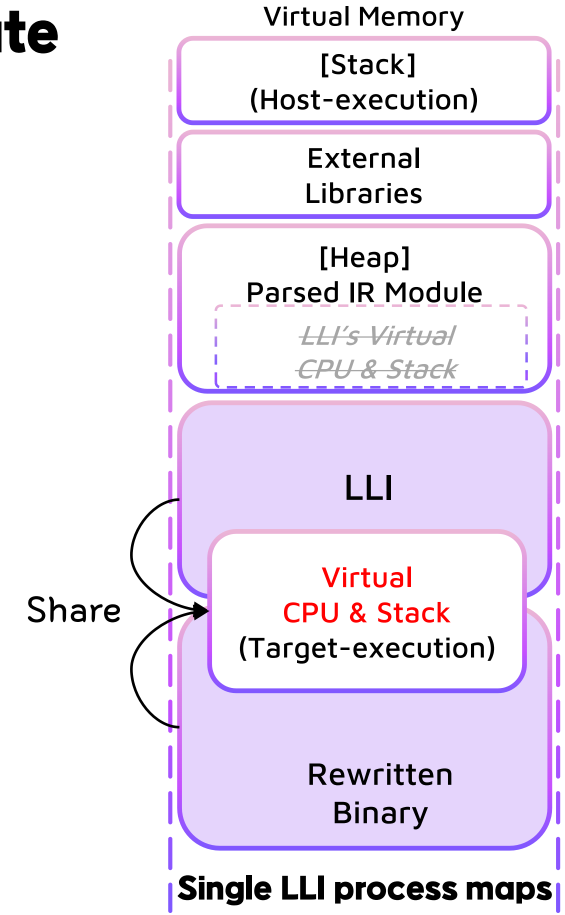


2. Finds virtual CPU address of the rewritten binary and Stores it in Execution Engine of the LLI

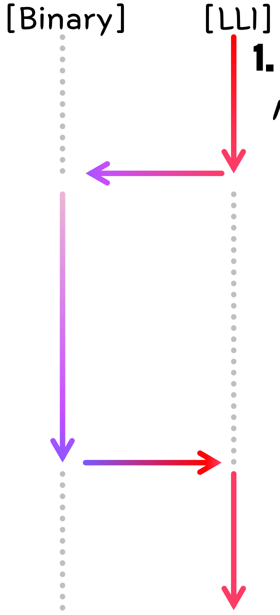
3. Updates virtual CPU address in the LLI

Using ExecutionEngine::updateGlobalMapping()



Domain Transition : Implementation details

- **# Change program counter**



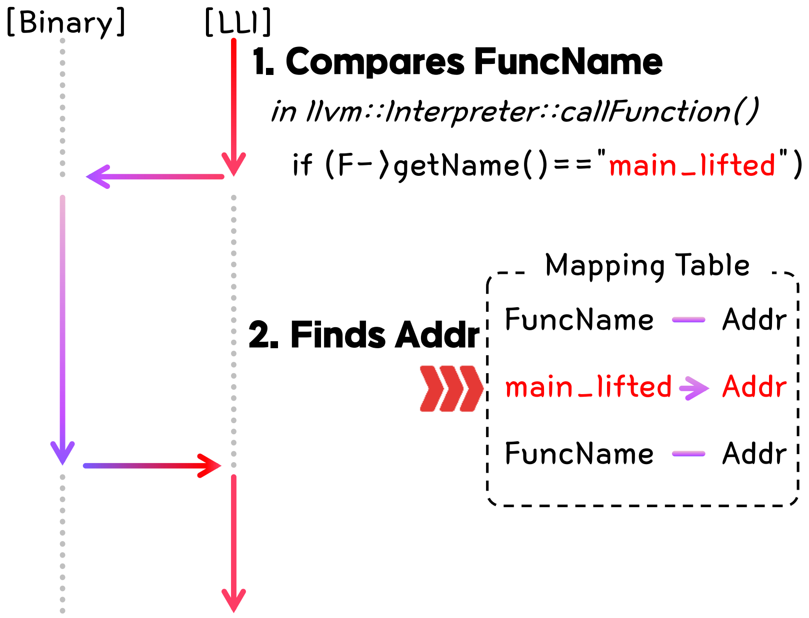
1. Compares FuncName

in llvm::Interpreter::callFunction()

```
if (F->getName()=="main_lifted")
```

Domain Transition : Implementation details

- **# Change program counter**



Domain Transition : Implementation details

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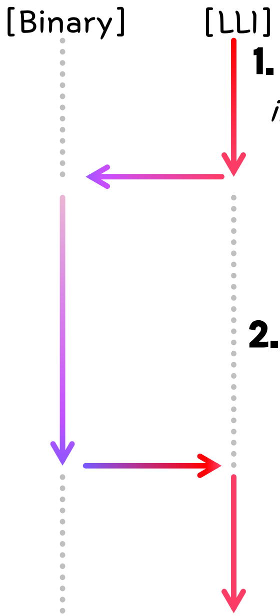


1. Compares FuncName

in llvm::Interpreter::callFunction()

```
if (F->getName()=="main_lifted")
```

2. Finds Addr

Mapping Table

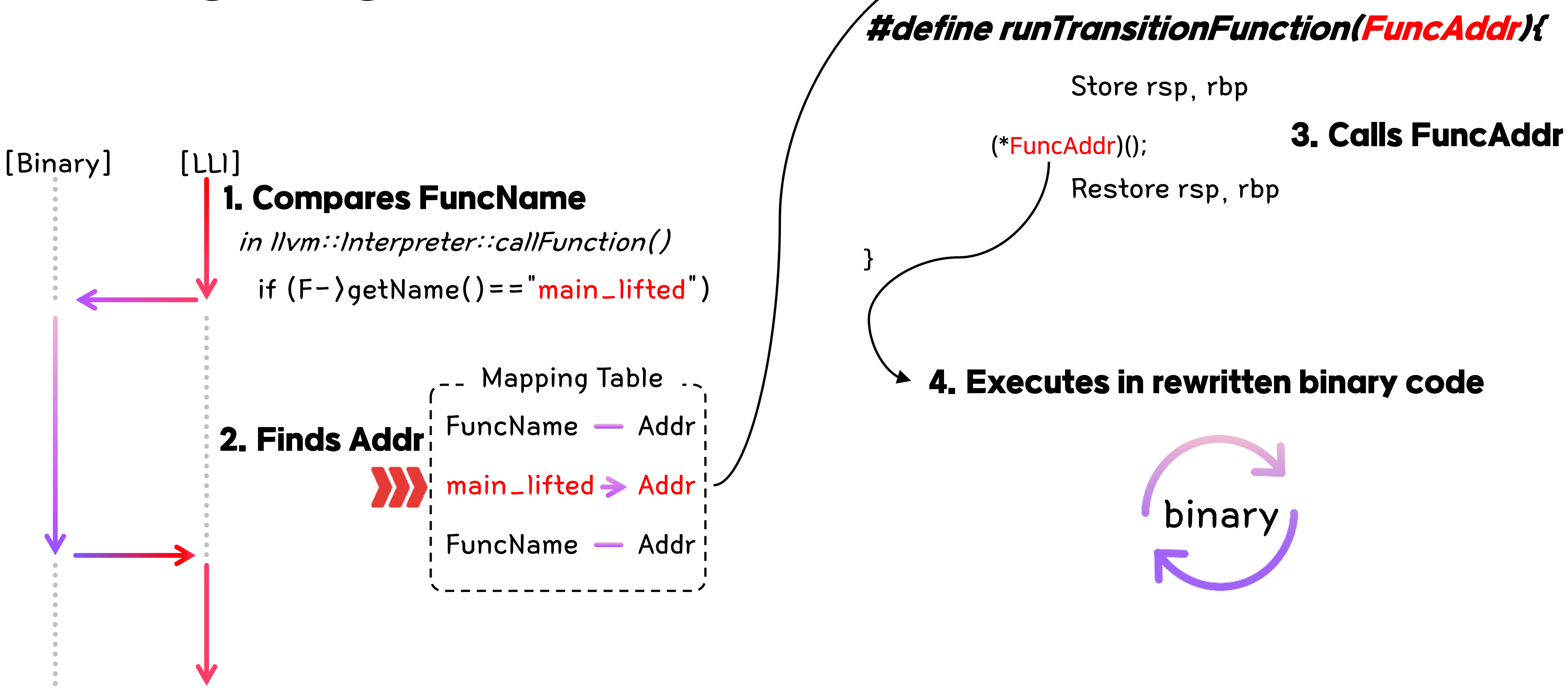
FuncName	Addr
main_lifted	Addr
FuncName	Addr

```
#define runTransitionFunction(FuncAddr){
        Store rsp, rbp
    (*FuncAddr)();
        Restore rsp, rbp
}
```

3. Calls FuncAddr

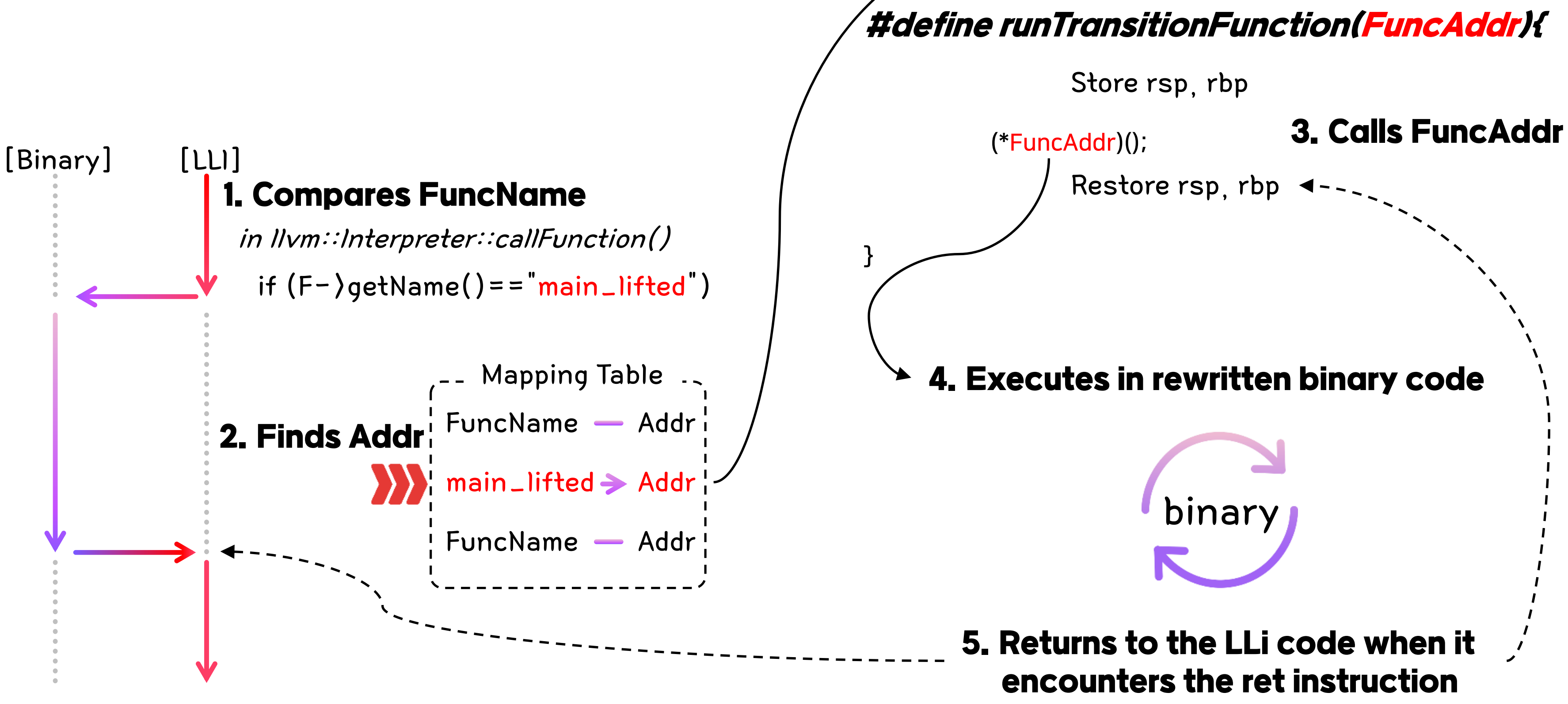
Domain Transition : Implementation details

- **# Change program counter**



Domain Transition : Implementation details

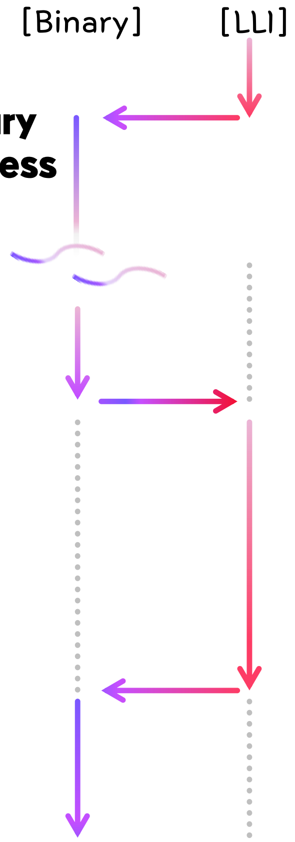
- **# Change program counter**



Domain Transition : Implementation details

- **# Change program counter**

(Initialize)The GlobalVariable of binary
to the lli's trampoline address

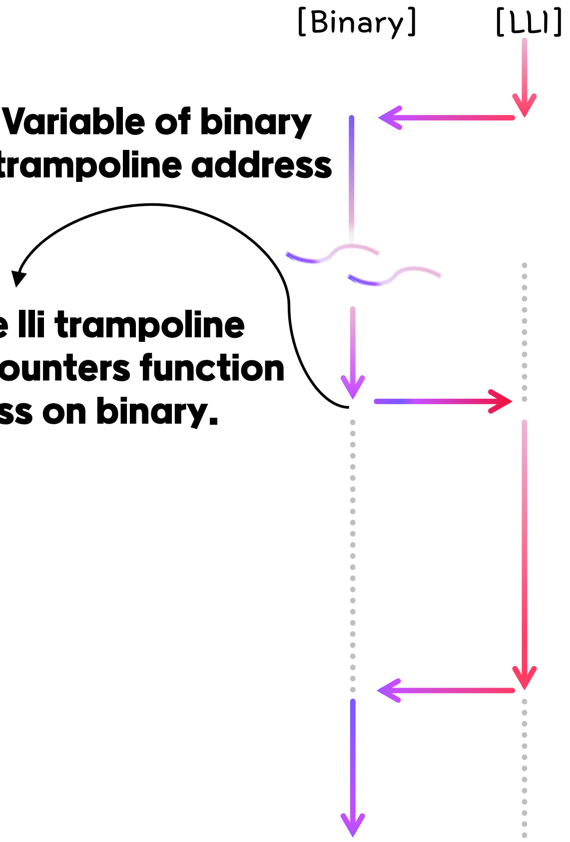


Domain Transition : Implementation details

- **# Change program counter**

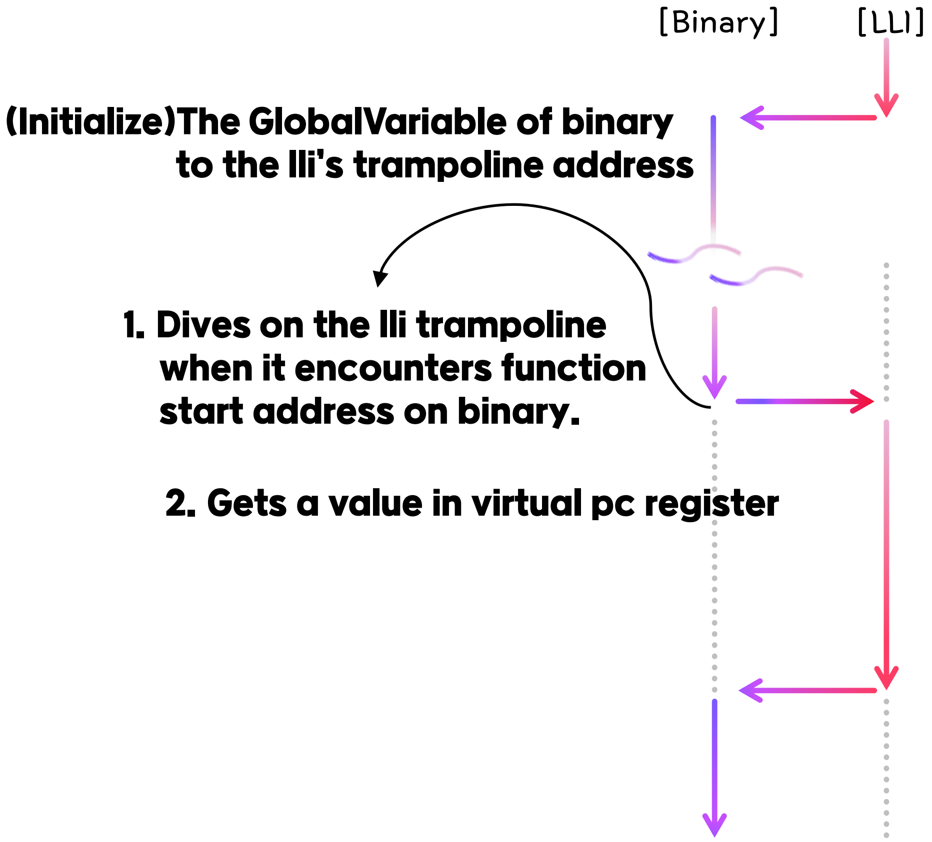
(Initialize)The GlobalVariable of binary to the lli's trampoline address

1. Dives on the lli trampoline when it encounters function start address on binary.



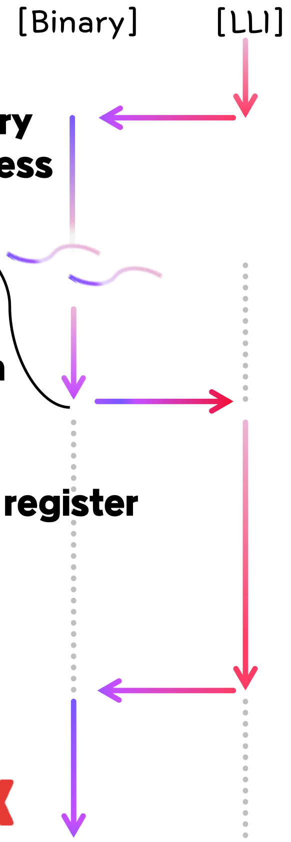
Domain Transition : Implementation details

- **# Change program counter**



Domain Transition : Implementation details

- # Change program counter



(Initialize)The GlobalVariable of binary to the lli's trampoline address

1. Dives on the lli trampoline when it encounters function start address on binary.

2. Gets a value in virtual pc register

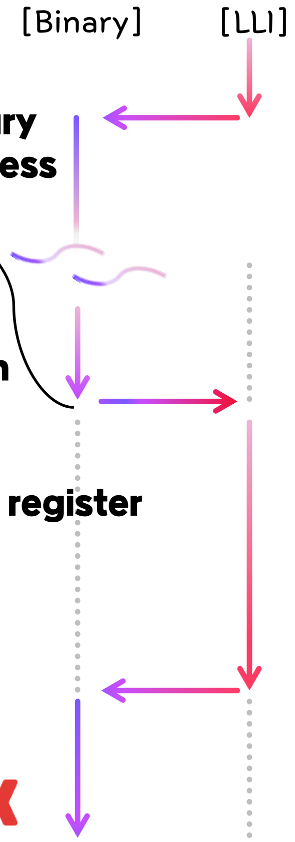
3. Finds a FuncName

Mapping Table

FuncName	—	Addr
malloc_lifted	←	Addr
FuncName	—	Addr

Domain Transition : Implementation details

- **# Change program counter**



(Initialize)The GlobalVariable of binary to the lli's trampoline address

1. Dives on the lli trampoline when it encounters function start address on binary.

2. Gets a value in virtual pc register

3. Finds a FuncName

4. Setups a ExecutionContext

```
struct ExecutionContext {
  Function            *CurFunction;
  BasicBlock           *CurBB;
  BasicBlock::iterator  CurInst;
  CallSite            Caller;
```

Mapping Table

FuncName	—	Addr
malloc_lifted	←	Addr
FuncName	—	Addr

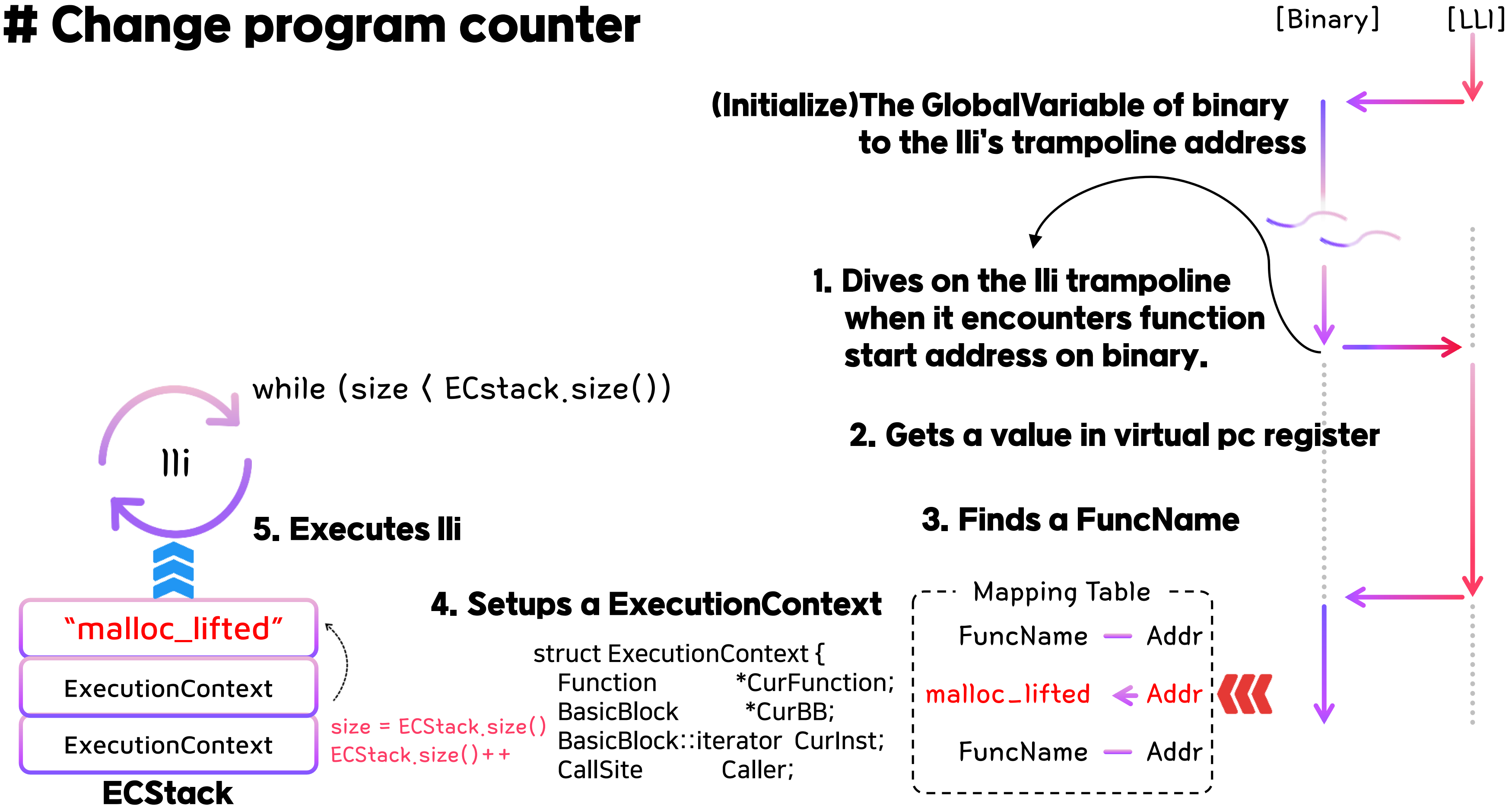
ECStack
"malloc_lifted"
ExecutionContext
ExecutionContext

size = ECStack.size()
ECStack.size()++

ECStack

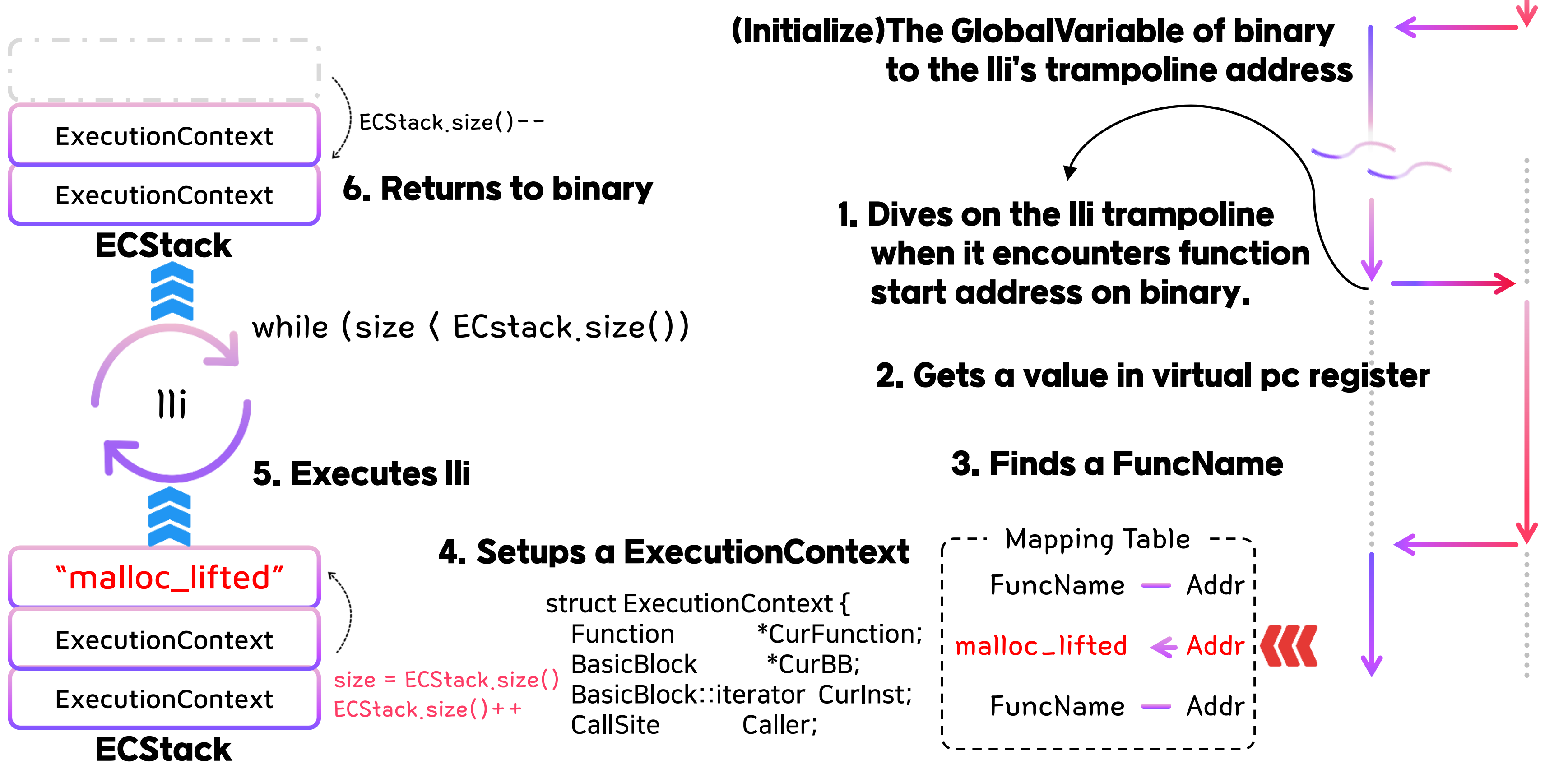
Domain Transition : Implementation details

- # Change program counter



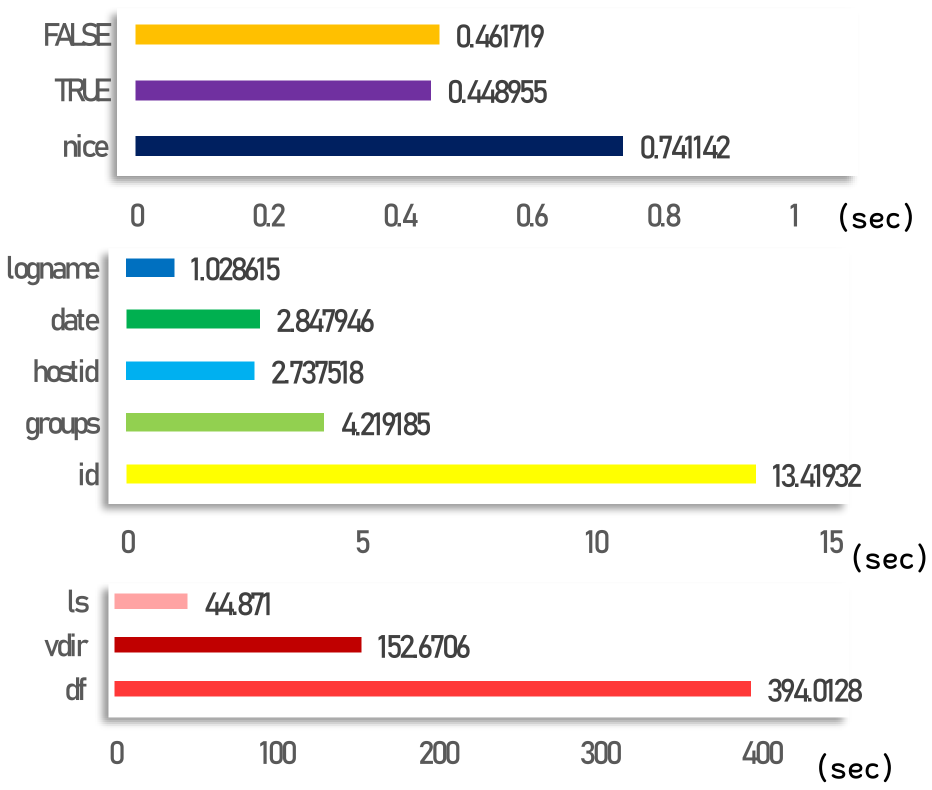
Domain Transition : Implementation details

- **# Change program counter**

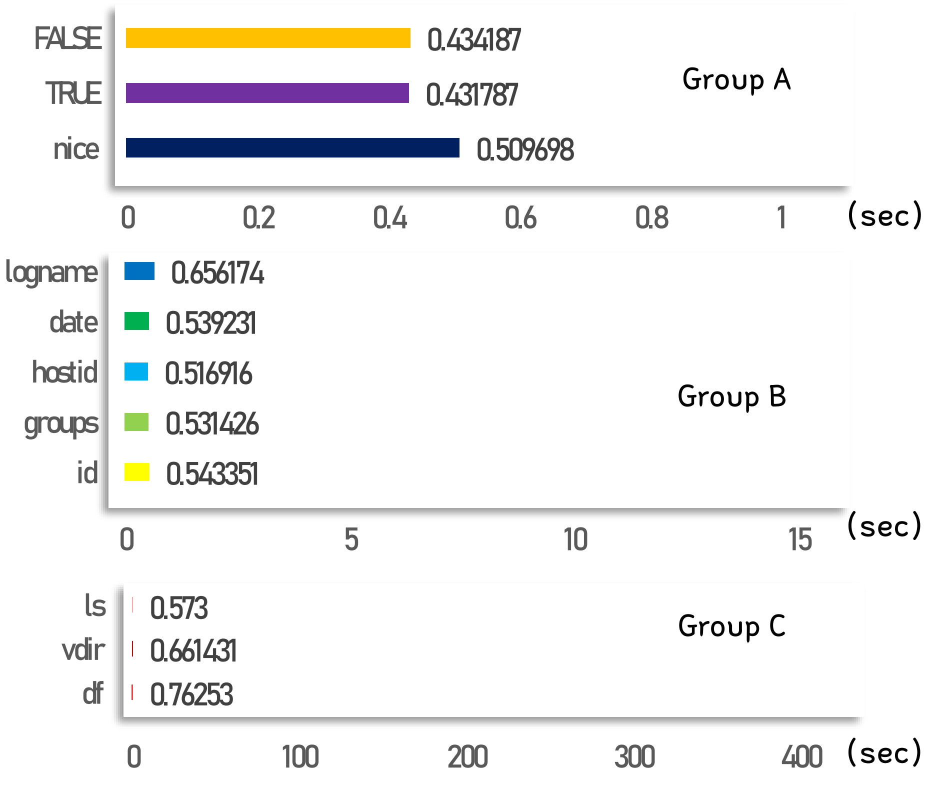


Experiment Result

- **Running time comparison**



The results of LLI



The results of conducted domain transition on LLI

Experiment Result

- **Running time comparison**
  - Result
    - Rate of Change = $(T_L - T_B)/T_L * 100$
    - Percentage= T_L / T_B

      ※ T_L : Only lli execution, no domain transition

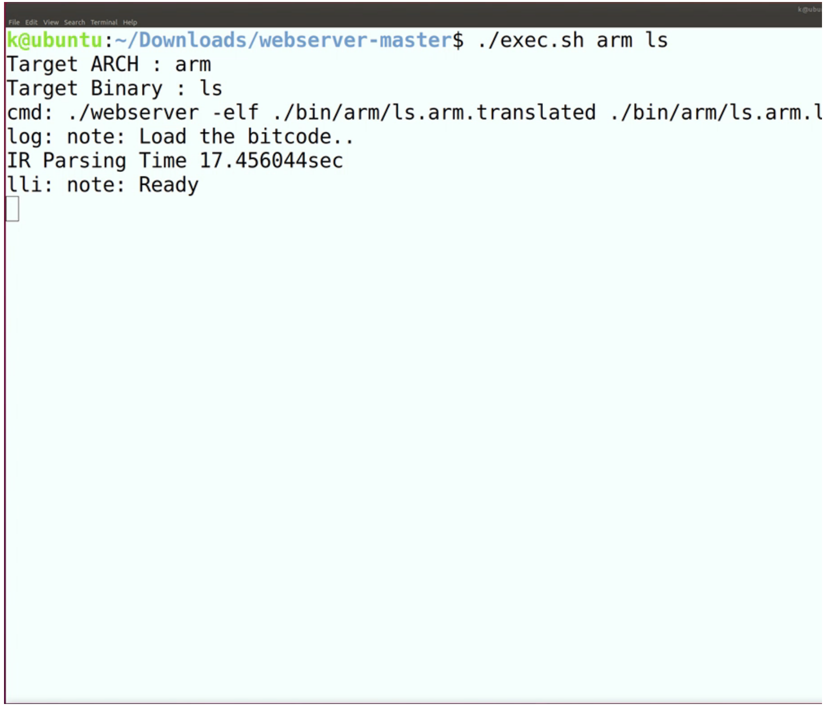
      ※ T_B : Domain transition for "main_lifted" function
  - Maximum 99.82% reduction on execution time
  - Achieved outstanding performance improvement especially on programs with frequent file searching and looping
  - conducted Domain Transition for lifted main function

	Rate of Change	Percentage
false	3.821%	x1.06
true	5.96%	x1.25
nice	31.23%	x1.45
logname	36.21%	x1.57
date	81.07%	x5.28
hostid	81.12%	x5.3
groups	87.40%	x7.94
id	95.95%	x24.7
ls	98.72%	x78.31
vdir	99.57%	x230.82
df	99.82%	x542.53

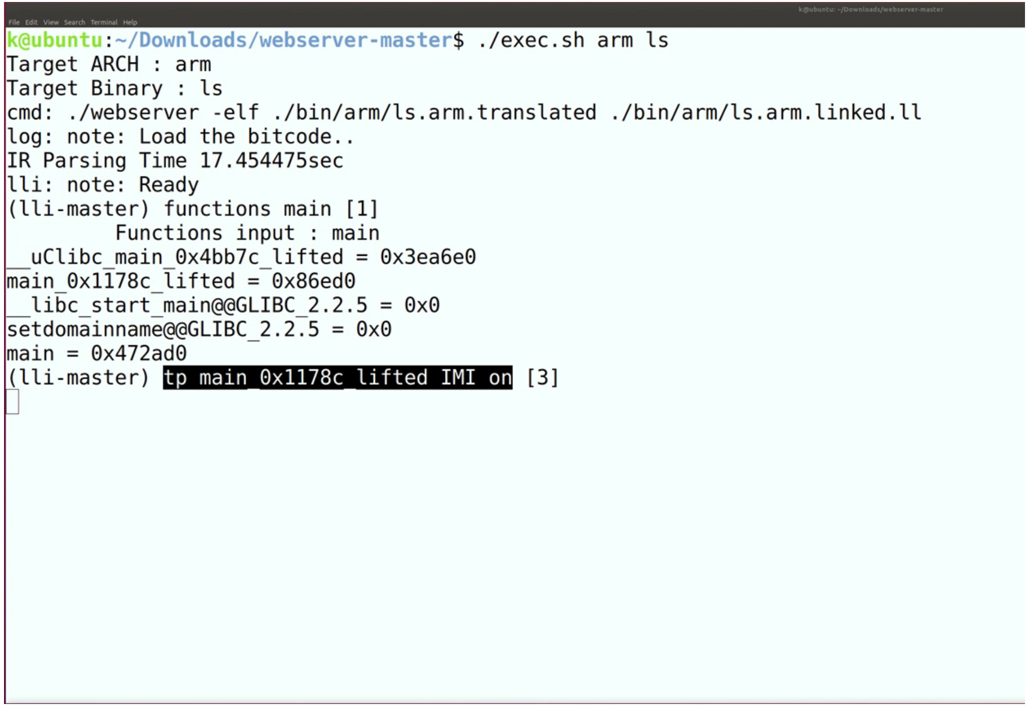
DEMO

DEMO

Demo



Before Transitioning Execution Domain



After Transitioning Execution Domain

Demo

```
k@ubuntu:~/Downloads/webserver-master$ ./exec.sh arm ls
Target ARCH : arm
Target Binary : ls
cmd: ./webserver -elf ./bin/arm/ls.arm.translated ./bin/arm/ls.arm.linked.ll
log: note: Load the bitcode..
IR Parsing Time 17.367615sec
lli: note: Ready
```

```
k@ubuntu:~/Downloads/webserver-master$ ./test q
{"Quit":"All processes died."}k@ubuntu:~/Downloads/webserver-master$
```

END

Thank you

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Q & A

bbxiix.4.4@gmail.com