Pointer Authentication

What Compiler Implementers and Language Designers Need to Know

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Agenda

Protecting control flow integrity

Pointer authentication basics

Pointer authentication in Clang and Swift

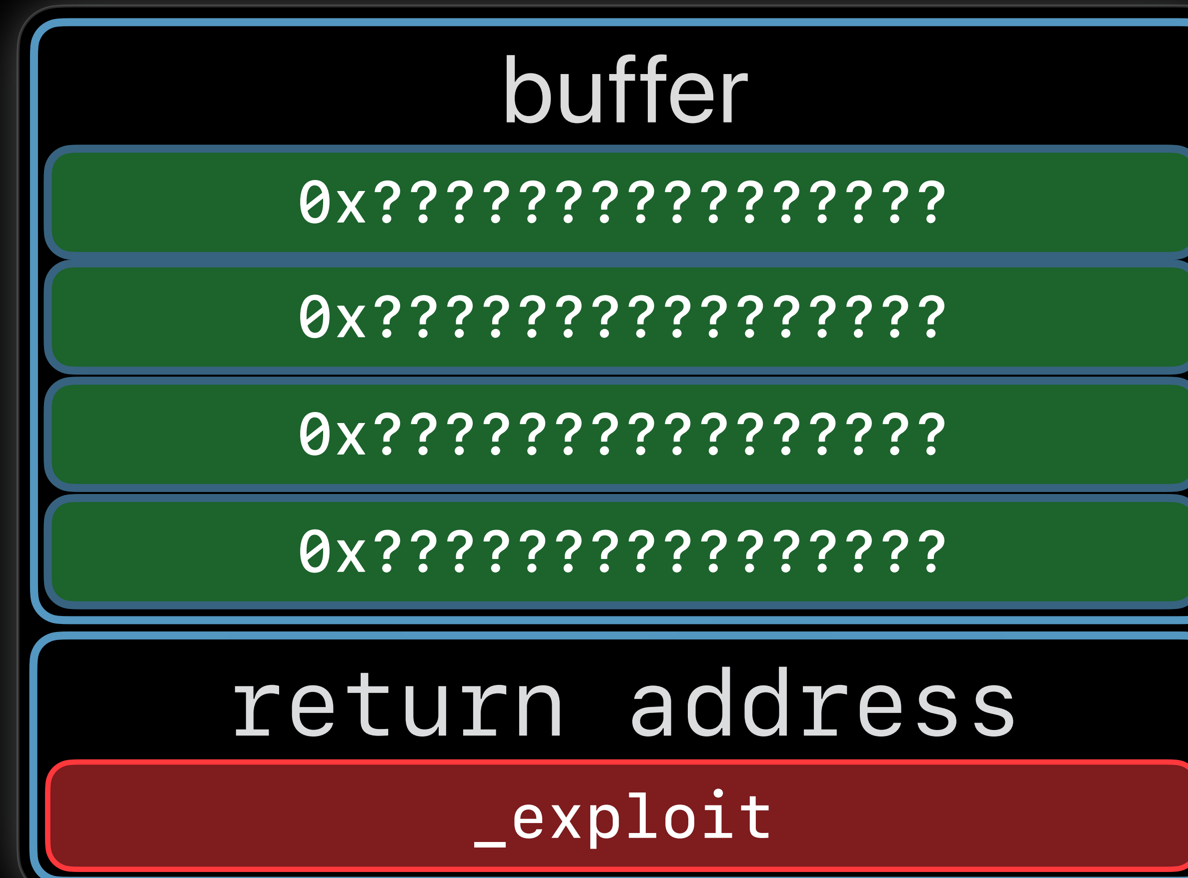
Supporting pointer authentication in your compiler

Designing features to support pointer authentication

Hijacking the return address

- Buffer overflow enables attack to overwrite return address
- This violates control flow integrity
- On return the attacker is in control

```c
void f(char *src, int sz) {
  char buffer[4];
  memcpy(buffer, src, sz);
}
```




```
_exploit:
  bl        _system
  ...
```

Pointer authentication protects control flow

- Hardware supported control flow integrity
- Embeds a cryptographic signature into high bits of pointers
- Signature validated prior to any future use

```
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```
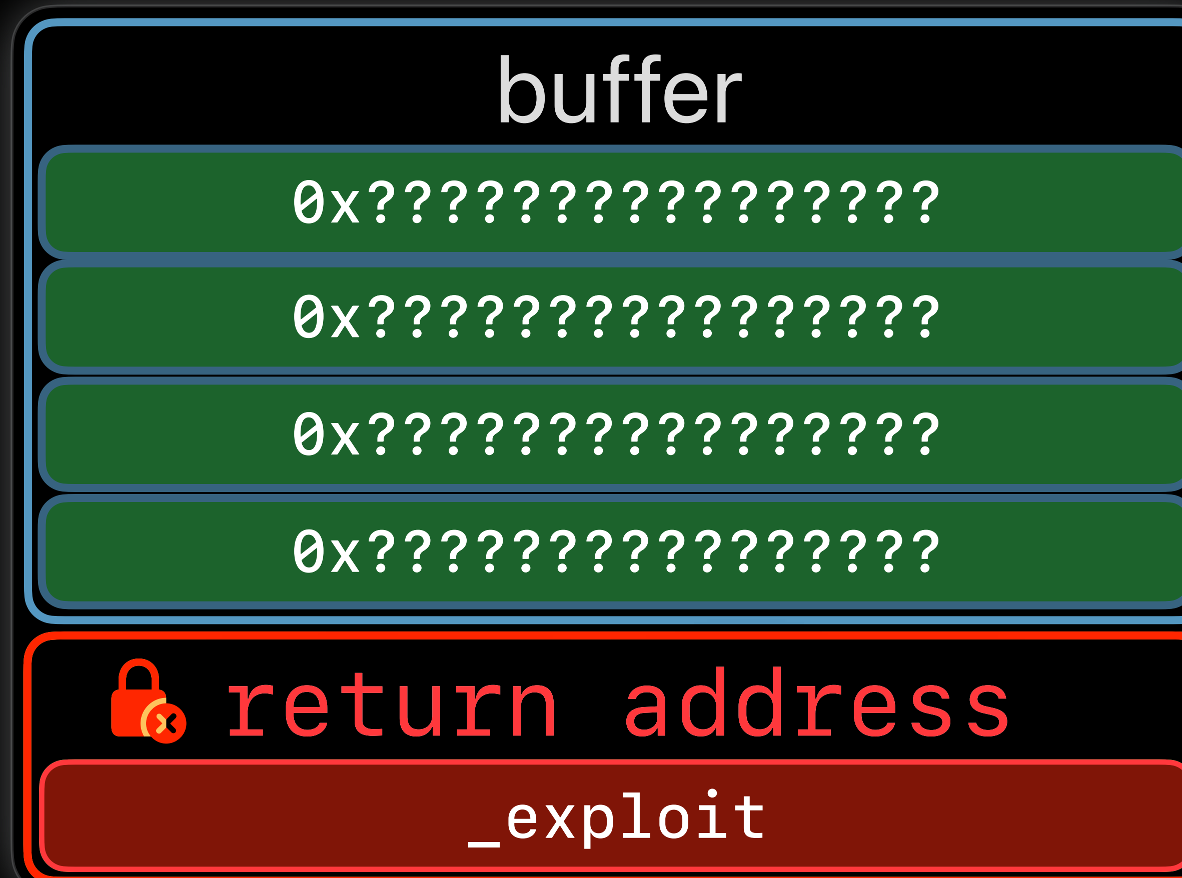
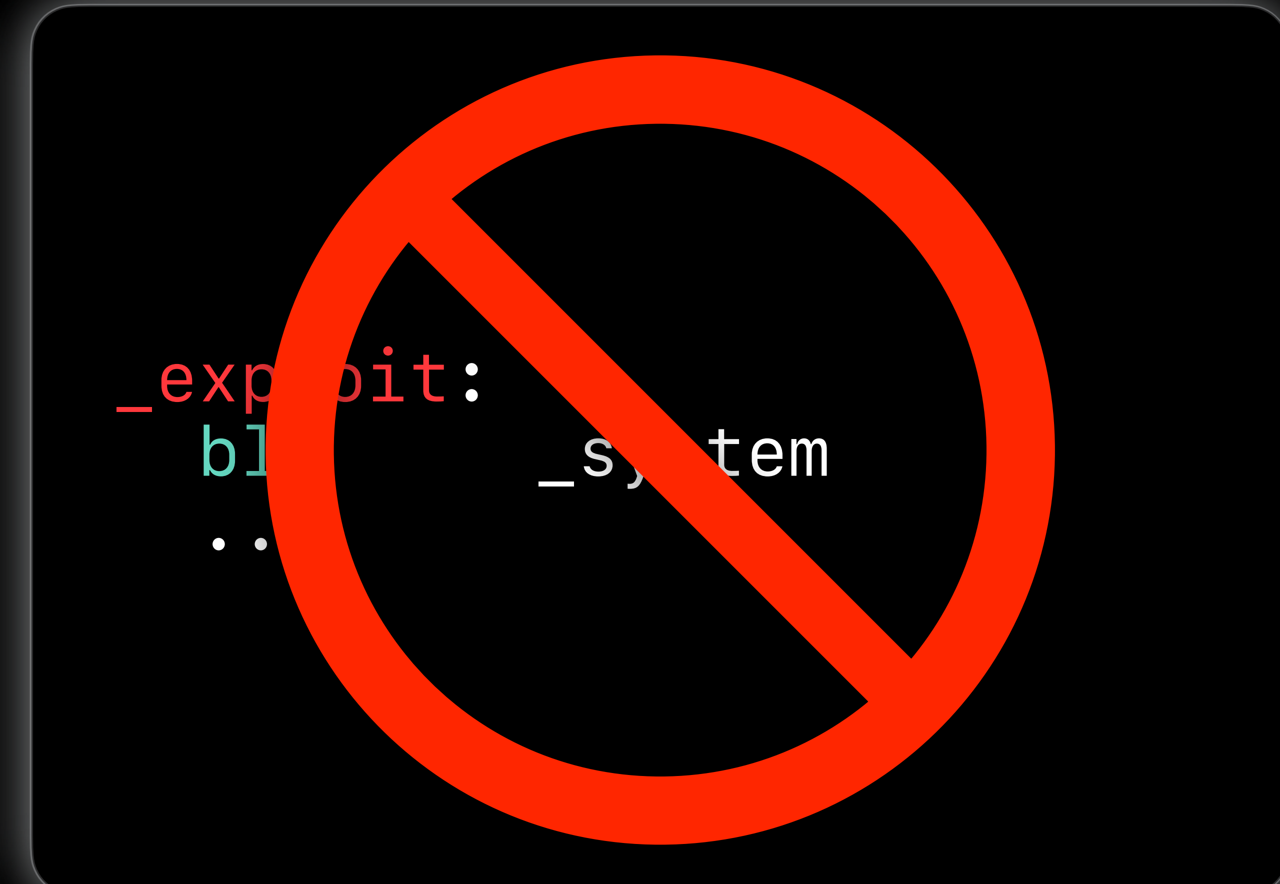





Safe languages require pointer authentication too

- Programs written in safe languages still rely on unsafe library code
- Memory safety bugs in unsafe code can corrupt data structures in safe code
- Must protect control flow integrity of safe languages

Pointer authentication in Clang and Swift

- Apple implemented extensive language support in all system languages
  - C, C++, Objective-C, and Swift
- Supported pointer authentication since iPhone Xs and all Apple silicon Macs
- Deployed across kernel- and userspace
- Backend and language support has been upstreamed to llvm.org

Not just an Apple technology

- Introduced in ARMv8.3 and is supported by an increasing number of CPU vendors across the industry
- Linux and Windows ARM64 support pointer authentication to protect call stack
- Support for advanced protection schemas being implemented in Linux
- Pointer authentication is becoming a baseline security expectation across the ARM ecosystem

Goals for this talk

- Convince you to implement support for pointer authentication in your language and compiler
- Explain how to design language features with compatibility for pointer authentication

Why your language needs pointer authentication

- Pointer authentication is a process wide ABI, so applications can only use your language if it also supports that ABI
- Unsafe code can undermine safety guarantees in safe languages
- Match the protection level of other languages in the process

Adopt pointer authentication in your language

- Enable basic pointer authentication support in LLVM
- Protect runtime data structures
- Design language features with pointer authentication in mind

Enable basic pointer authentication support in LLVM

- LLVM already provides the basic pointer authentication ABI
- Make pointer authentication instructions and intrinsics available
  - Include `+pauth` feature in TargetMachine configuration
- Make LLVM use platform pointer authentication ABI
  - Attach `ptrauth-returns` and `ptrauth-calls` attributes to llvm::Function definitions

Protect runtime data structures

- Programming languages and their compilers are responsible for protecting their own languages features
- Identify what data needs to be protected
- Design authentication schemes to protect that data
- Implement those schemes

Identify what needs to be protected

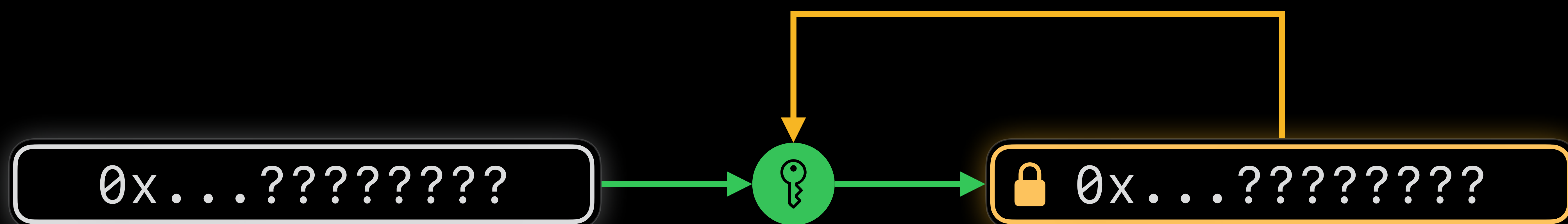
- Focus on features that impact control flow
- Critical to protect all forms of dynamic dispatch: function pointers, virtual functions, existential type tables, etc.
- Languages with rich runtime metadata need to protect information that can influence type and object behavior

Design authentication schemes to protect that data

- Any form of pointer authentication prevents an attacker from corrupting a pointer
- Attackers now have to copy and reuse validly signed pointers in invalid places
- Compilers can provide a custom discriminator for signing and authentication
- Compilers need to use different authentication schemes for different data to prevent pointer reuse attacks

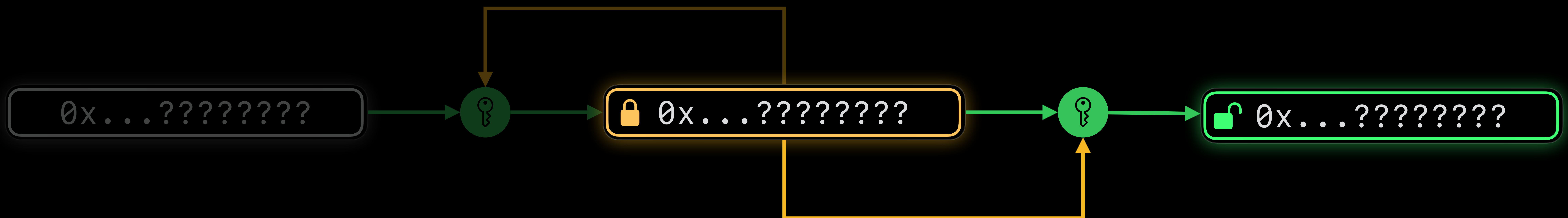
Address discrimination

- Special case is address discrimination
- Compiler uses the storage address of a pointer as discriminator



Address discrimination

- Special case is address discrimination
- Compiler uses the storage address of a pointer as discriminator
- Signature is only valid when the pointer is stored at that specific location in memory
- An attacker can no longer copy the pointer at all



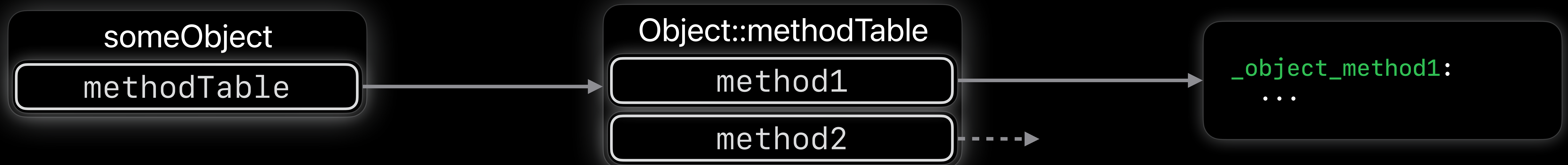
Trade offs in authentication schemes

- Choice of discriminator impacts the security properties of the signature
- Strongest options may not be compatible with existing language features or code
- Address discrimination provides tremendous security value but is incompatible with memcpy semantics

Protect dynamic dispatch

Protect class based polymorphism

- Object instances contain pointers to class metadata or method table
- Structures like this are powerful attack vectors and should be authenticated

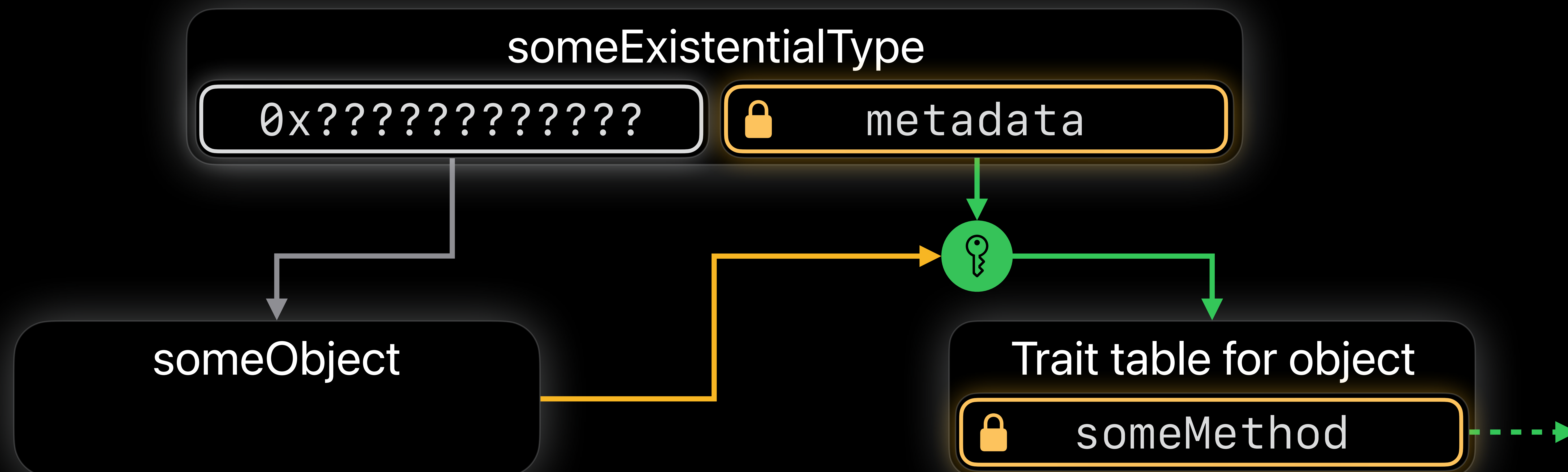


Protect class based polymorphism

- Object instances contain pointers to class metadata or method table
- Structures like this are powerful attack vectors and should be authenticated
- Use pointer authentication to protect each link in dispatch chain
  - Authentication should incorporate identity of owning object

Protect existential types

- Implemented as tuple of an object and metadata pointer
- Compromising the metadata is as powerful as class based polymorphism
- Even though separate values, authentication can still include object address



Implement your authentication schemes

- LLVM has all you need
- The `llvm.ptrauth.sign` and `llvm.ptrauth.auth` intrinsics do the heavy lifting
- The `llvm.ptrauth.blend` intrinsic lets a compiler combine constant and dynamic discriminators
- Compilers should not update a signature by authenticating and then signing the pointer. Use the `llvm.ptrauth.resign` to this safely and automatically

Do not design to require memcpy semantics

Design features with pointer authentication in mind

- Do not design to require memcpy semantics
- Avoid designs that require pointer tagging to be implemented efficiently
- Features can never require a compiler to generate code that could sign untrusted data
  - Untrusted does not mean from the internet, it means from writable memory

Summary

- Pointer authentication is proven, hardware-backed protection against control flow attacks with industry-wide adoption
- Safe languages also need pointer authentication
- Enable basic pointer authentication provided by LLVM
- Protect runtime data structures to close additional control-flow attack surfaces
- Design language features compatible with pointer authentication

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