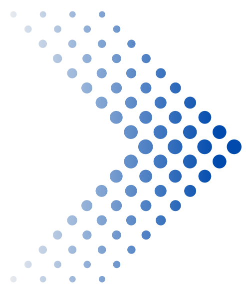
NATIVE WINDOWS JITING IN LLVM

JITLINK

by Sunho Kim



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clang-repl demo

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Tips on using JITLink in COFF

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Usual executable generation pipeline in LLVM

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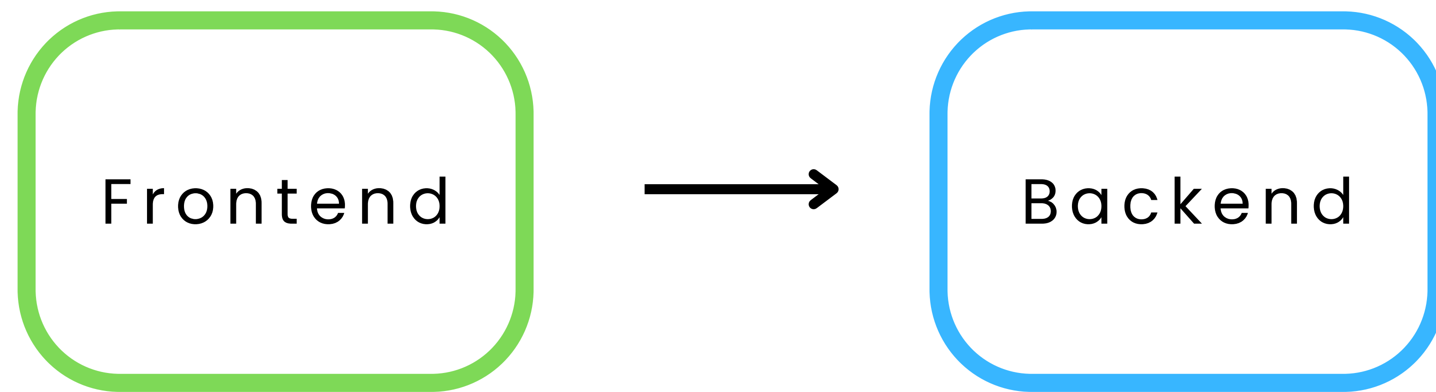

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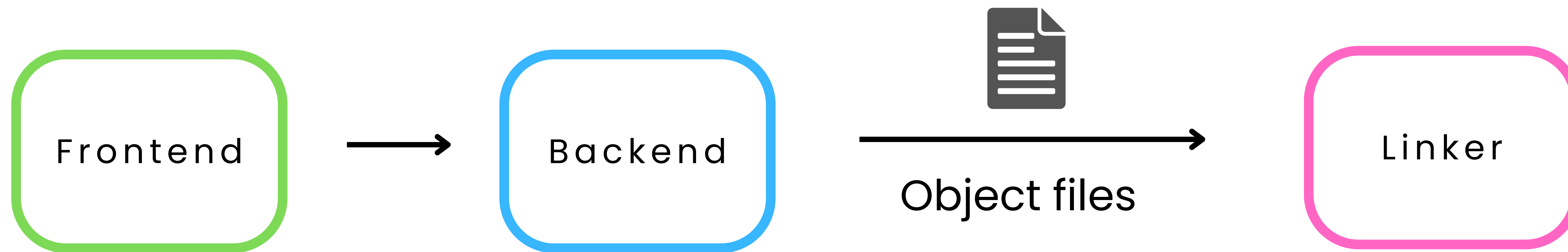
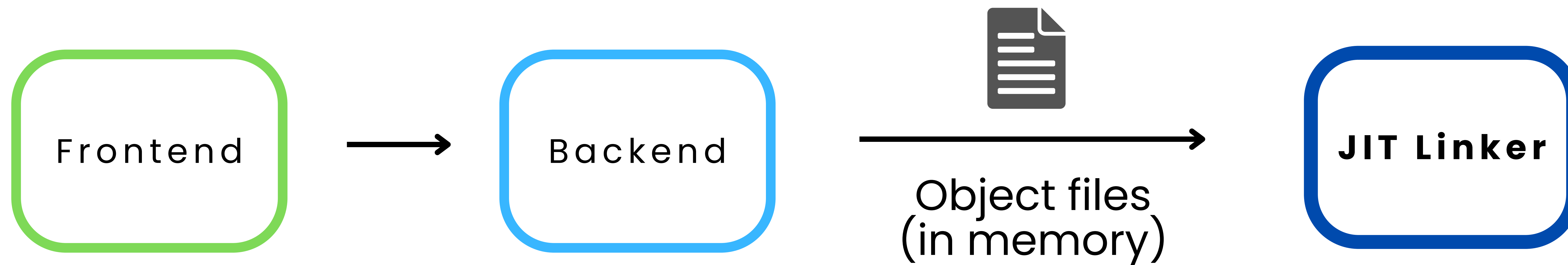


HOW DOES JIT WORK IN LLVM

JIT execution pipeline in LLVM



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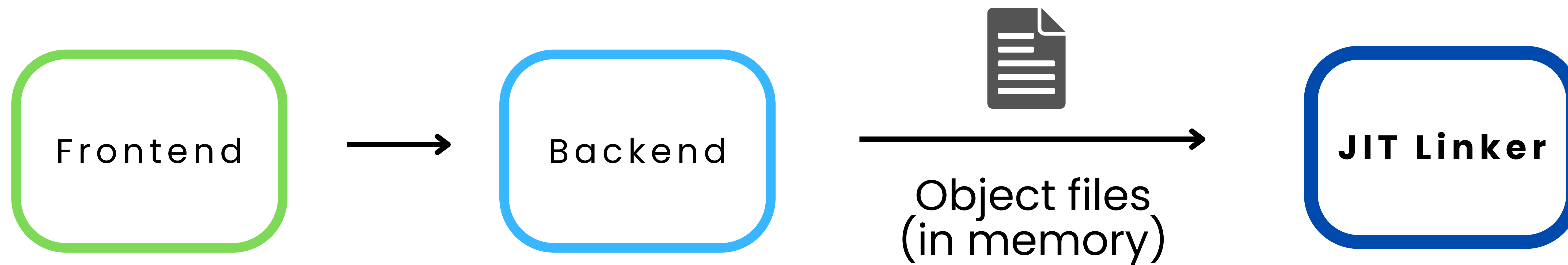
JIT execution pipeline in LLVM



- Share a huge portion of pipeline with AOT
- Fewer breakage by LLVM internal code changes

MOTIVATION FOR JITLINK

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- Runtime features fully supported including static initializers and thread local storage
- Generic linker object abstraction LinkGraph
- Easy to fully implement native object file features

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- **c++ exception handling** support
- **Structured Exception Handling (SEH)** support
- **Incremental linking** works by default

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- Since it's targetting Windows COFF right now, it's **MSVC compliant interactive c++ REPL**

WINDOWS COFF JITLINK EXAMPLE

LLVM IR executor

We're going to build a simple JIT application

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- We're reading IRs from file for simplicity

WINDOWS COFF JITLINK EXAMPLE

LLVM IR executor

We're going to build a simple JIT application

- Executes the **LLVM IRs** written inside main.ll using JIT
- main.ll will be generated from clang
- We're reading IRs from file for simplicity
    - IRs can be generated just in time entirely within memory

WINDOWS COFF JITLINK EXAMPLE

LLVM IR executor

```
auto Builder = LLJITBuilder();
...
std::unique_ptr<LLJIT> J = ExitOnErr(Builder.create());

ExitOnErr(J->loadOrcRuntime("ort_rt-x86_64.lib"));
ExitOnErr(J->addIRModule(readIRModule("main.ll")));

ExecutorAddr MainAddr = ExitOnErr(J->lookup("main"));
ExitOnErr(J->initialize(J->getMainJITDylib()));

int (*Main)(void) = MainAddr.toPtr<int(void)>();
int Result = Main();
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LLJIT::loadOrcRuntime function can be used to load orc runtime into JIT session.

orc_rt-x86_64.lib file is inside compiler-rt build

WINDOWS COFF JITLINK EXAMPLE

LLVM IR executor

Loading SDL library built by MSVC into JIT session

WINDOWS COFF JITLINK EXAMPLE

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JITDylib = emulated dylib inside JIT session

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WINDOWS COFF JITLINK PLUGIN EXAMPLE

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Overview of JITLink

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- JITLink **converts** object file into generic linker object representation **LinkGraph**
  - ELFLinkGraphBuilder, COFFLinkGraphBuilder, MachOLinkGraphBuilder

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- JITLink **converts** object file into generic linker object representation **LinkGraph**
  - ELFLinkGraphBuilder, COFFLinkGraphBuilder, MachOLinkGraphBuilder
- Then, it performs generic **memory allocation, symbol resolution** as described in **LinkGraph** and perform architecture-specific **relocations** as needed

WINDOWS COFF JITLINK PLUGIN EXAMPLE

Overview of LinkGraph

Block (Code)

```
mov   rdi, 1
mov   rsi, message
jmp   printf
```

Block (Data)

```
"Hello, world"
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WINDOWS COFF JITLINK PLUGIN EXAMPLE

Overview of LinkGraph

Block (Code)

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Symbol

Message

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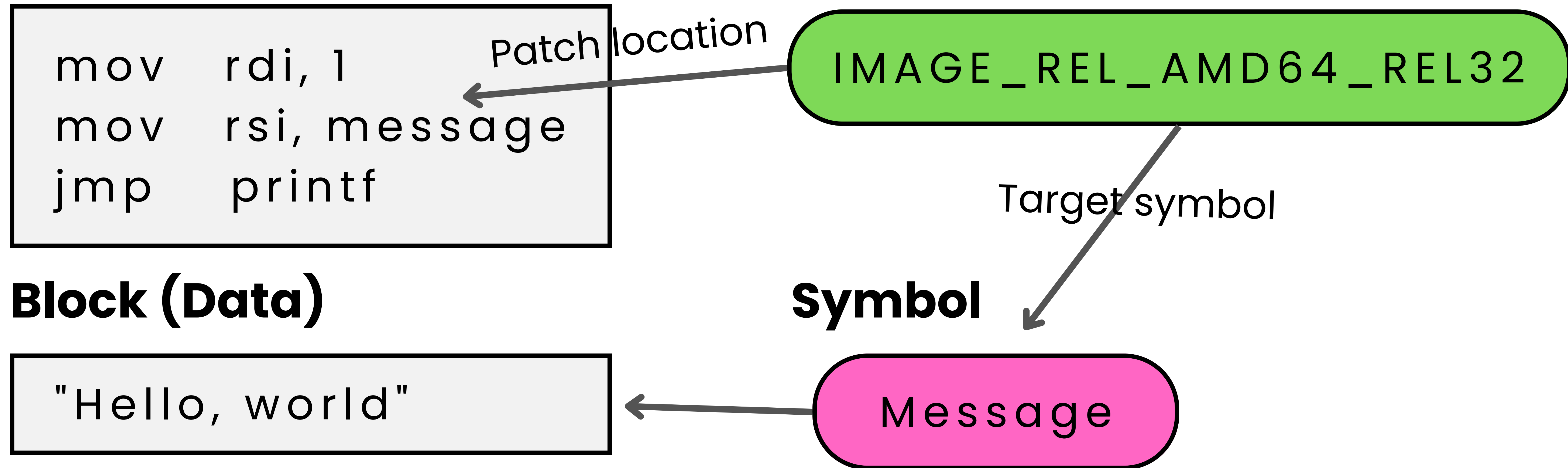

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Basic plugin

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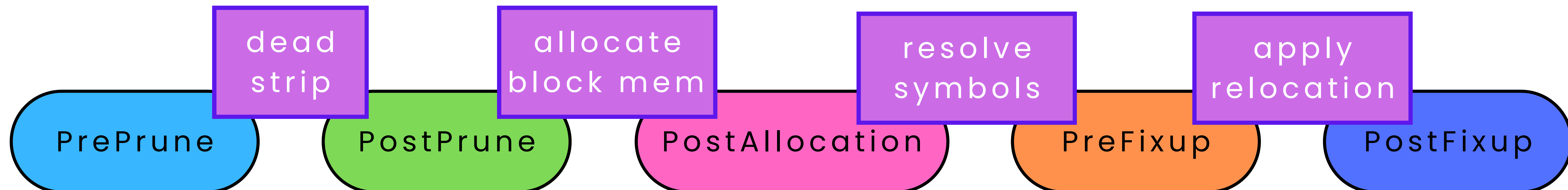

WINDOWS COFF JITLINK PLUGIN EXAMPLE

Exception instrumentation plugin

Exception instrumentation plugin

- Print the name of the function that just raised exception

WINDOWS COFF JITLINK PLUGIN EXAMPLE

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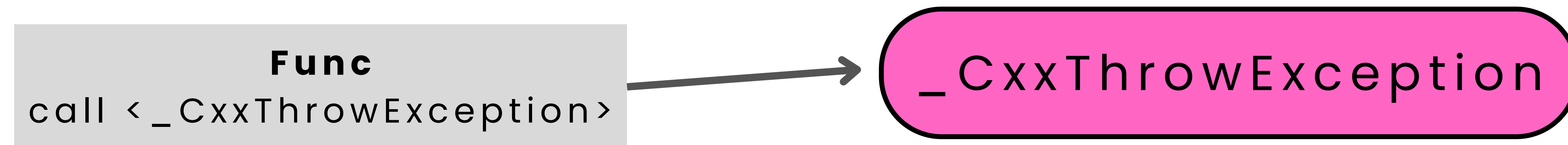

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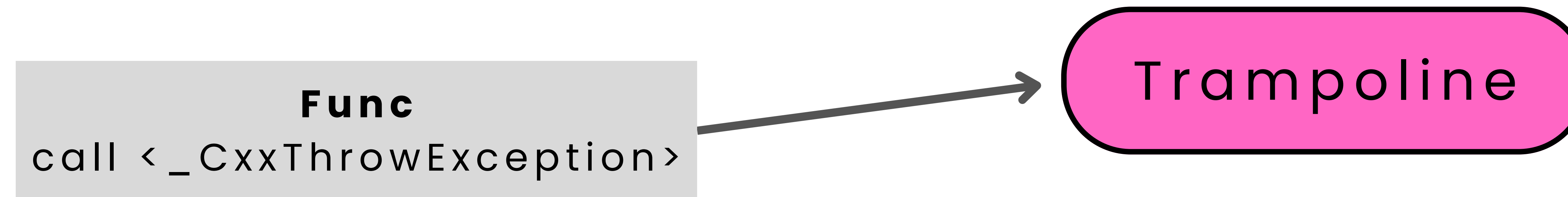

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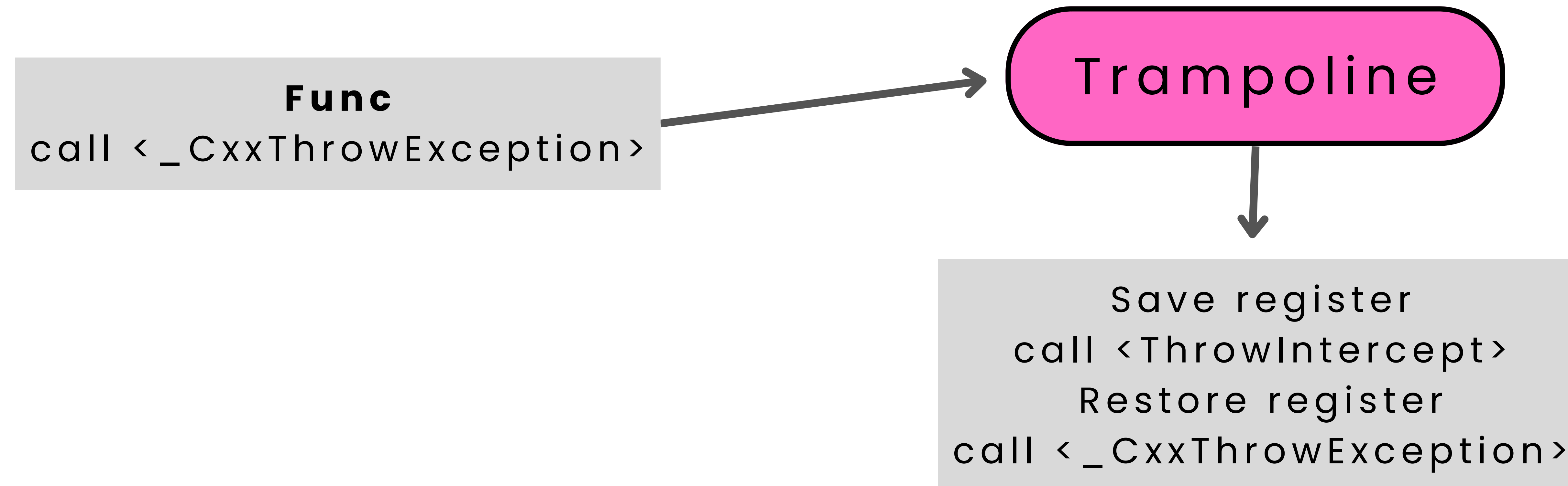

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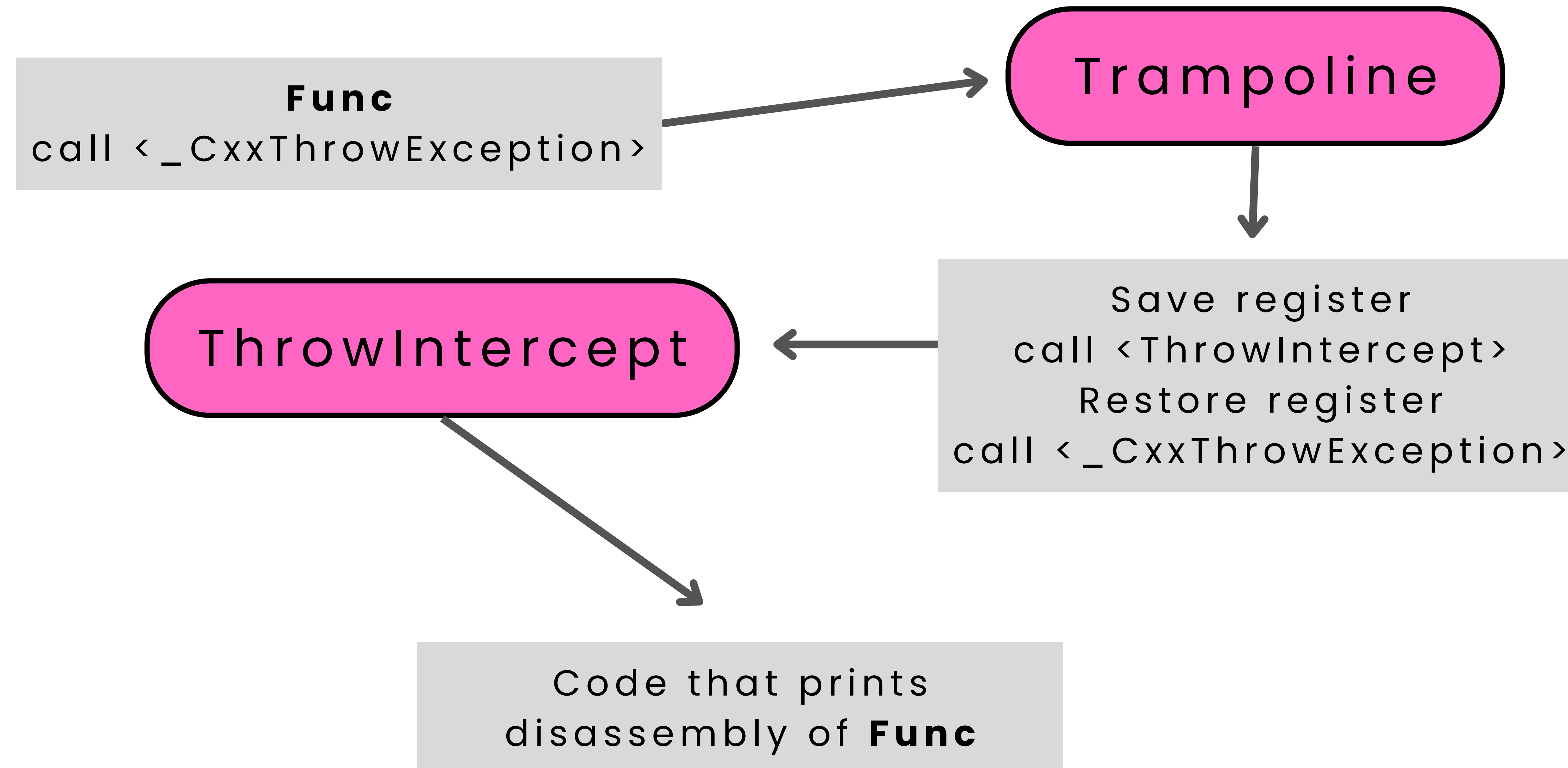

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Exception instrumentation plugin

```
// Create trampoline JITLink block within given LinkGraph
jitlink::Symbol *createTrampoline(jitlink::LinkGraph &G) {
  std::vector<jitlink::Edge> Edges;
  std::vector<char> CodeBuf;

  // Write x86 assembly code to CodeBuf
  WriteSaveRegsCode(CodeBuf);
  WriteCallFuncCode(CodeBuf);
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CodeBuf (content bytes of block)

```
1  0: pushq   %rbp
2  1: movq    %rsp, %rbp
3  4: subq    $512, %rsp
4  b: movq    %rcx, -16(%rbp)
5  f: movq    %rdx, -24(%rbp)
6  13: movq   %rsi, -32(%rbp)
7  17: movq   %rdi, -40(%rbp)
8  ...
9  6f: e8 00 00 00 00 callq <ThrowIntercept>
```

WINDOWS COFF JITLINK PLUGIN EXAMPLE

Exception instrumentation plugin

```
// Create trampoline JITLink block within given LinkGraph
jitlink::Symbol *createTrampoline(jitlink::LinkGraph &G) {
  std::vector<jitlink::Edge> Edges;
  std::vector<char> CodeBuf;

  // Write x86 assembly code to CodeBuf
  WriteSaveRegsCode(CodeBuf);
  WriteCallFuncCode(CodeBuf);
```

CodeBuf (content bytes of block)

```
1   0: pushq   %rbp
2   1: movq    %rsp, %rbp
3   4: subq    $512, %rsp
4   b: movq    %rcx, -16(%rbp)
5   f: movq    %rdx, -24(%rbp)
6   13: movq   %rsi, -32(%rbp)
7   17: movq   %rdi, -40(%rbp)
8   ...
9   6f: e8 00 00 00 00 callq <ThrowIntercept>
```

WINDOWS COFF JITLINK PLUGIN EXAMPLE

Exception instrumentation plugin

```cpp
// Create trampoline JITLink block within given LinkGraph
jitlink::Symbol *createTrampoline(jitlink::LinkGraph &G) {
  std::vector<jitlink::Edge> Edges;
  std::vector<char> CodeBuf;

  // Write x86 assembly code to CodeBuf
  WriteSaveRegsCode(CodeBuf);
  WriteCallFuncCode(CodeBuf);

  // Add relocation edge to ThrowIntercept
  auto ThrowInterceptSymbol =
      &G.addExternalSymbol("ThrowIntercept", 0, jitlink::Linkage::Strong);
  Edges.push_back(jitlink::Edge(jitlink::x86_64::PCRel32, CodeBuf.size() - 4,
                                *ThrowInterceptSymbol, 0));
```

CodeBuf (content bytes of block)

```
1   0: pushq   %rbp
2   1: movq    %rsp, %rbp
3   4: subq    $512, %rsp
4   b: movq    %rcx, -16(%rbp)
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7   17: movq   %rdi, -40(%rbp)
8   ...
9   6f: e8 00 00 00 00 callq <ThrowIntercept>
```

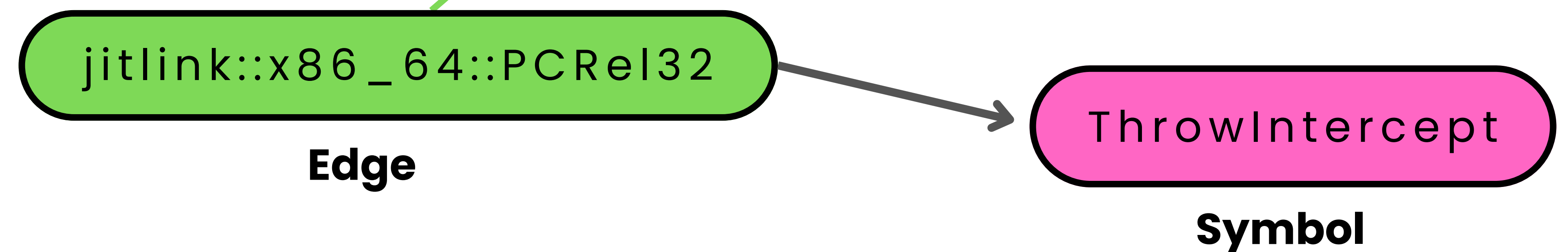

WINDOWS COFF JITLINK PLUGIN EXAMPLE

Exception instrumentation plugin

```
Config.PrePrunePasses.push_back([&](jitlink::LinkGraph &G) {
```

WINDOWS COFF JITLINK PLUGIN EXAMPLE

Exception instrumentation plugin

```
Config.PrePrunePasses.push_back([&](jitlink::LinkGraph &G) {
  jitlink::Symbol *Trampoline = nullptr;
```

WINDOWS COFF JITLINK PLUGIN EXAMPLE

Exception instrumentation plugin

```
Config.PrePrunePasses.push_back([&](jitlink::LinkGraph &G) {
  jitlink::Symbol *Trampoline = nullptr;
  for (jitlink::Block *Block : G.blocks()) {
```

WINDOWS COFF JITLINK PLUGIN EXAMPLE

Exception instrumentation plugin

```
Config.PrePrunePasses.push_back([&](jitlink::LinkGraph &G) {
  jitlink::Symbol *Trampoline = nullptr;
  for (jitlink::Block *Block : G.blocks()) {
    for (jitlink::Edge &Edge : Block->edges()) {
```

WINDOWS COFF JITLINK PLUGIN EXAMPLE

Exception instrumentation plugin

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Config.PrePrunePasses.push_back([&](jitlink::LinkGraph &G) {
  jitlink::Symbol *Trampoline = nullptr;
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      if (Edge.getTarget().getName() == "_CxxThrowException") {
```

WINDOWS COFF JITLINK PLUGIN EXAMPLE

Exception instrumentation plugin

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      if (Edge.getTarget().getName() == "_CxxThrowException") {
        if (!Trampoline)
          Trampoline = createTrampoline(G);
```

WINDOWS COFF JITLINK PLUGIN EXAMPLE

Exception instrumentation plugin

```
Config.PrePrunePasses.push_back([&](jitlink::LinkGraph &G) {
  jitlink::Symbol *Trampoline = nullptr;
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WINDOWS COFF JITLINK PLUGIN EXAMPLE

Exception instrumentation plugin

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      if (Edge.getTarget().getName() == "_CxxThrowException") {
        if (!Trampoline)
          Trampoline = createTrampoline(G);
        Edge.setTarget(*Trampoline);
      }
    }
  }
  return Error::success();
});
```

WINDOWS COFF JITLINK PLUGIN EXAMPLE

Exception instrumentation plugin

```
std::map<uint64_t, std::string> AddrToSymbolName;
```

WINDOWS COFF JITLINK PLUGIN EXAMPLE

Exception instrumentation plugin

```
std::map<uint64_t, std::string> AddrToSymbolName;
```

```
Config.PostFixupPasses.push_back([&](jitlink::LinkGraph &G) {
  for (auto *S : G.defined_symbols()) {
    AddrToSymbolName[S->getAddress().getValue()] = S->getName();
  }
  return Error::success();
});
```

WINDOWS COFF JITLINK PLUGIN EXAMPLE

Exception instrumentation plugin

```
std::map<uint64_t, std::string> AddrToSymbolName;
```

```
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Exception instrumentation plugin

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```
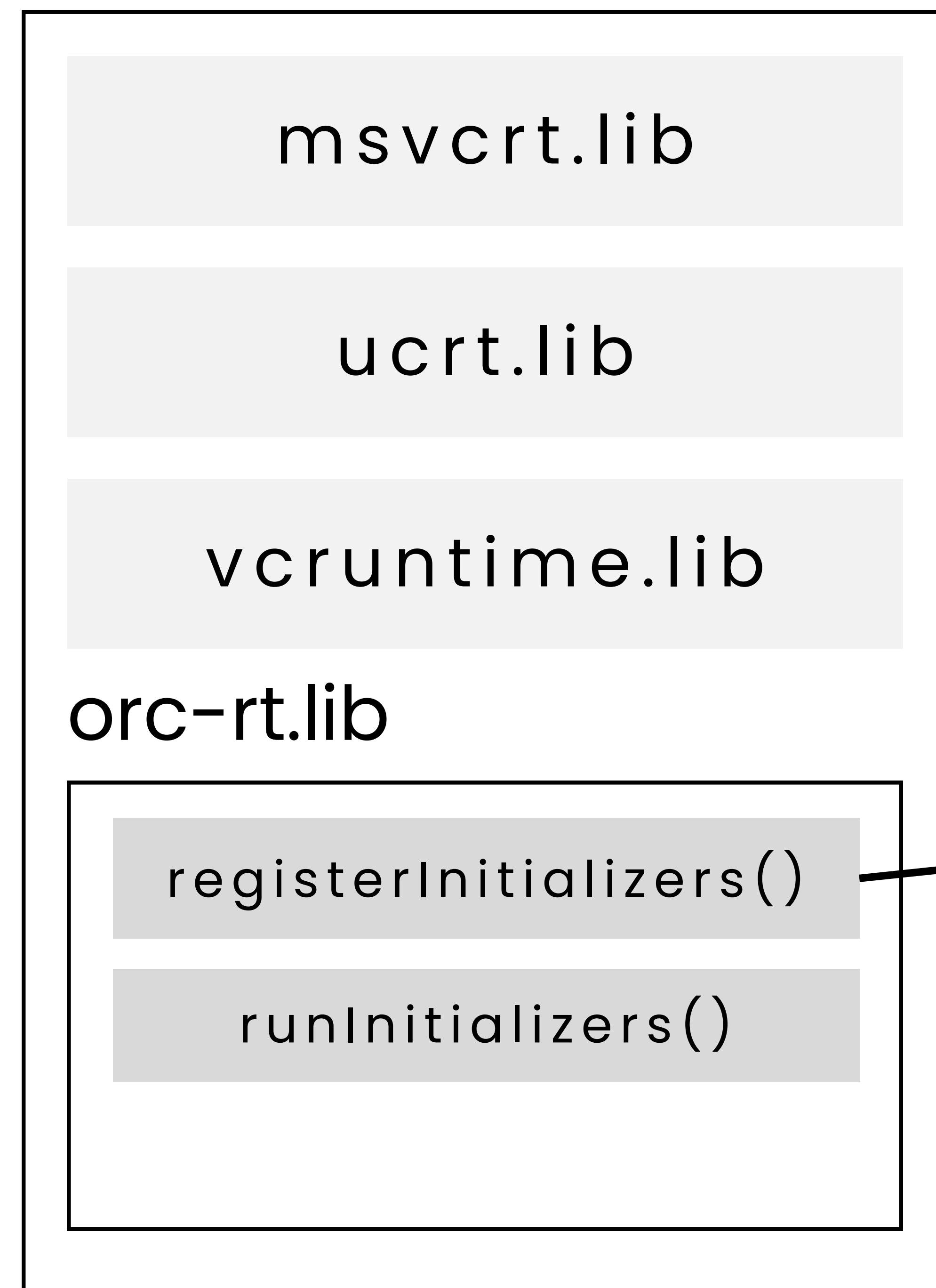
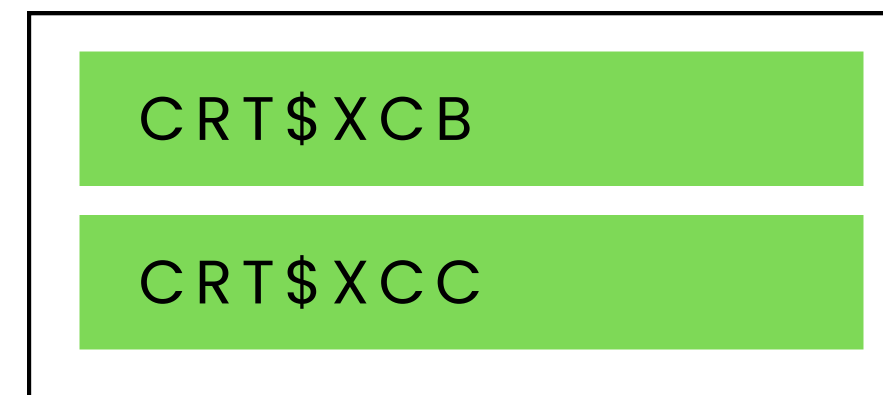

TIPS ON USING JITLINK IN COFF

ORC Runtime at startup



- COFFPlatform loads up vcruntime lib files and ORC runtime lib file.
- Uses JIT-linked orc runtime function to register and run static initializers
- ORC runtime itself uses JIT-linked STL library



TIPS ON USING JITLINK IN COFF

ORC Runtime at startup

Tips

- Care is needed to make sure ORC and vc runtime library files are available
  - by default, vc runtime libraries automatically detected from VC toolchain directories (can fail)
- Customizing vc runtime loading can be done by COFFVCRuntimeBootstrapper class
- It is still possible to use in-process vc runtime symbols, but need to export required symbols manually by using linker directive
  - #pragma comment(linker, "/export:??_7type_info@@6B@")

TIPS ON USING JITLINK IN COFF

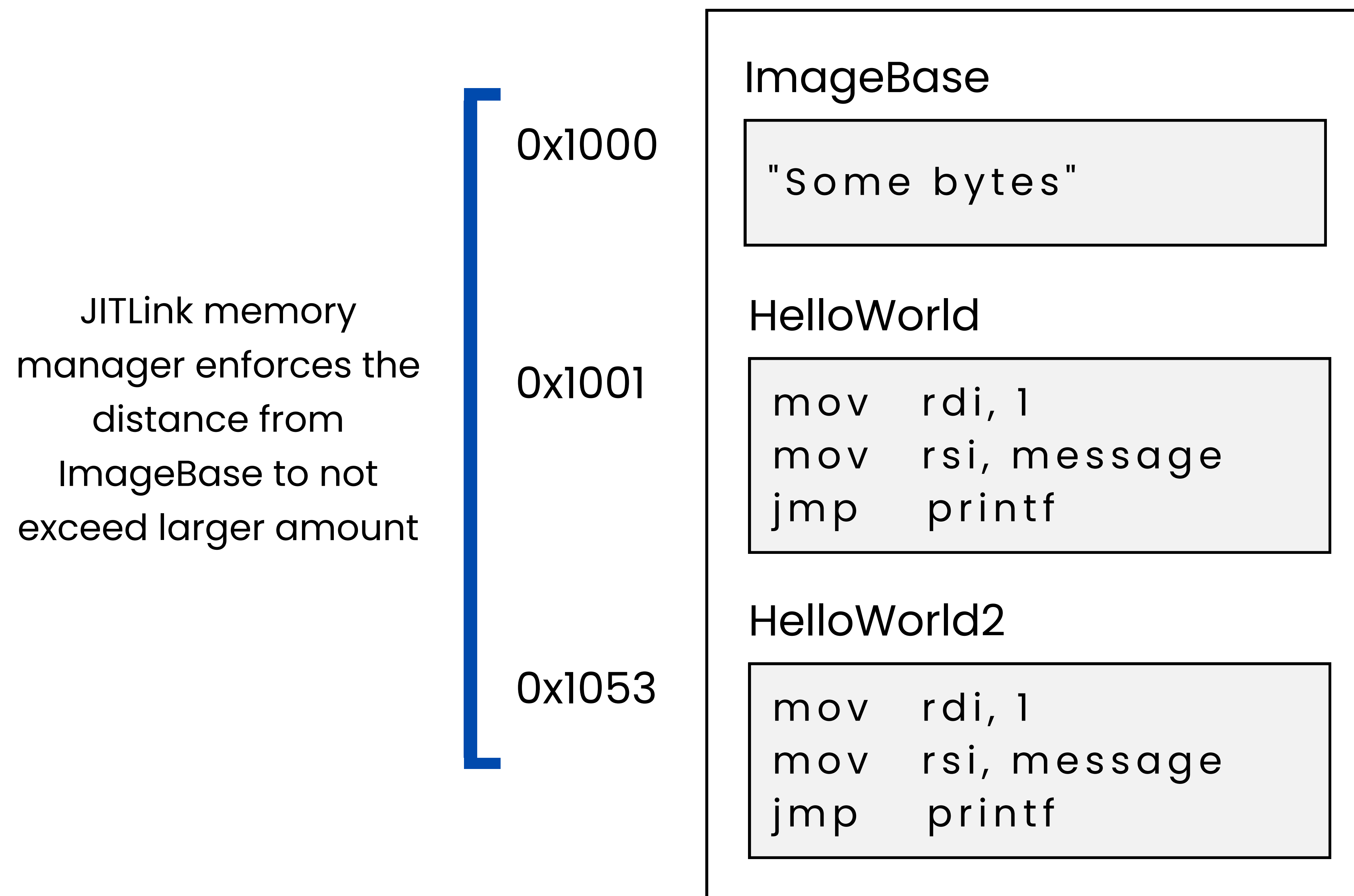
JITDYLIB: Emulated DYLIB inside JIT session

Challenges with COFF small code model

- Compilers assume that all symbols within the same executable or dylib are allocated close together
- It is not possible to "patch" instructions to use GOT pointer on demand when the required displacement exceeds 2Gb
- COFF x86 relocation points to the middle of instruction bytes
    - x86 encoding is not possible to be read backwards to know the start of instruction (for instructions of interest because of presence of RAX prefix)
    - -> can't patch this part

TIPS ON USING JITLINK IN COFF

JITDYLIB: Emulated DYLIB inside JIT session

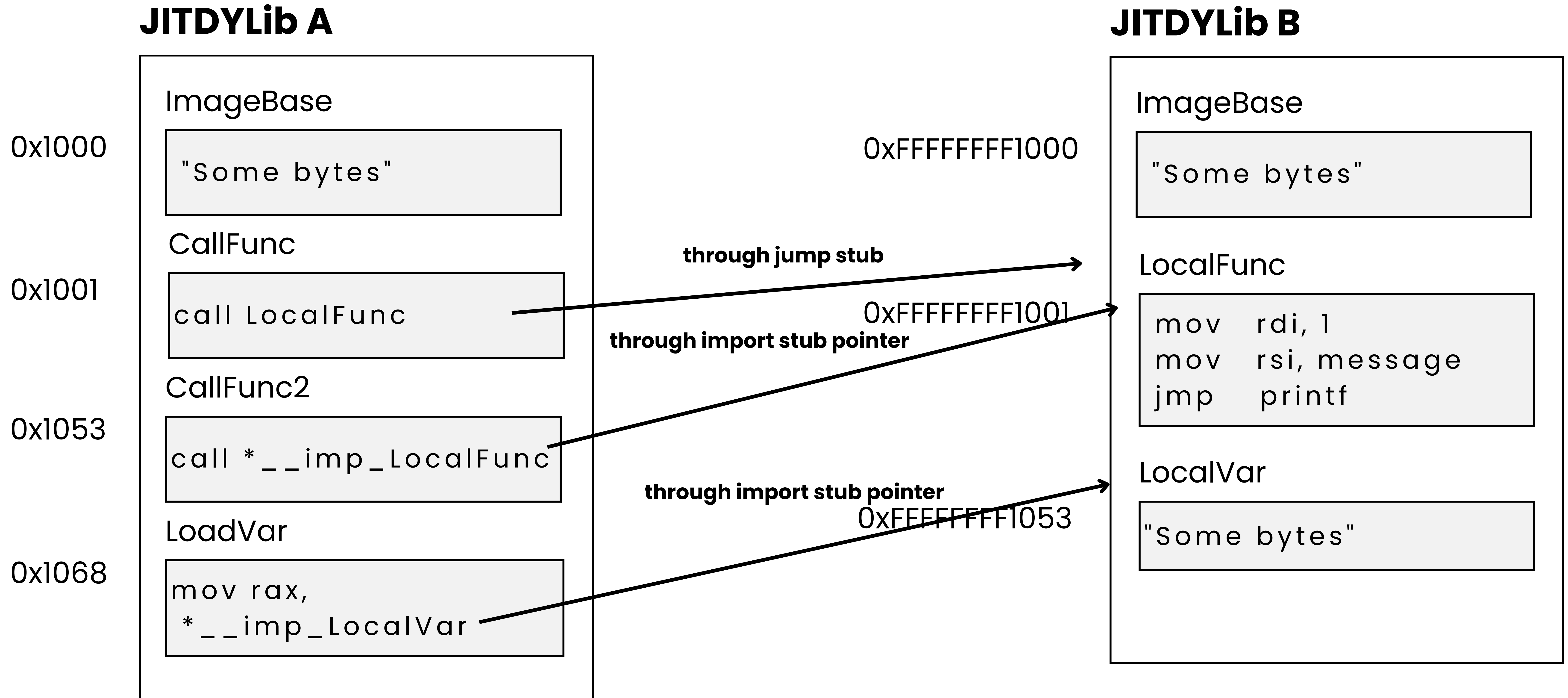


- Emulated dylib inside JIT session
- dlopen and dlclose JITDYLib inside JITted code

code linked by JITLink added

TIPS ON USING JITLINK IN COFF

JITDYLIB: Emulated DYLIB inside JIT session



TIPS ON USING JITLINK IN COFF

JITDYLIB: Emulated DYLIB inside JIT session

Tips

- Call function of another JITDYLib through usual call or dllimport attribute (__imp_)
- Access data of another JITDYLib only through dllimport attirbute (__imp_)
- Same practices are required in AOT world too but less clear in JIT world

THANKS

Code discussed today is available at:
https://github.com/sunho/LLVM-JITLink-COFF-Example