ORC

LLVM’s Next Generation of JIT API

Contents

- LLVM JIT APIs Past, Present and Future
- I will praise MCJIT
- Then I will critique MCJIT
- Then I'll introduce ORC
- Code examples available in the *Building A JIT* tutorial on llvm.org

Use Cases

Kaleidoscope

Simple and safe

LLDB

Cross-target compilation

High Performance JITs

Ability to configure optimizations and codegen

Interpreters and REPLs

Lazy compilation

Equivalence with static compile

Requirements

- Simple for beginners, configurable for advanced users
- Cross-target for LLDB, in-process for application scripting
- Lazy for interpreters, non-lazy for high-performance cases

We can support all of these requirements

But not behind a single interface…

ExecutionEngine

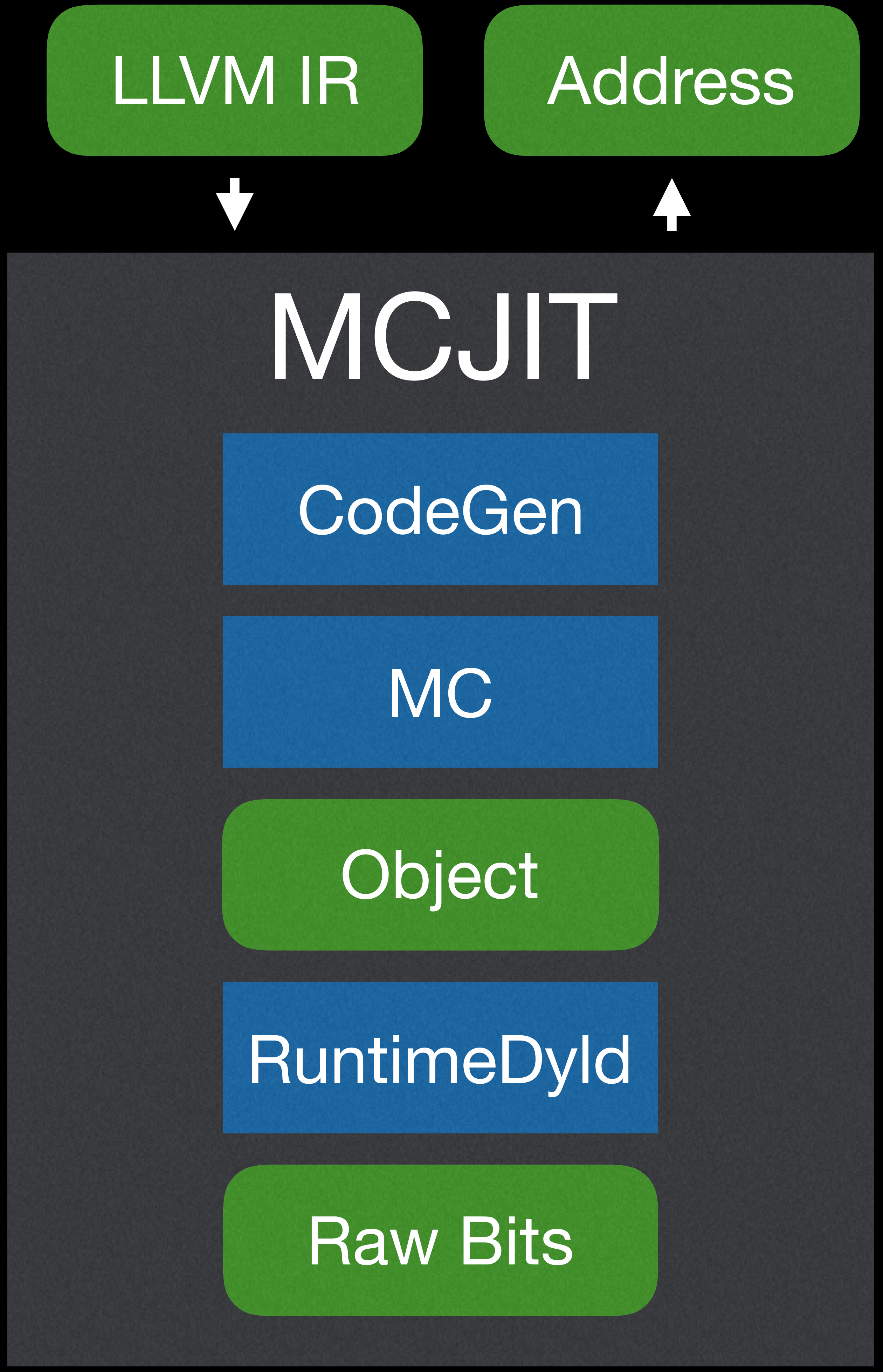
```
void addModule(Module*);

void *getPointerToFunction(Function*);

void addGlobalMapping(Function*, void*);

// Many terrible things that, trust me, you
// really don't want to know about.
```

JIT Implementations

- Legacy JIT (LLVM 1.0 — 3.5)
  - Introduced ExecutionEngine
  - Lazy compilation, in-process only
- MCJIT (LLVM 2.9 — present)
  - Implements ExecutionEngine
  - Cross-target, no lazy compilation
- ORC (LLVM 3.7 — present)
  - Forward looking API
  - Does NOT implement ExecutionEngine

MCJIT Design

- Static Pipeline with JIT Linker
- Efficient code and tool re-use
- Supports cross-target JITing
- Does not support lazy compilation



MCJIT Implementation

- Only accessible via ExecutionEngine
- Caused ExecutionEngine to bloat
- Can not support all of ExecutionEngine

ExecutionEngine

Symbol Query Horrors...

```
    void *getPointerToFunction(Function*)
uint64_t getFunctionAddress(const std::string&)
    void *getPointerToNamedFunction(StringRef)
    void *getPointerToFunctionOrStub(Function*)
uint64_t getAddressToGlobalIfAvailable(StringRef)
    void *getPointerToGlobalIfAvailable(StringRef)
    void *getPointerToGlobal(const GlobalValue*)
uint64_t getGlobalValueAddress(const std::string&)
    void *getOrEmitGlobalVariable(const GlobalVariable*)
```

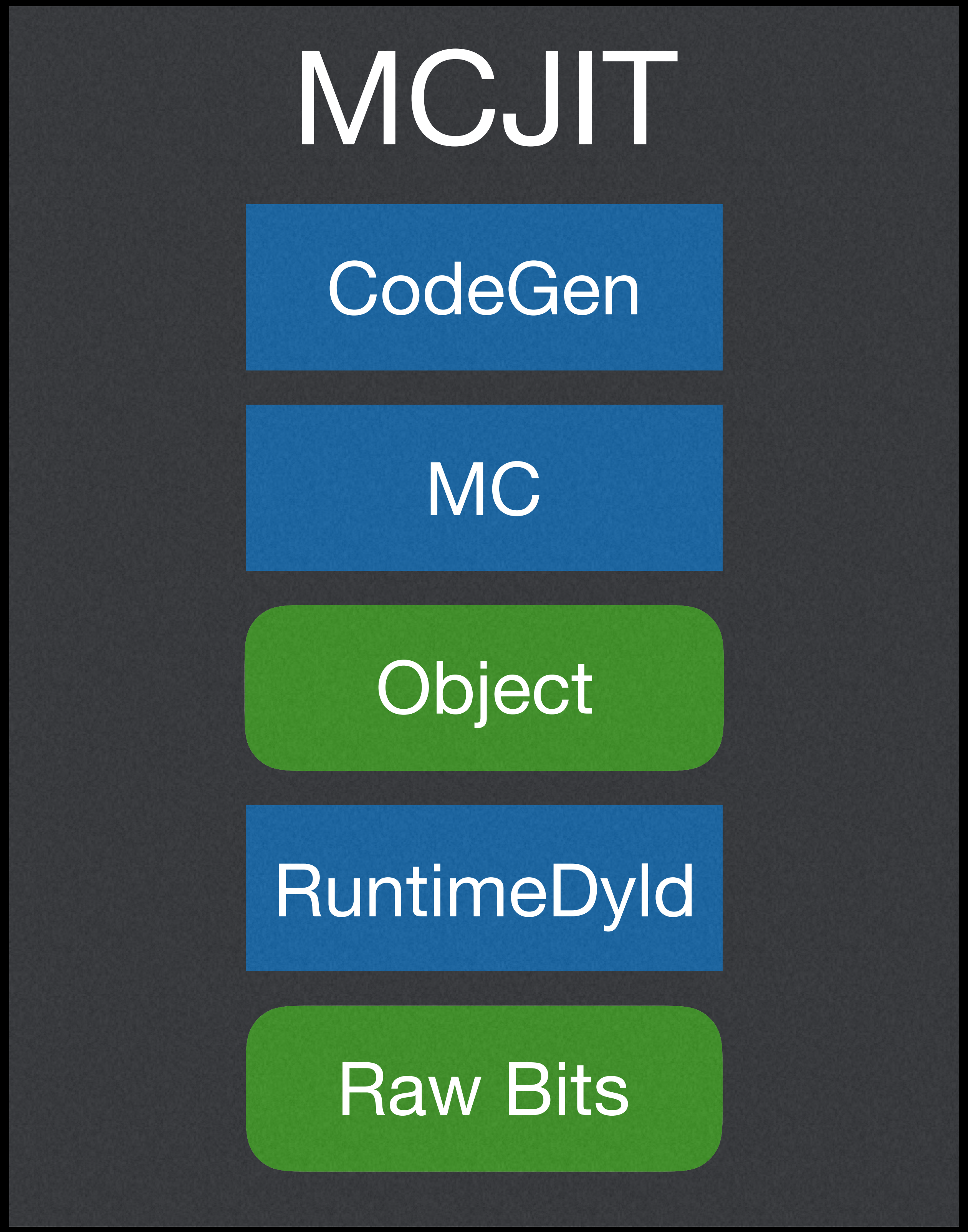
MCJIT Implementation

- Only accessible via ExecutionEngine
- Caused ExecutionEngine to bloat
- Can not support all of ExecutionEngine
- Limited visibility into internal actions
- No automatic memory management

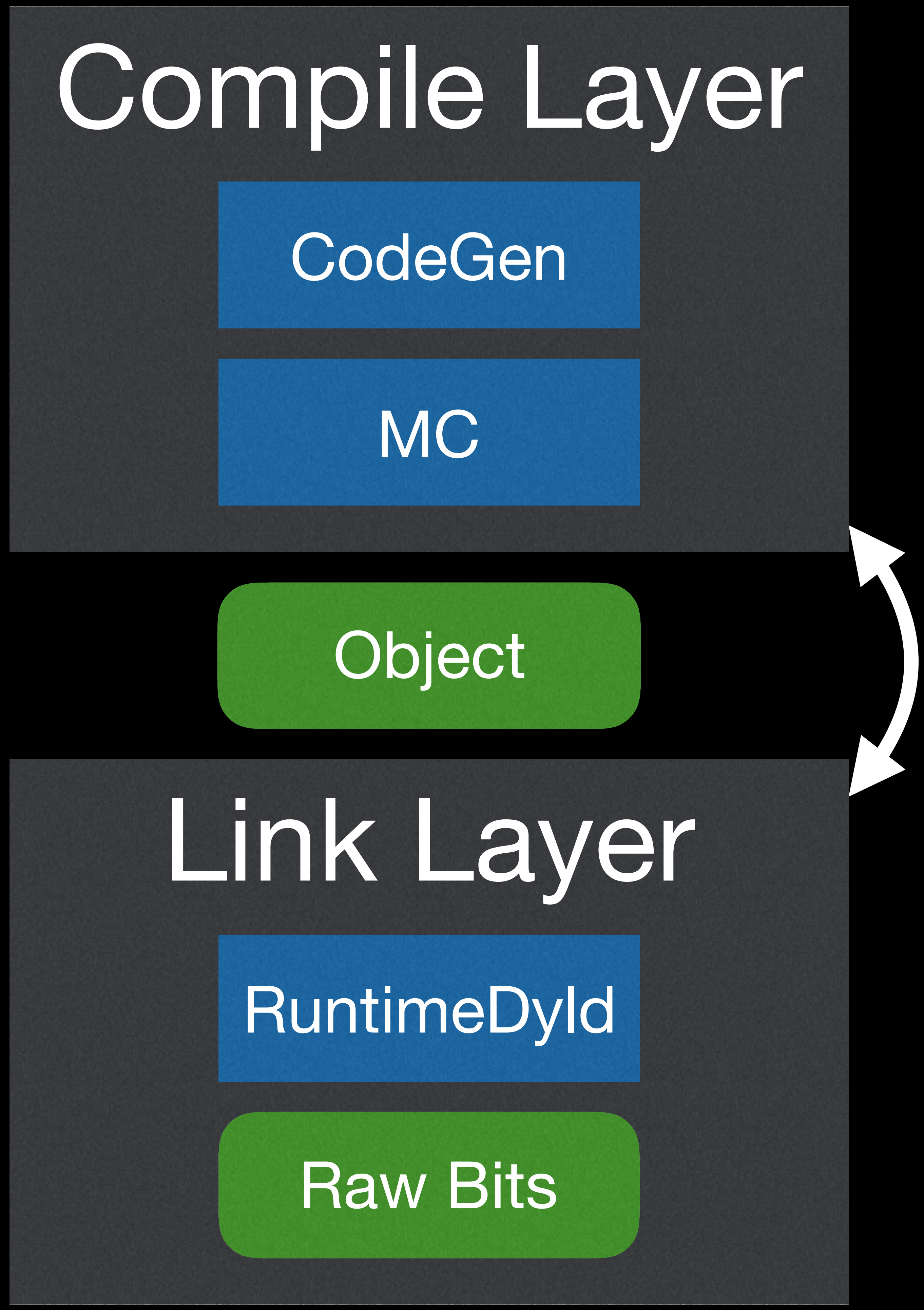
ORC — On Request Compilation

A Modular MCJIT

Modularizing MCJIT



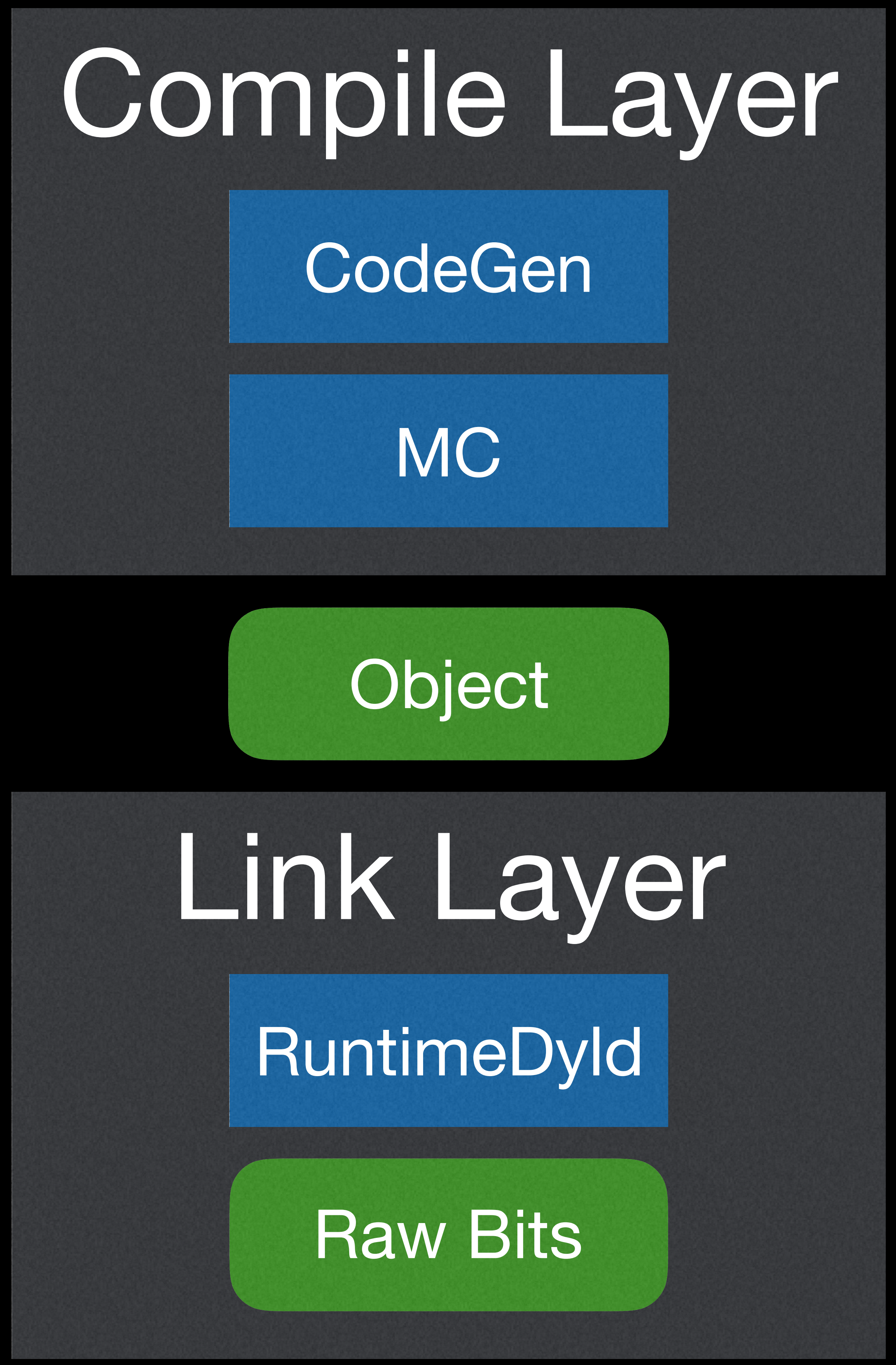
Modularizing MCJIT



Compile Layer forwards symbol queries to the link layer

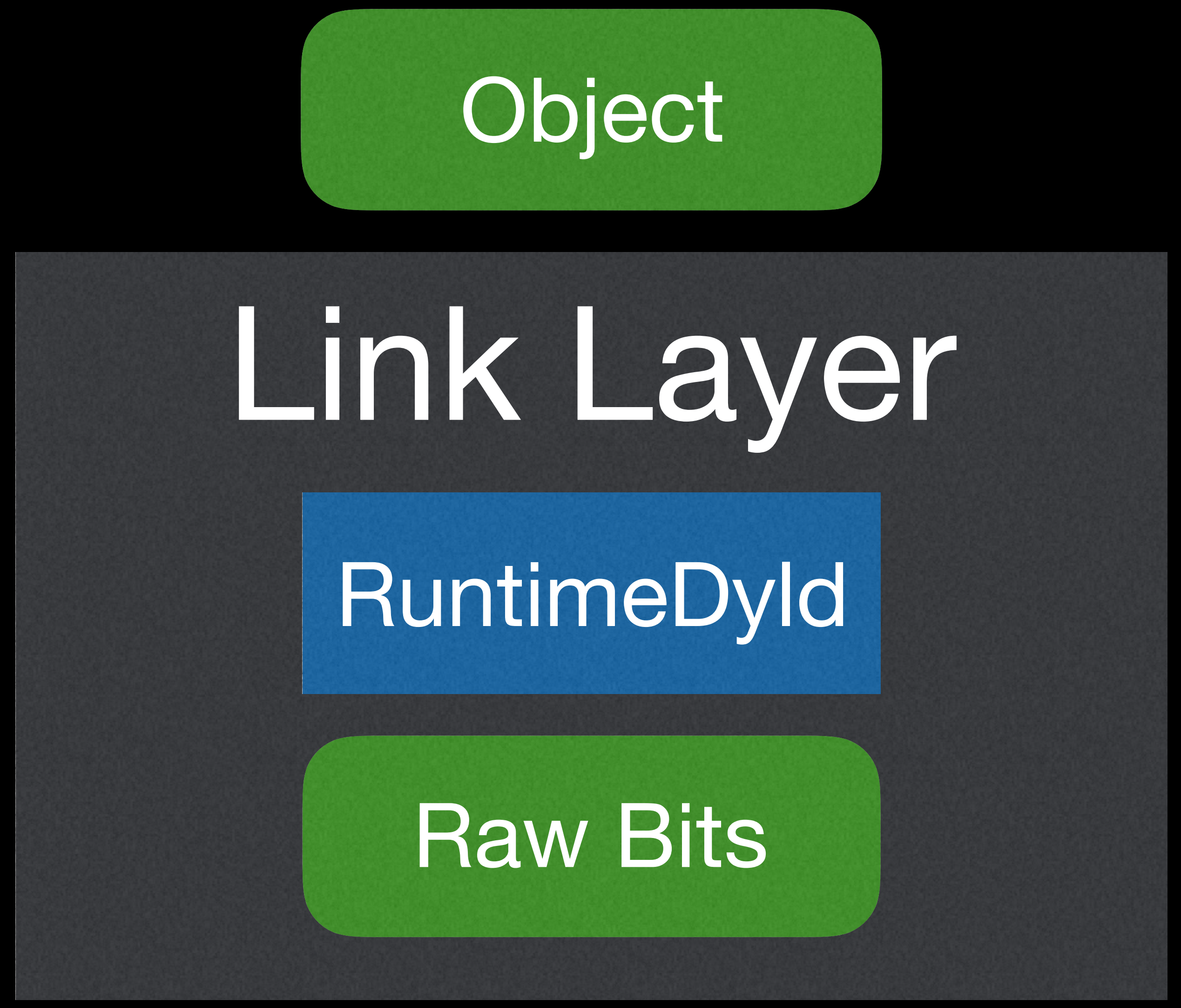
Initial Benefits

- Layers can be tested in isolation



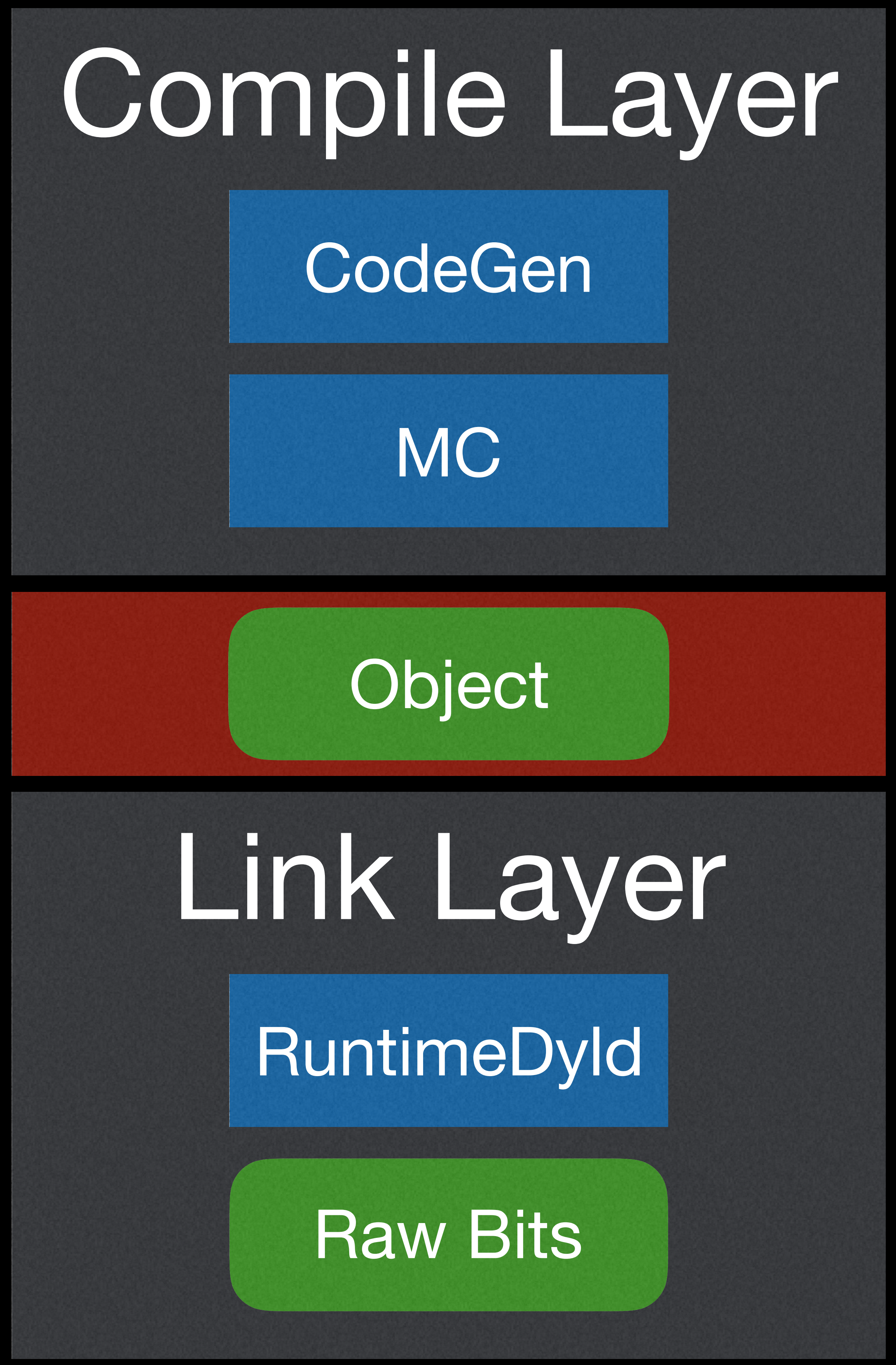
Initial Benefits

- Layers can be tested in isolation
  - E.g. Unit test the link layer



Initial Benefits

- Layers can be tested in isolation
  - E.g. Unit test the link layer
- Observe events without callbacks
  - E.g. Add a notification layer



The Layer Interface

- `Handle addModule(Module*, MemMgr*, Resolver*)`
  - Memory manager owns executable bits
  - Resolver provides symbol resolution
- `JITSymbol findSymbol(StringRef, bool)`
- `void removeModule(Handle)`

Example: Basic Composition

```
…
ObjectLinkingLayer LinkLayer;
SimpleCompiler Compiler(TargetMachine());
IRCompileLayer<…> CompileLayer(LinkLayer, Compiler);
…
```

Example: Basic Composition

```
class MyJIT {
  …
  ObjectLinkingLayer LinkLayer;
  SimpleCompiler Compiler(TargetMachine());
  IRCompileLayer<…> CompileLayer(LinkLayer, Compiler);
  …
};
```

Example: Basic Composition

```
…
ObjectLinkingLayer LinkLayer;
SimpleCompiler Compiler(TargetMachine());
IRCompileLayer<…> CompileLayer(LinkLayer, Compiler);
…
```

Example: Basic Composition

```
…
ObjectLinkingLayer LinkLayer;
SimpleCompiler Compiler(TargetMachine());
IRCompileLayer<…> CompileLayer(LinkLayer, Compiler);

CompileLayer.addModule(Mod, MemMgr, SymResolver);
auto FooSym = CompileLayer.findSymbol("foo", true);
auto Foo = reinterpret_cast<int(*)()>(FooSym.getAddress());
int Result = Foo(); // <— Call into JIT'd code.
…
```

Memory Managers

- Own executable code, free it on destruction
- Inherit from RuntimeDyld::MemoryManager
- Custom memory managers supported
- SectionMemoryManager provides a good default

Symbol Resolvers

```
auto Resolver =
  createLambdaResolver(
    [&](StringRef Name) {
      return CompileLayer.findSymbol(Name, false);
    },
    [&](StringRef Name) {
      return getSymbolAddressInProcess(Name);
    });
```

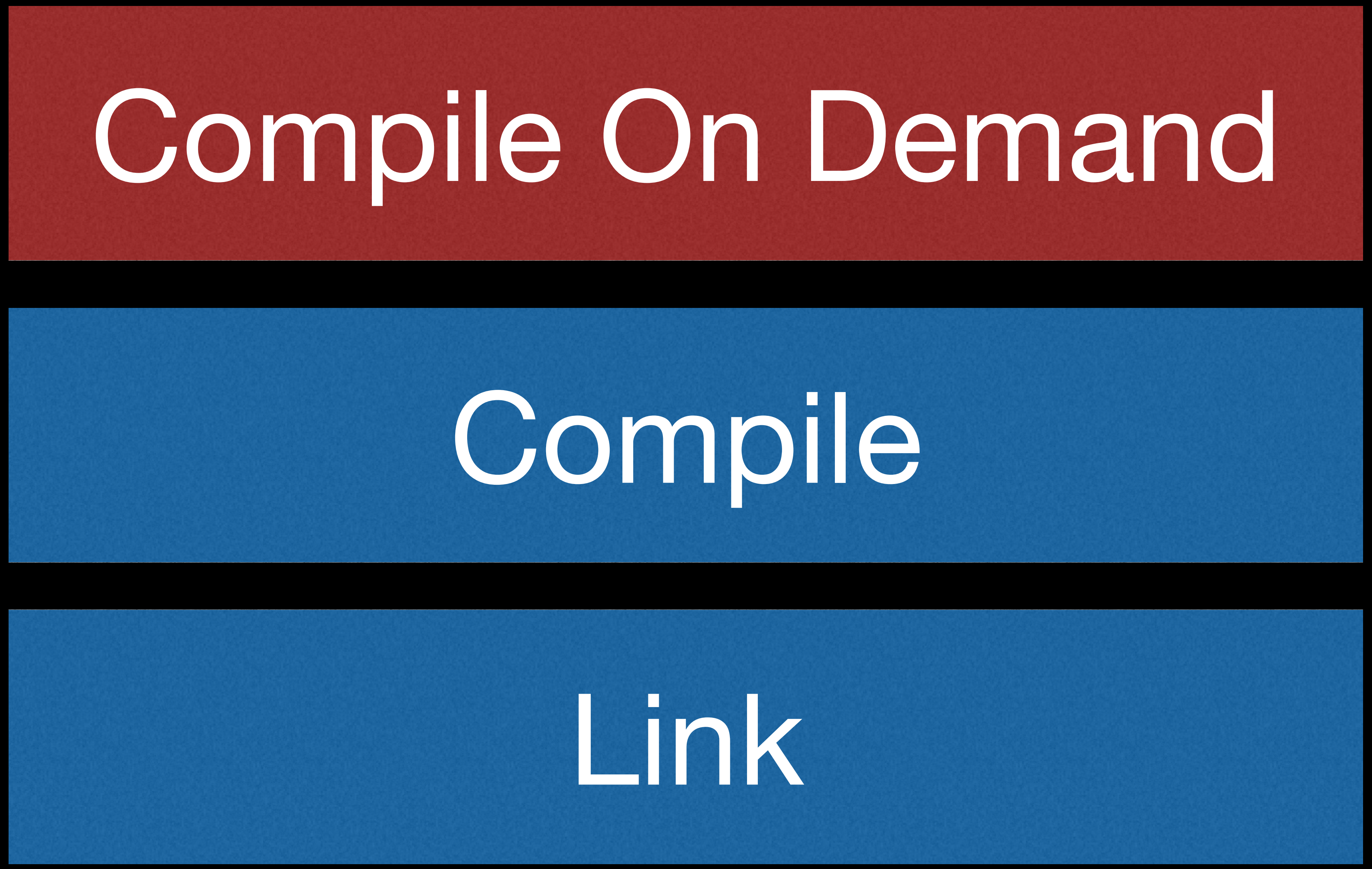
- First lambda implements in-image lookup
- Second implements external lookup

The Story So Far

- Layers wrap up JIT functionality to make it composable
- Build custom JITs by composing layers
- Memory managers handle memory ownership
- Symbol resolvers handle symbol resolution

Adding New Features

- New layers provide new features
- Compile On Demand Layer
  - addModule builds function stubs that trigger lazy compilation
  - Symbol queries resolve to stubs



Without Laziness

```
ObjectLinkingLayer LinkLayer;
SimpleCompiler Compiler(TargetMachine());
IRCompileLayer<…> CompileLayer(LinkLayer, Compiler);

CompileLayer.addModule(Mod, MemMgr, SymResolver);
auto FooSym = CompileLayer.findSymbol("foo", true);
auto Foo = reinterpret_cast<int(*)()>(FooSym.getAddress());
int Result = Foo(); // <—— Call foo.
```

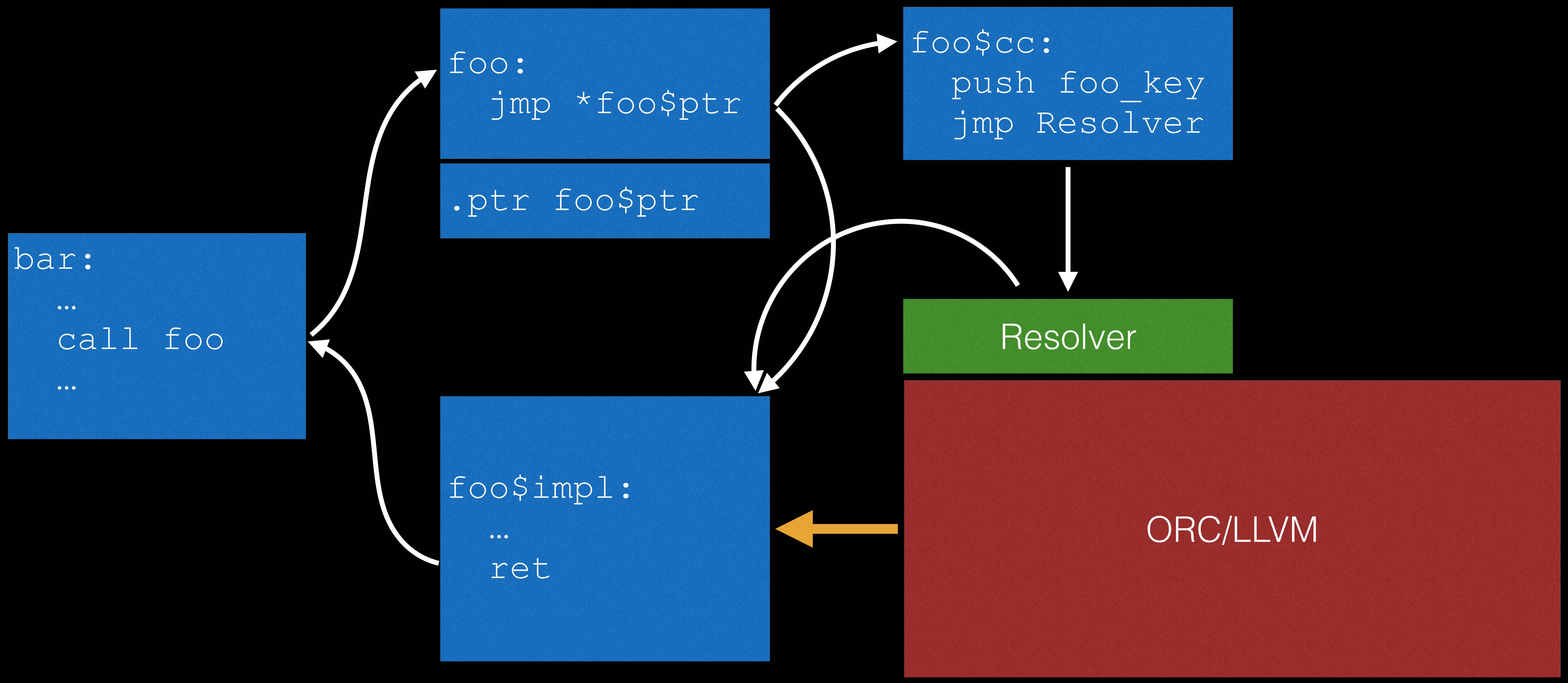
With Laziness

```
ObjectLinkingLayer LinkLayer;
SimpleCompiler Compiler(TargetMachine());
IRCompileLayer<…> CompileLayer(LinkLayer, Compiler);
CompileOnDemandLayer<…> CODLayer(CompileLayer, …);

CODLayer.addModule(Mod, MemMgr, SymResolver);
auto FooSym = CODLayer.findSymbol("foo", true);
auto Foo = reinterpret_cast<int(*)()>(FooSym.getAddress());
int Result = Foo(); // <—— Call foo's stub.
```

COD Layer Requirements

- Indirect Stubs Manager
  - Create named indirect stubs (indirect jumps via pointers)
  - Modify stub pointers
- Compile Callback Manager
  - Create compile callbacks (re-entry points in the compiler)

Compile Callbacks



Callbacks and Stubs

```
auto StubsMgr = … ;
auto CCMgr = … ;

auto CC = CCMgr.getCompileCallback();
StubsMgr.createStub("foo", CC.getAddress(), Exported);

CC.setCompileAction([&]() -> TargetAddress {
  printf("Hello world");
  return 0;
});

auto FooSym = StubsMgr.findStub("foo", true);
auto Foo = static_cast<int(*)()>(FooSym.getAddress());
int Result = Foo();
```

Prints “Hello world”, then jumps to 0

Callbacks and Stubs

```
auto StubsMgr = … ;
auto CCMgr = … ;

auto CC = CCMgr.getCompileCallback();
StubsMgr.createStub("foo", CC.getAddress(), Exported);

CC.setCompileAction([&]() -> TargetAddress {
  CompileLayer.addModule(FooModule, MemMgr, Resolver);
  return CompileLayer.findSymbol("foo", true).getAddress();
});

auto FooSym = StubsMgr.findStub("foo", true);
auto Foo = static_cast<int(*)()>(FooSym.getAddress());
int Result = Foo();
```

Lazily compiles “foo” from existing IR

Callbacks and Stubs

```
auto StubsMgr = … ;
auto CCMgr = … ;

auto CC = CCMgr.getCompileCallback();
StubsMgr.createStub("foo", CC.getAddress(), Exported);

CC.setCompileAction([&]() -> TargetAddress {
  CompileLayer.addModule(IRGen(FooAST), MemMgr, Resolver);
  return CompileLayer.findSymbol("foo", true).getAddress();
});

auto FooSym = StubsMgr.findStub("foo", true);
auto Foo = static_cast<int(*)()>(FooSym.getAddress());
int Result = Foo();
```

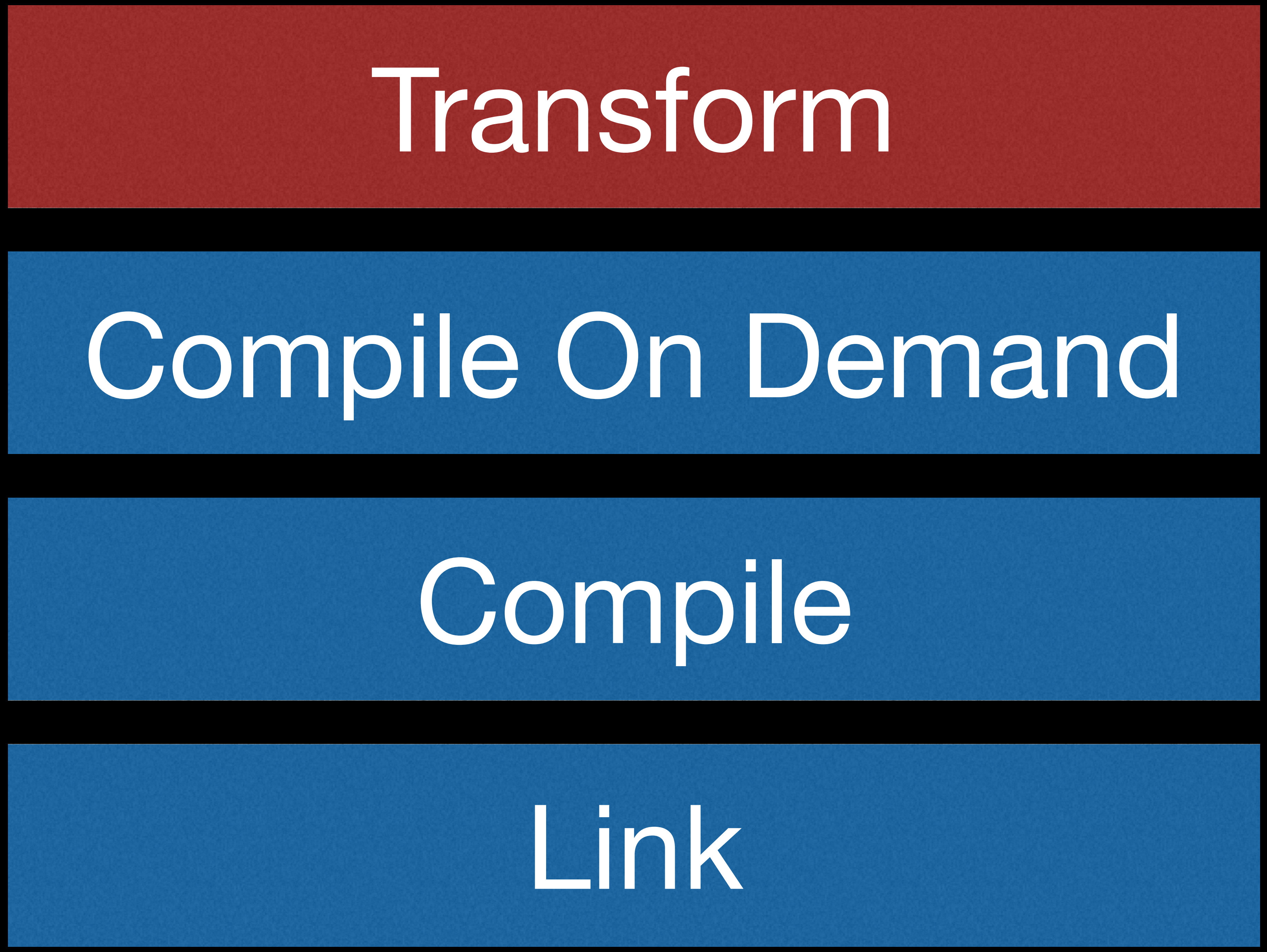
Lazily compiles “foo” from AST

Laziness Recap

- Callbacks and Stubs
  - Provide direct access to lazy compilation
  - Push laziness earlier in the compiler pipeline
- CompileOnDemand provides off-the-shelf laziness for IR
- ORC supports arbitrary laziness with a clean API

Adding New Layers

- Transform Layer
  - addModule runs a user-supplied transform function on the module
  - Symbol queries are forwarded
  - Above C.O.D.: Eager optimizations
  - Below C.O.D.: Lazy optimizations



Layers and Modularity

Pick features “off the shelf”

Mix and match components:
experiment with new designs

Create, modify and share new features
without breaking existing clients

Remote JIT Support

Remote JIT Support

- Execute code on a different process / machine / architecture
- Enables JIT code to be sandboxed
- MCJIT supported remote compilation, but required a lot of manual work
- OrcRemoteTarget client/server provides high level API
  - Remote mapped memory, stub and callback managers
  - Symbol queries
  - Execute remote functions

Local Laziness

```
auto StubsMgr = … ;
auto CCMgr = … ;

auto CC = CCMgr.getCompileCallback();
StubsMgr.createStub(“foo”, CC.getAddress(), Exported);

CC.setCompileAction([&]() -> TargetAddress {
  CompileLayer.addModule(IRGen(FooAST), MemMgr, Resolver);
  return CompileLayer.findSymbol(“foo”, true).getAddress();
});

auto FooSym = StubsMgr.findStub(“foo”, true);
auto Foo = static_cast<int(*)()>(FooSym.getAddress());
int Result = Foo();
```

Remote Laziness

```
auto RT = … ;
auto StubsMgr = RT.createStubsMgr();
auto CCMgr = RT.createCallbackMgr();

auto CC = CCMgr.getCompileCallback();
StubsMgr.createStub("foo", CC.getAddress(), Exported);

CC.setCompileAction([&]() -> TargetAddress {
  CompileLayer.addModule(IRGen(FooAST), RT.createMemMgr(),
                         Resolver);
  return CompileLayer.findSymbol("foo", true).getAddress();
});

auto FooSym = StubsMgr.findStub("foo", true);
int Result = RT.callIntVoid(FooSym.getAddress());
```

Demo

Remote JIT Support

- Remote JITing with ORC is easy
- Remoteness is orthogonal to other features, including laziness
- Security implications are serious
    - Sandbox the server, authenticate the client, encrypt the channel
    - Treat like mains electricity: very useful, but safety first!

Future Opportunities

- New development modes: edit/test vs edit/compile/test
- Remote interpreters for development on embedded devices
- Distributing work for clusters
  - Compute
  - Database queries

ORC vs MCJIT

- Same underlying architecture: static compiler + JIT linker
- ORC
  - Offers a strict superset of features
  - A more flexible API
  - Supports remoteness and laziness
  - Has better memory management
- OrcMCJITReplacement provides a transition path

Future Goals

- Kill off ExecutionEngine, design a new in-tree JIT (for LLI and C-API)
- New layers and components (e.g. hot function recompilation)
- API cleanup: Core abstractions are in place but need polish
- More architectural and relocation support (Fix RuntimeDyldELF!)
- Check out the Building A JIT tutorial
- Get involved: http://llvm.org/bugs, OrcJIT component